Colorado State University

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

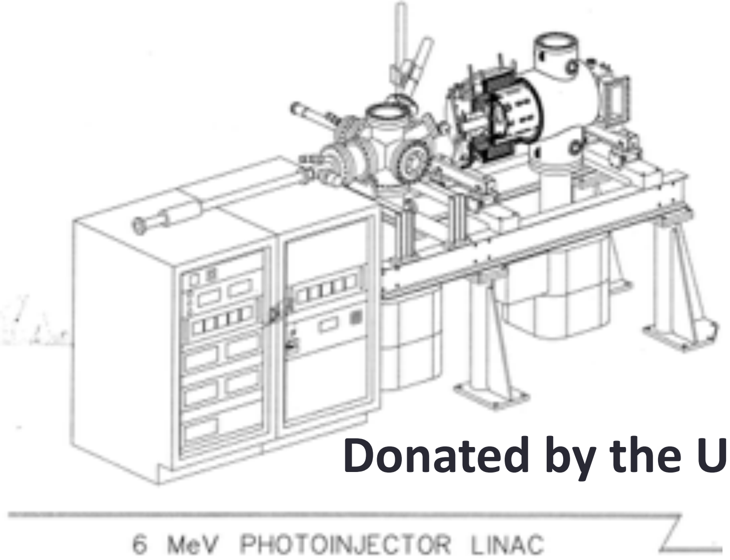
Background

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

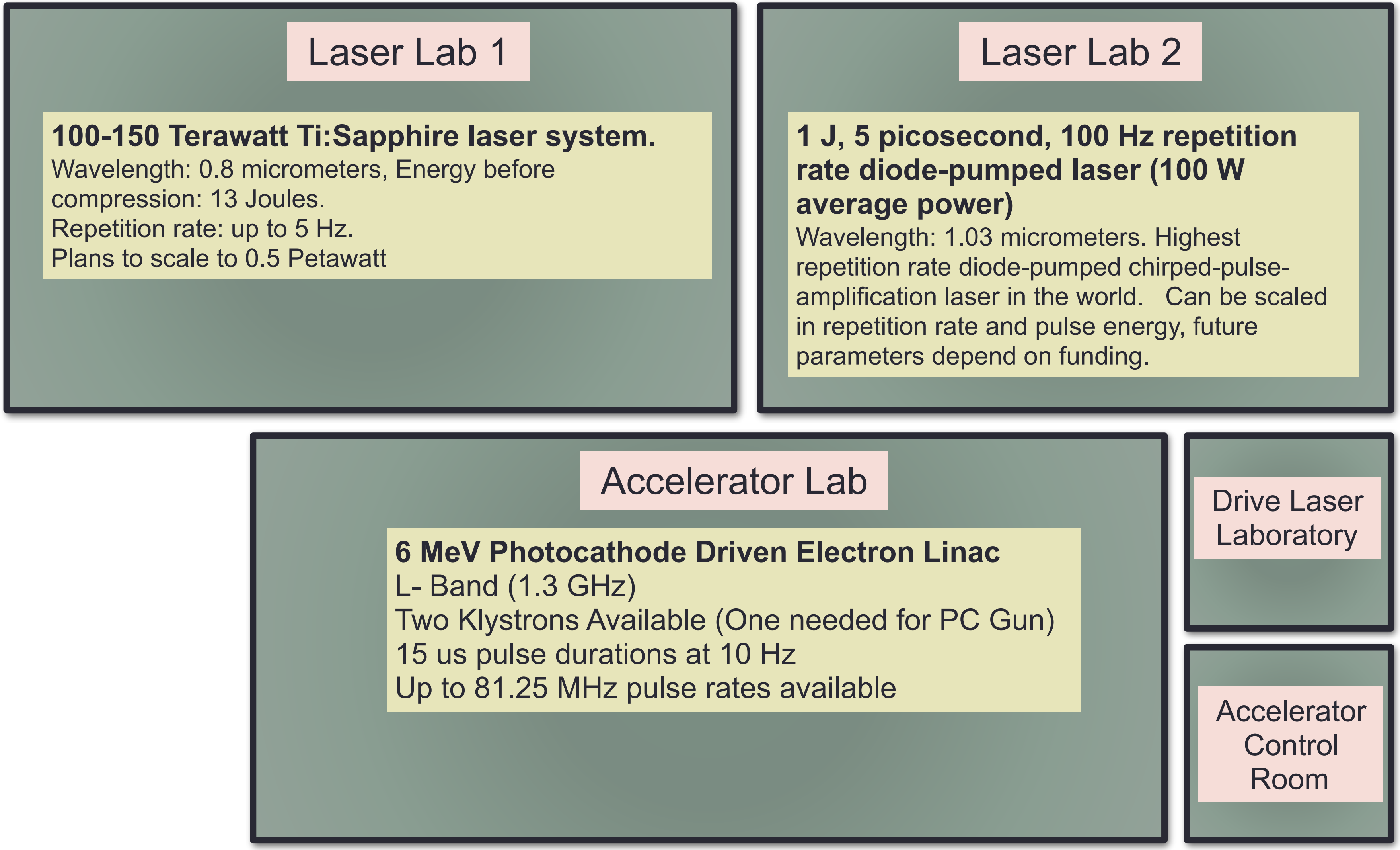
CSU Accelerator Laboratory



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.

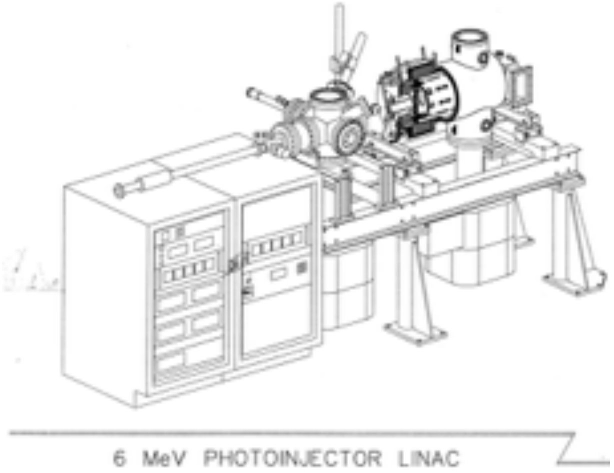
Accelerator Lab

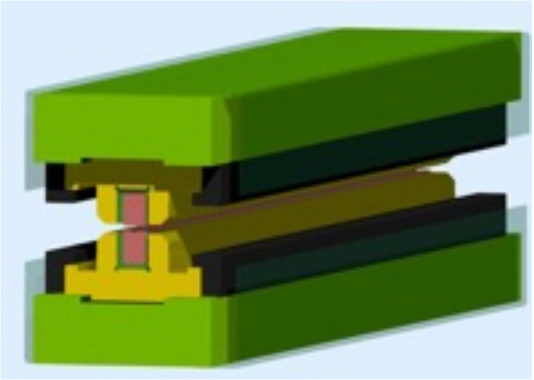
6 MeV Photocathode Driven Electron Linac
L- Band (1.3 GHz)
Two Klystrons Available (One needed for PC Gun)
15 us pulse durations at 10 Hz
Up to 81.25 MHz pulse rates available

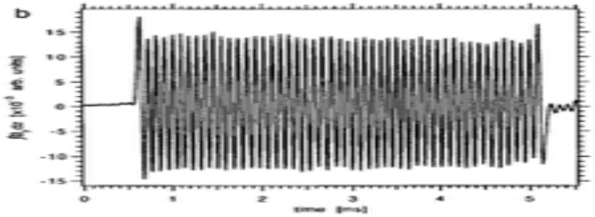
Drive Laser Laboratory

Accelerator Control Room

System Performance Parameters



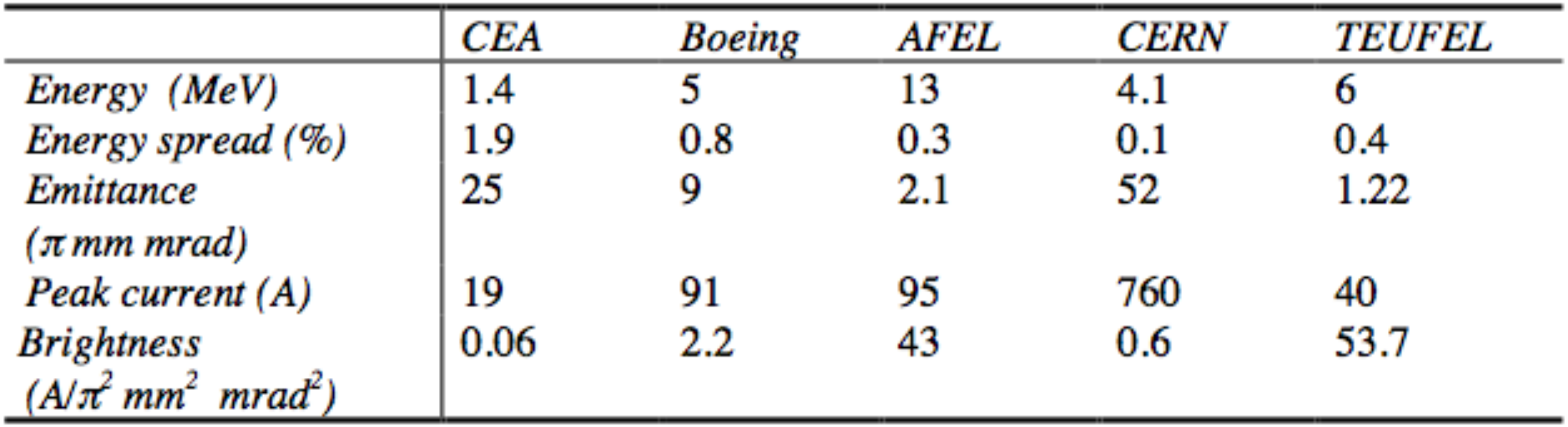




Major System Parameters	
Linac	
Frequency	1.3 GHz
Repetition Rate	10 Hz
Mircopulse Rep. Rate	81.25 MHz (max.)
Klystron	
Type	TH 2022C (Thales)
Power	20 MW
Modulator	
Type	PFN
Pulse Duration	15 μsec
Undulator	
Type	Hybrid: NdFeB
K	1 (at 8 mm gap)
Period	25 mm
Periods	50

Past Performance of Linac System

- As Achieved at the University of Twente



	CEA	*Boeing*	*AFEL*	*CERN*	*TEUFEL*
Energy (MeV)	1.4	5	13	4.1	6
Energy spread (%)	1.9	0.8	0.3	0.1	0.4
Emittance (π mm mrad)	25	9	2.1	52	1.22
Peak current (A)	19	91	95	760	40
Brightness (A/π^2 mm^2 $mrad^2$)	0.06	2.2	43	0.6	53.7

A High Brightness Electron Beam for Free Electron Lasers

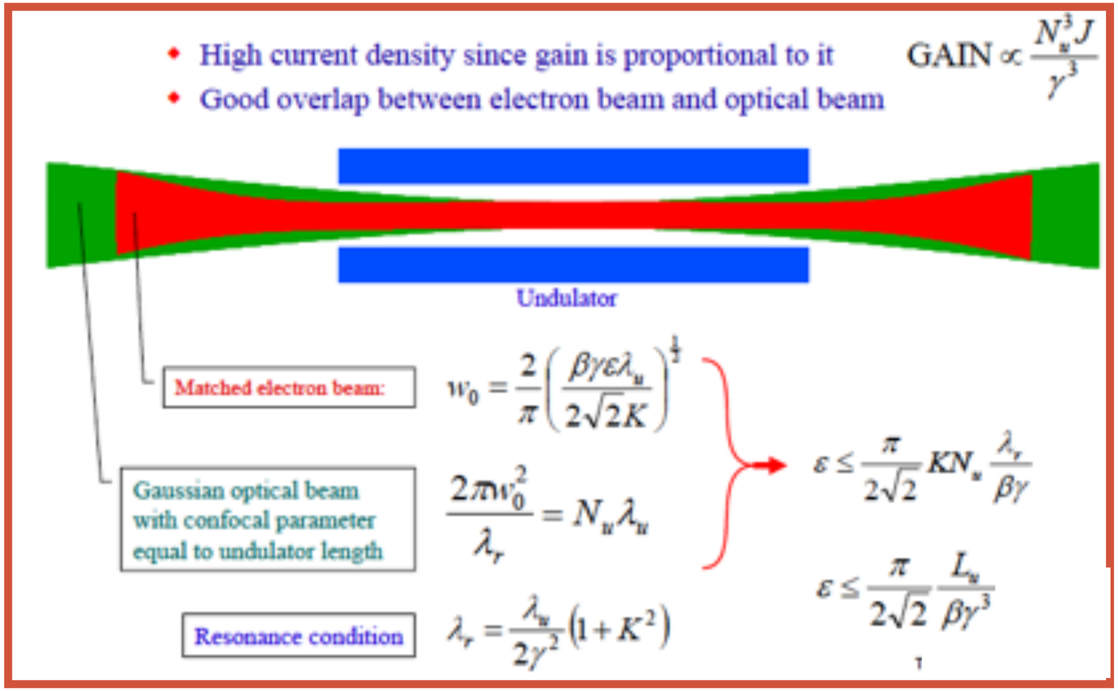
Van Oerle, Bartholomeus Mathias

ISBN 90 365 0949 1

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)



- High current density since gain is proportional to it
- Good overlap between electron beam and optical beam

$$\text{GAIN} \propto \frac{N_u^3 J}{\gamma^3}$$

Matched electron beam: $w_0 = \frac{2}{\pi}\left(\frac{\beta\gamma\varepsilon\lambda_u}{2\sqrt{2}K}\right)^{\frac{1}{2}}$

Gaussian optical beam with confocal parameter equal to undulator length $\frac{2\pi w_0^2}{\lambda_r} = N_u\lambda_u$

$$\rightarrow \varepsilon \le \frac{\pi}{2\sqrt{2}} K N_u \frac{\lambda_r}{\beta\gamma}$$

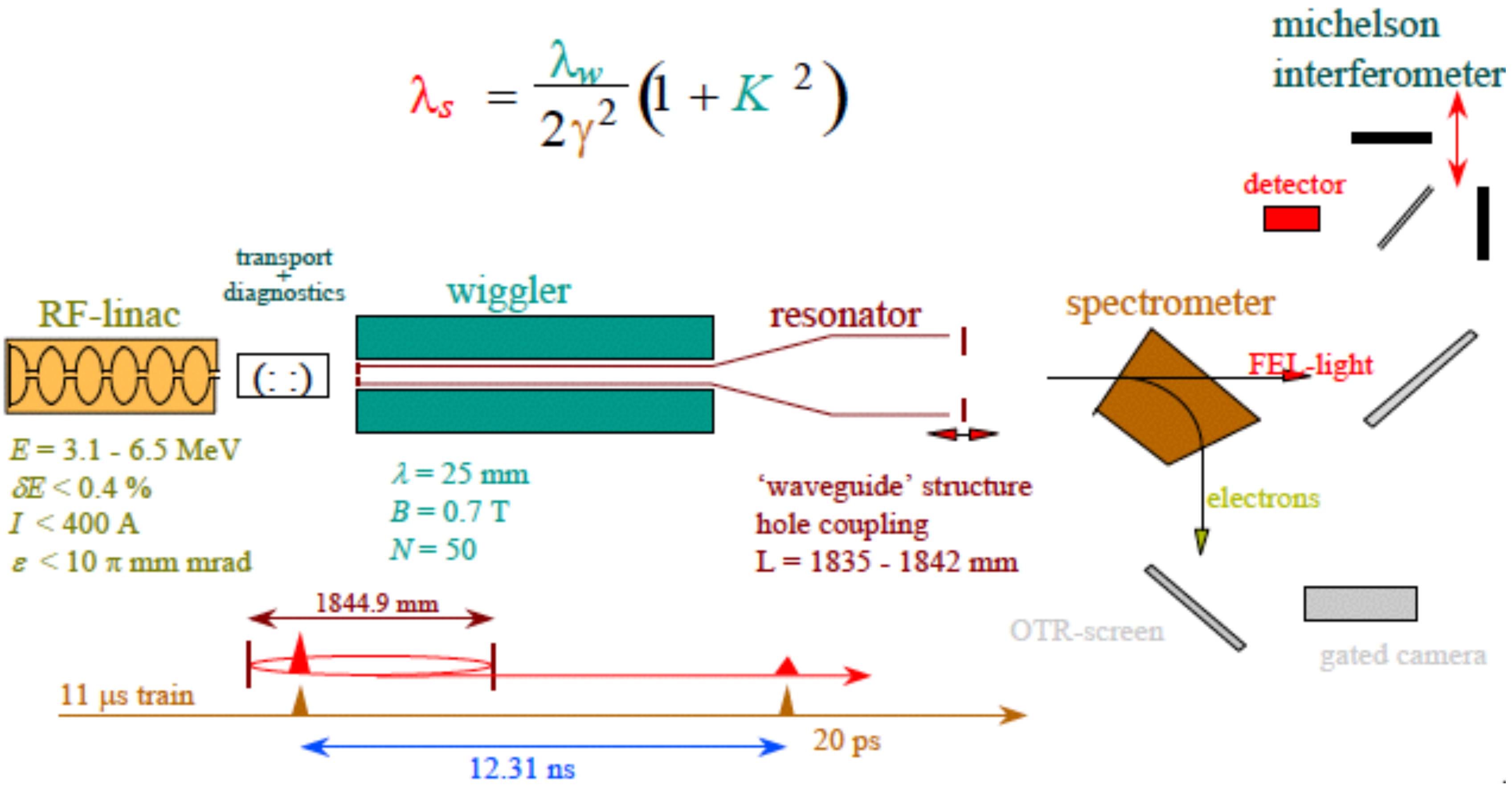
Resonance condition $\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+K^2\right)$

$$\varepsilon \le \frac{\pi}{2\sqrt{2}} \frac{L_u}{\beta\gamma^3}$$

Courtesy Univ. of Twente

Cartoon of Original Set up

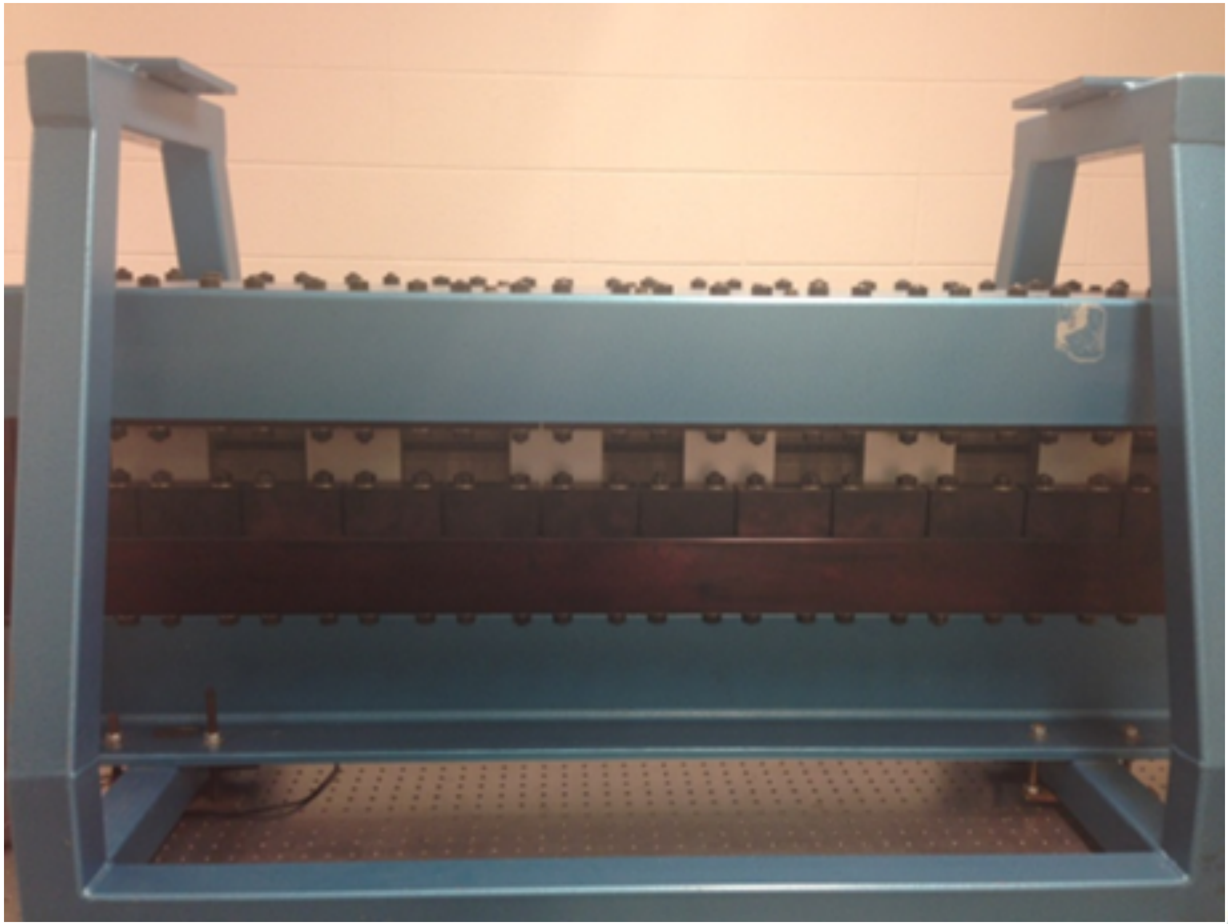
$$\lambda_s = \frac{\lambda_w}{2\gamma^2}\left(1 + K^2\right)$$



Courtesy Univ. of Twente

The Problem

The Problem, or at least one of them.



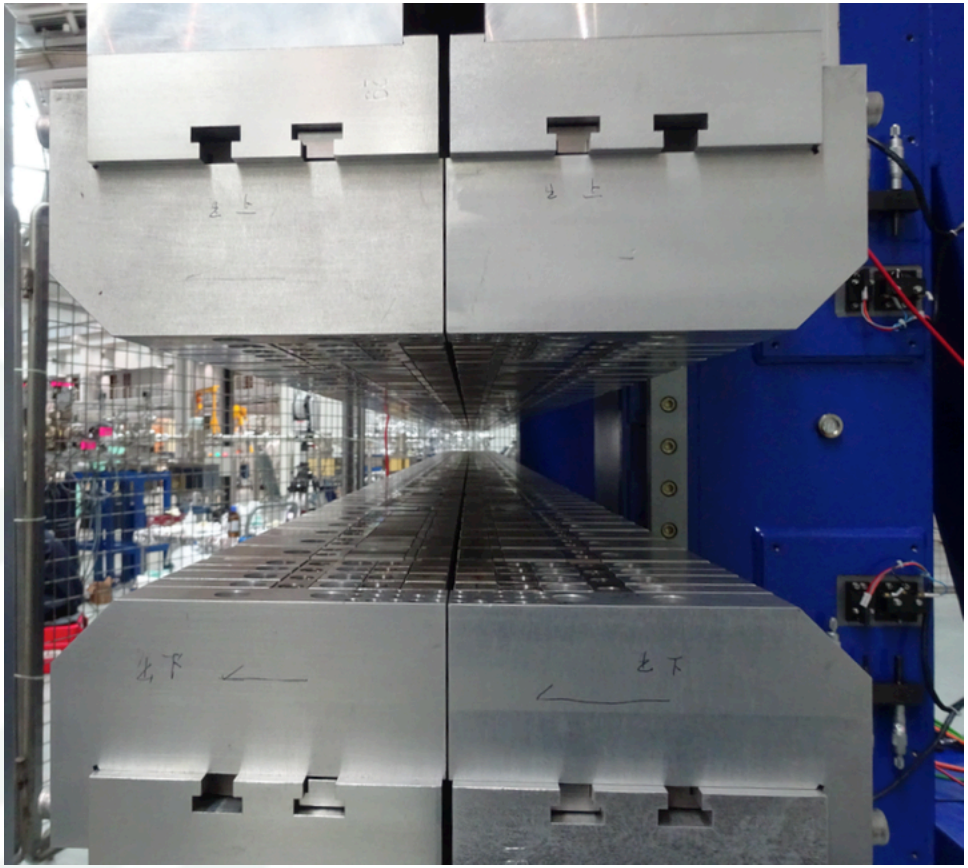
The Problem, or at least one of them.

Undulator Characterization: Most Common

- Traditional Hall probe

Undulator Characterization: Most Common

- **Traditional Hall probe: Works best with clear access**

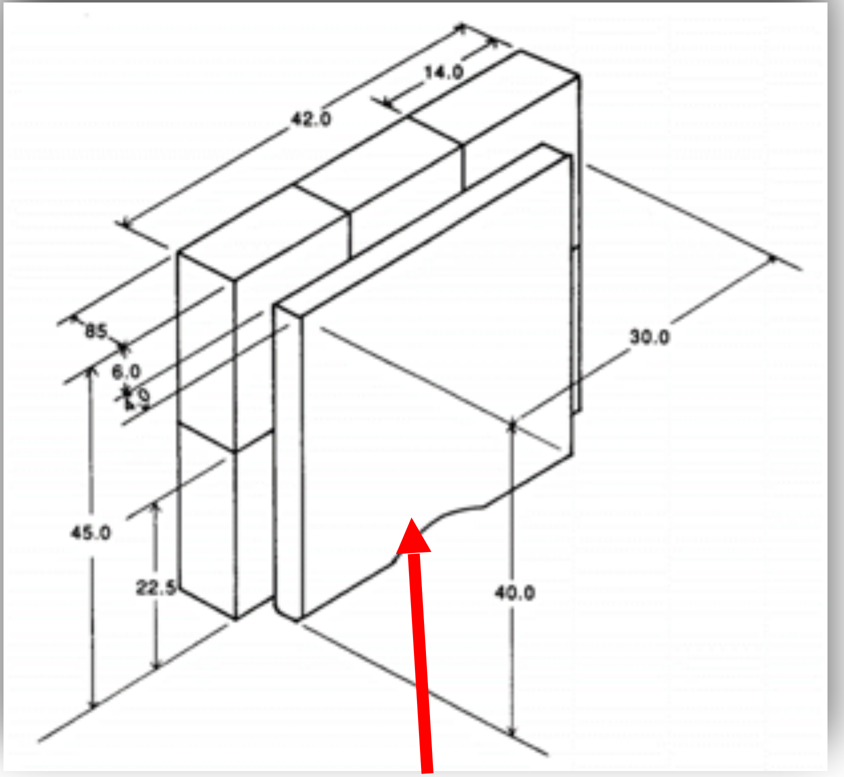


CSU Undulator Specs

Parameter	**Value**
K	1 (0.61 T)
Period	2.5 cm
Gap	8 mm
Material	Sm_2CO_5
Periods	50
Length	1.25 m

CSU Undulator Specs

Undulator Design Parameters [mm]		
Half Gap		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

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

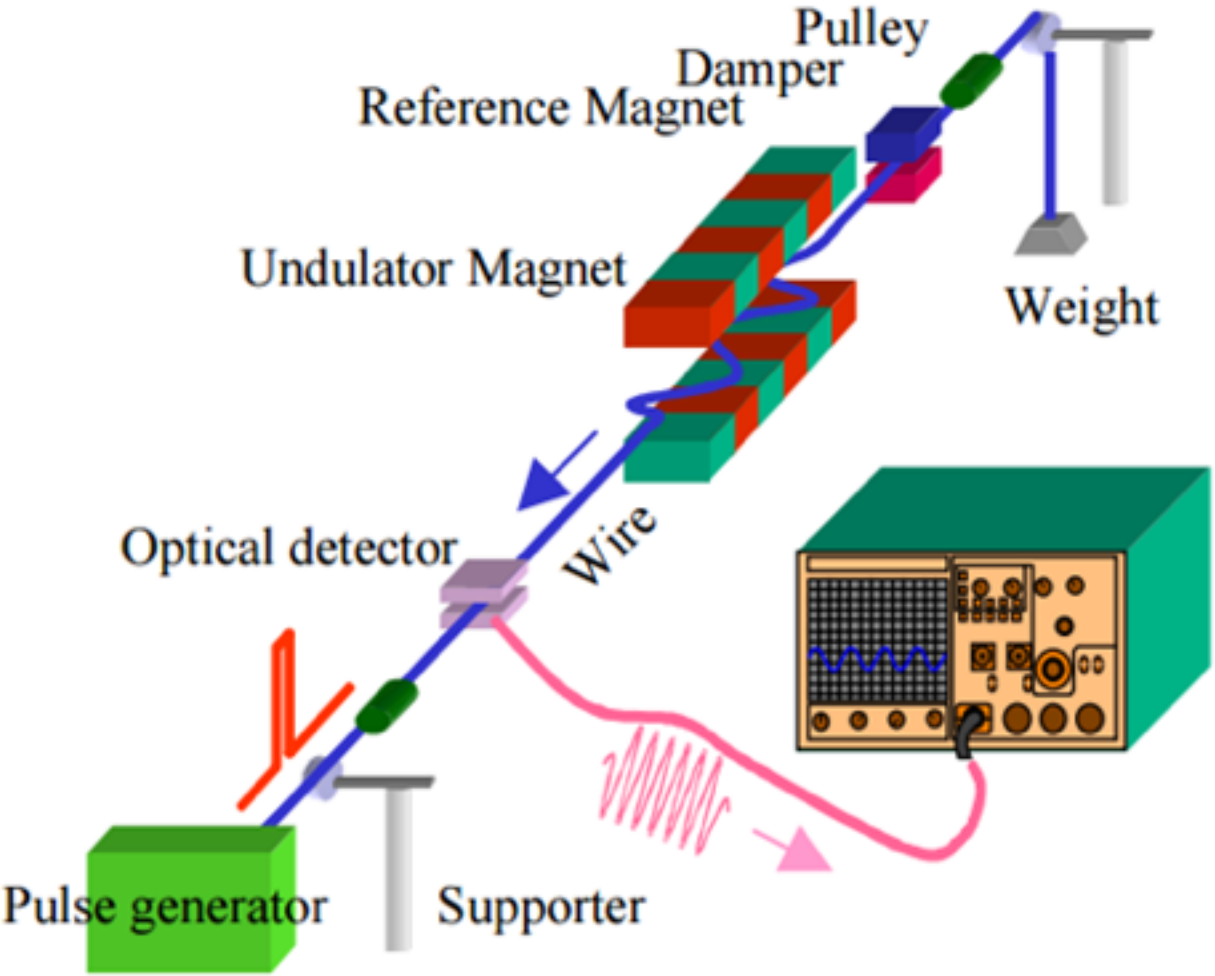
Students Involved

- 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

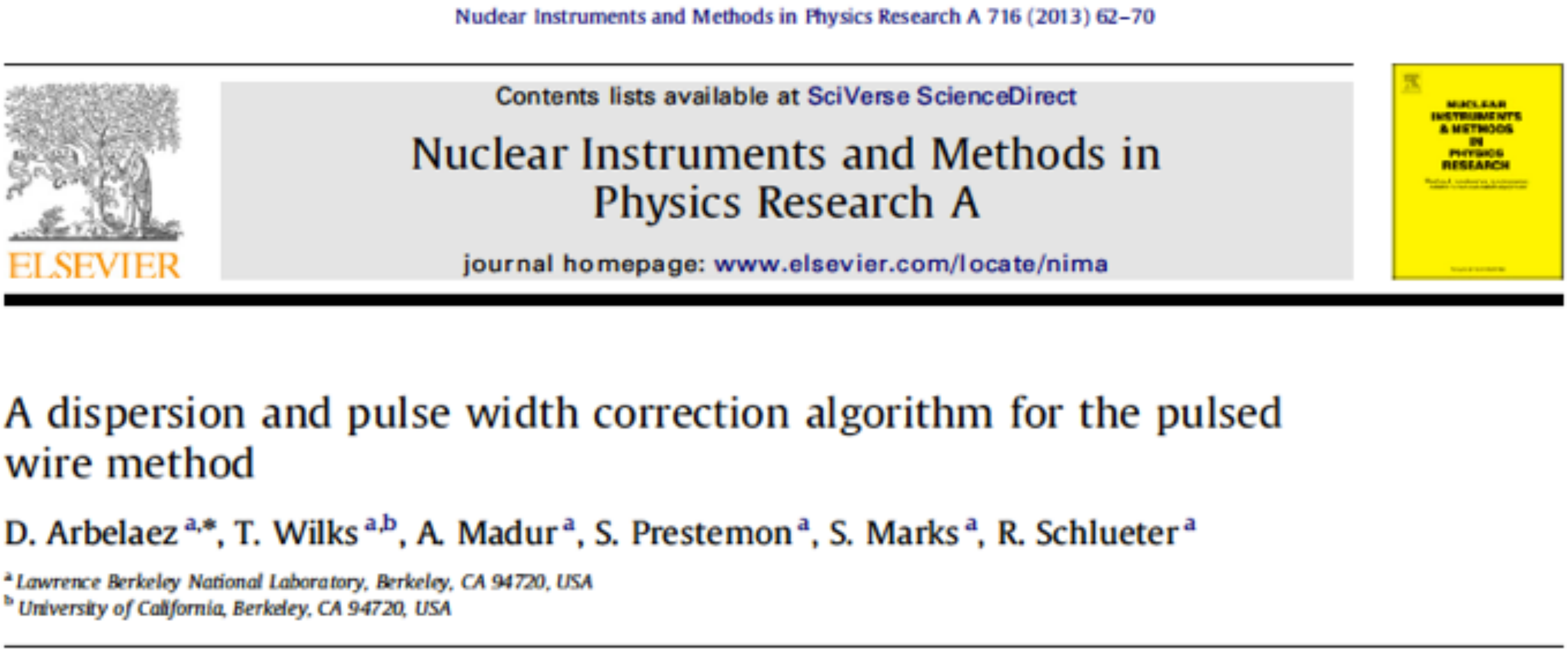
- Concept first developed by R. W. Warren at LANL in 1988.
- Has been used in a variety of specialized cases in the characterization of magnetic fields.
- The method’s accuracy was previously limited due to dispersive effects in the wire and the finite pulse width.
- Newly developed mathematical algorithms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

Basic Understanding



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

LBNL Correction Algorithm



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

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[a] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
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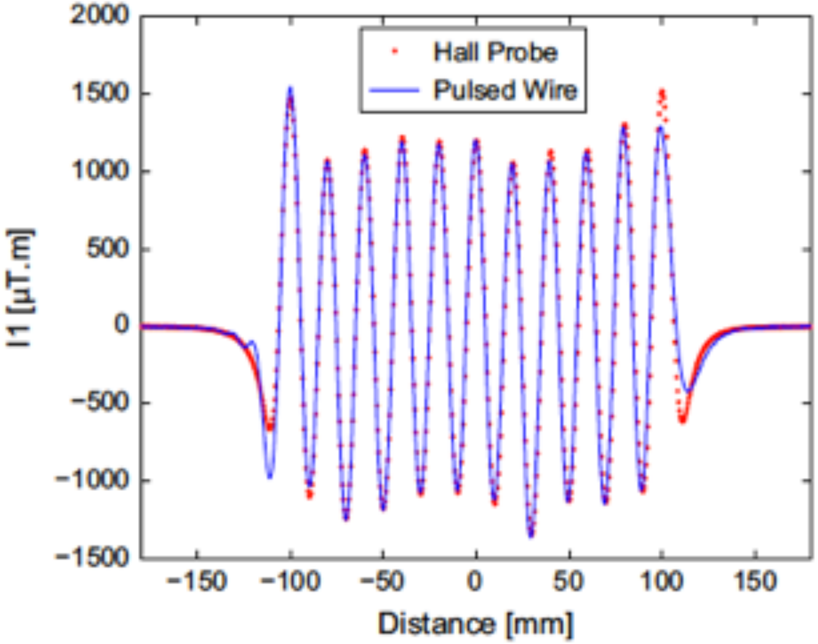
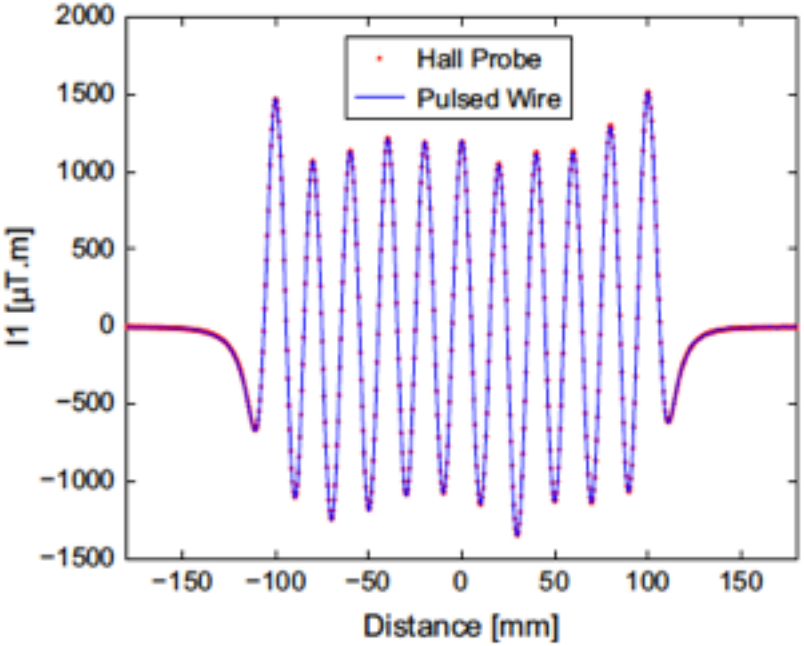
LBNL Results

Uncorrected



Corrected



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.

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

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

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.

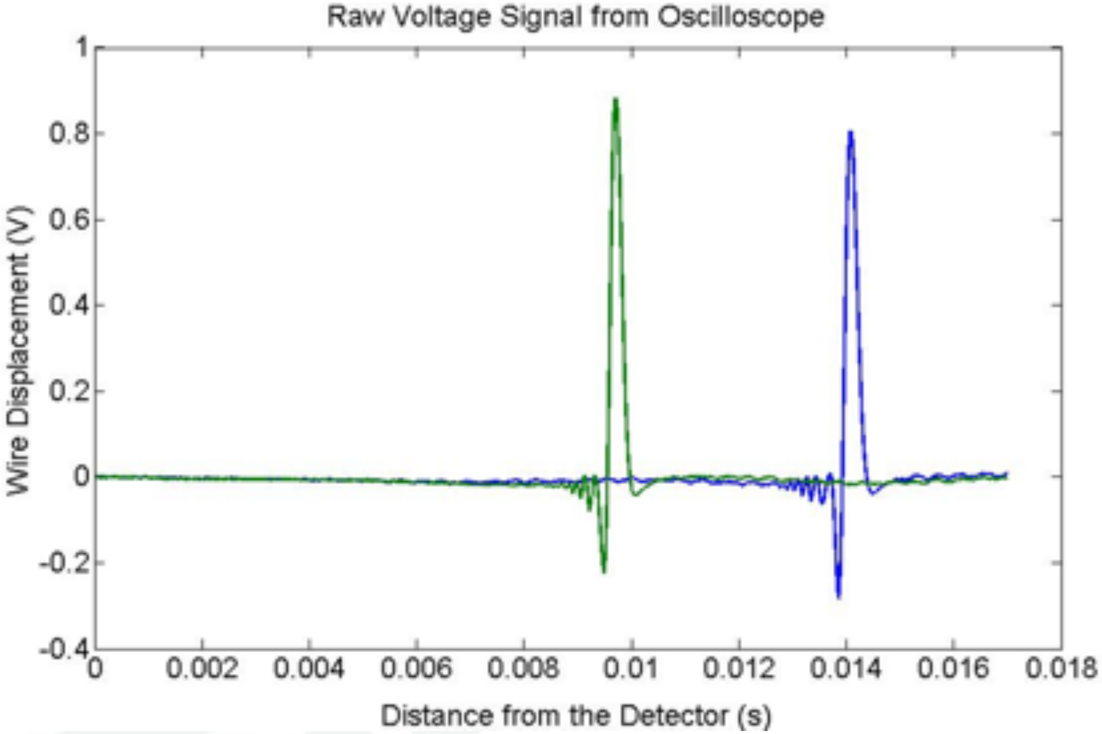
Dispersion

A reference magnet can then be measured and the signal recorded for two different positions along the wire spaced by Δx. 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

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

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

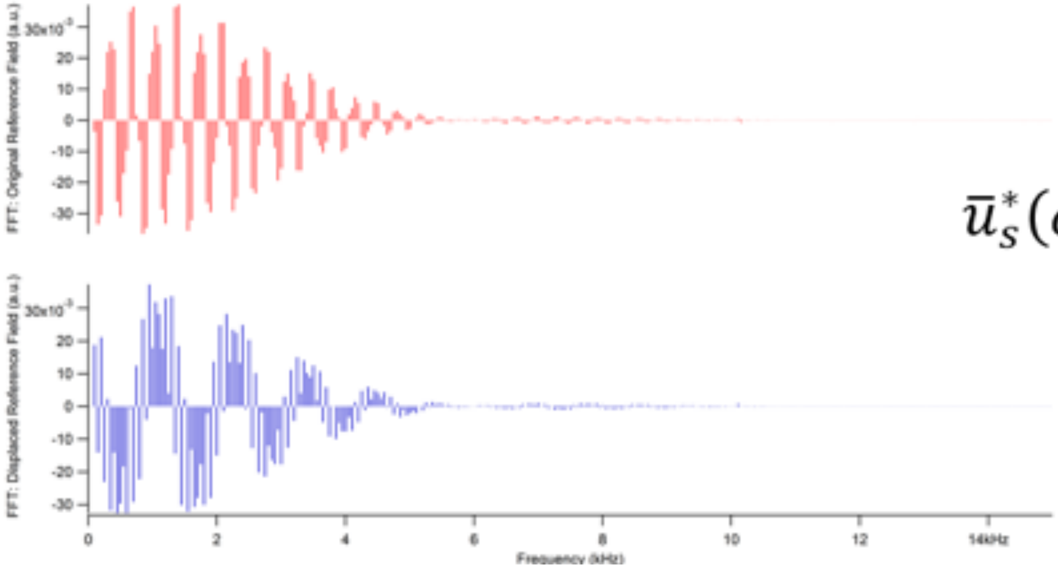
Wave Speed Determination



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

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

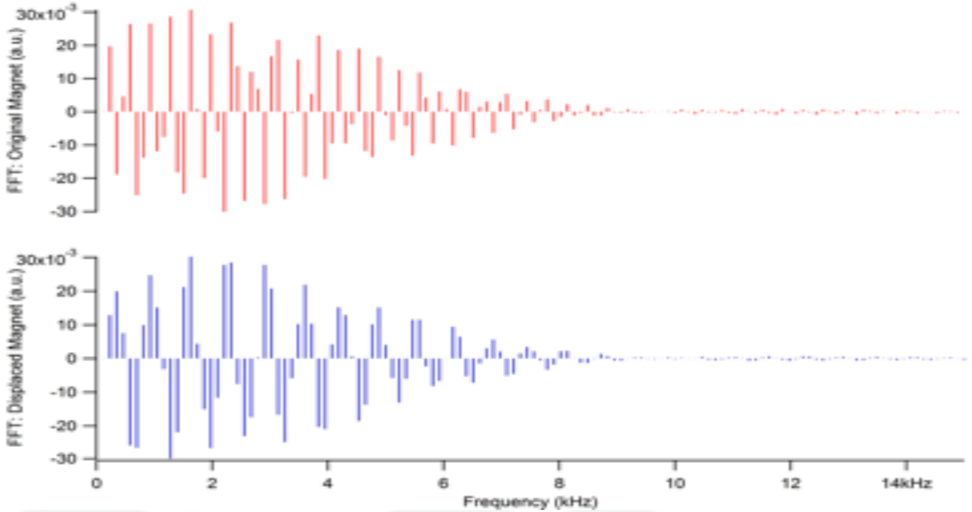
FFTs of Reference Magnet Signals



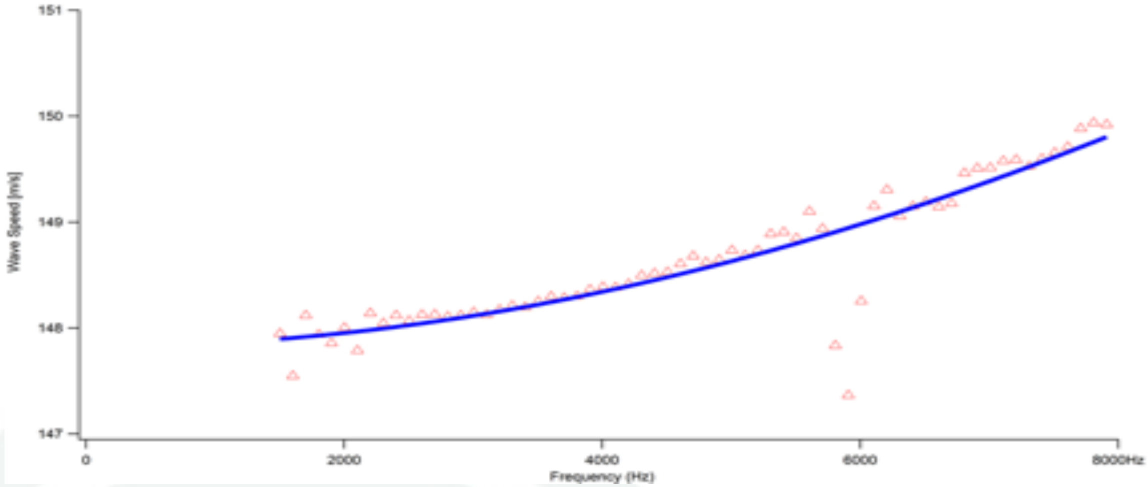
$$\bar{u}_s^*(\omega)\bar{u}_{s\Delta z}(\omega) = |G(\omega)|^2 e^{i\kappa\Delta z}$$

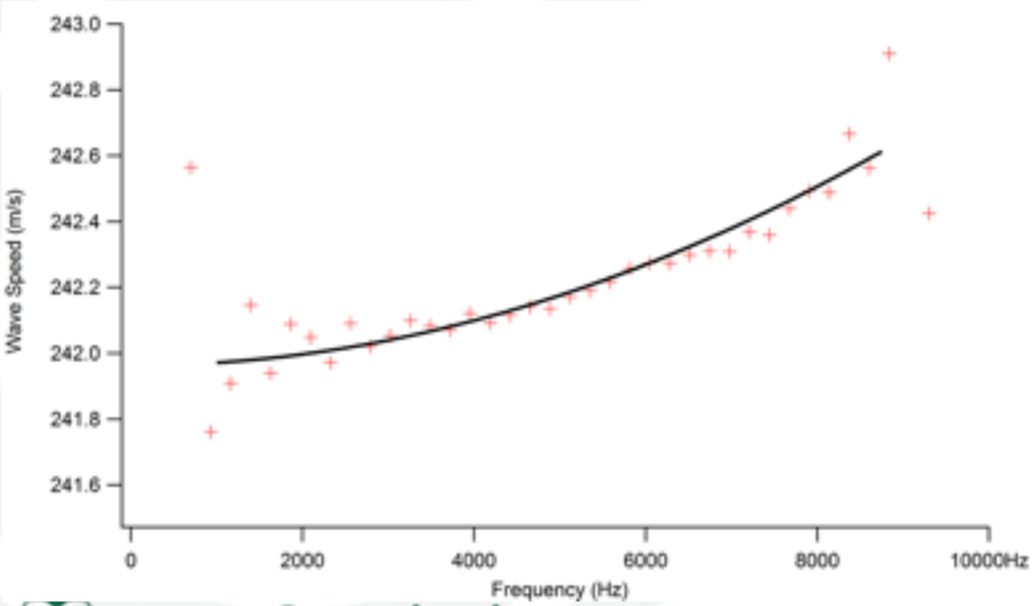
$$c = \frac{\omega\Delta z}{\phi}$$

$$\Delta z = 30cm$$



Dispersive Wave Speed





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

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 ω_i .

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

3. Using the dispersion relationship calculate unequally spaced values of $\kappa_i = \kappa\left(\omega_i\right)$, that are associated with $H\left(\kappa_i\right) = G\left(\omega_i\right)$

Correction Algorithm Summary

4. Multiply $H(\kappa_i)$ by $F(\kappa_i)$, where for the short pulse case

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

to obtain $H_o(\kappa)$.

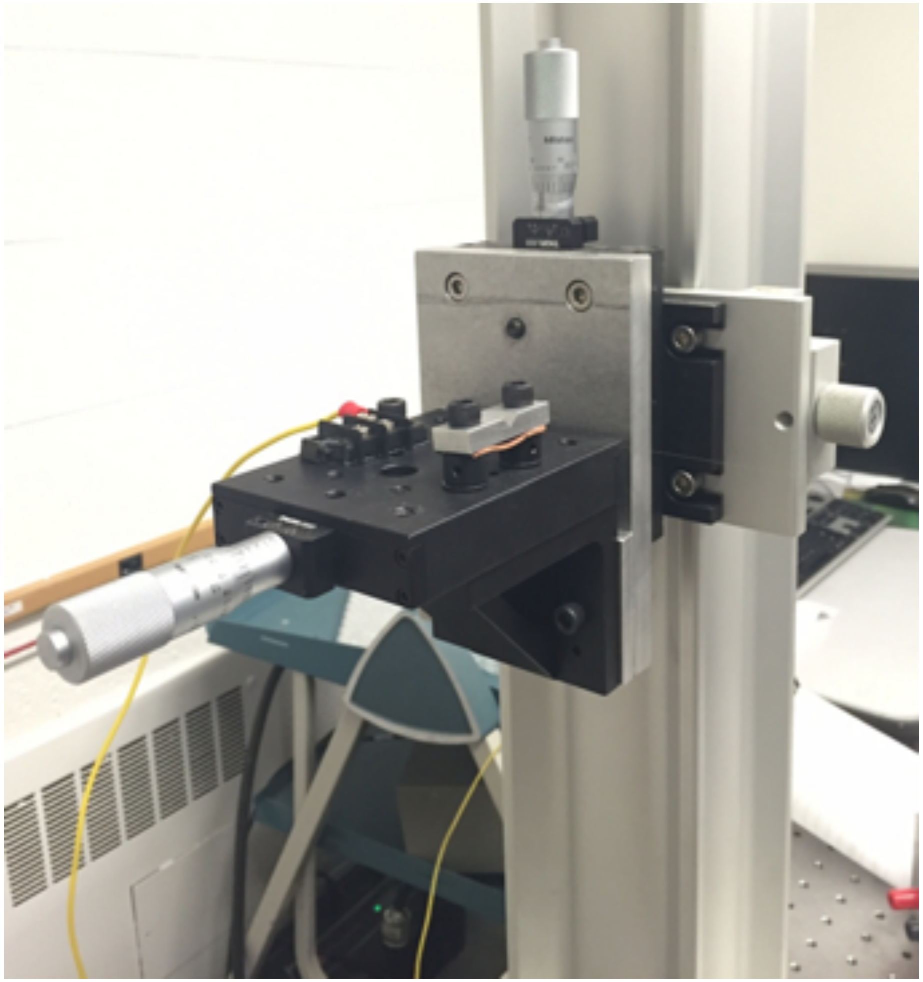
5. For each time t_i numerically integrate

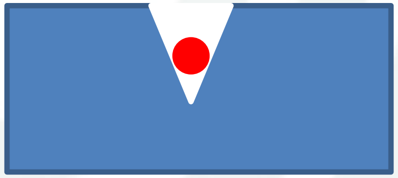
$$u_{s0}(t_i) = c_o \int_{-\infty}^{\infty} H_o(\kappa) e^{-jc_o\kappa t_i}\, d\kappa$$

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

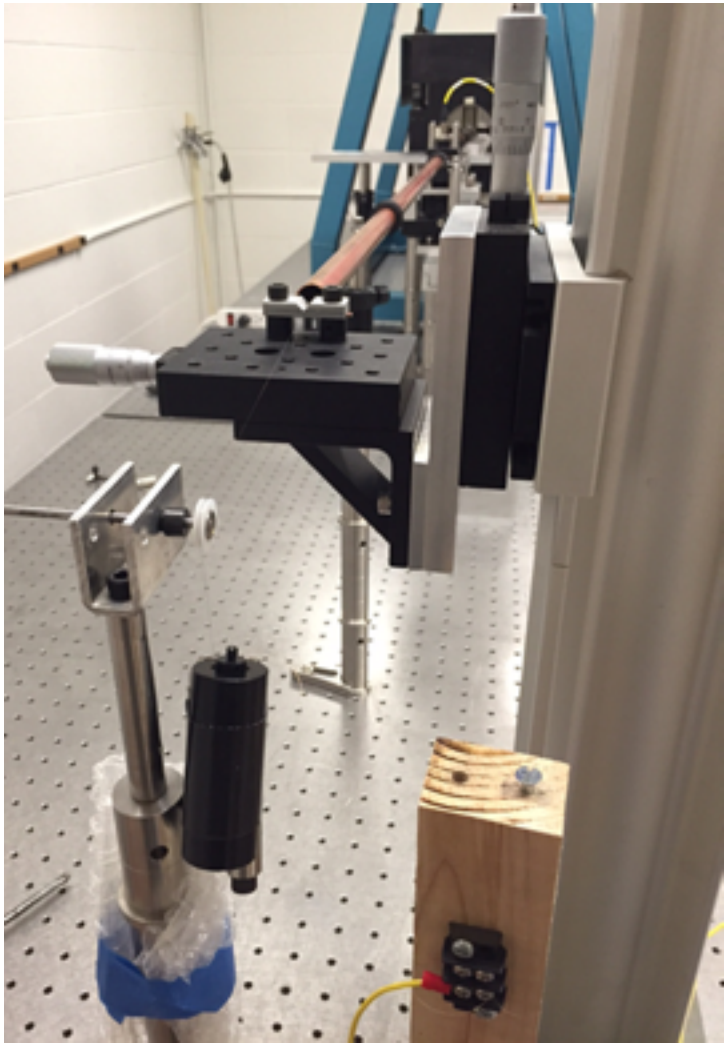
- 2-Axis Translation Stage with 25µm resolution.
- “V-Blocks” to hold wire steady during alignment and experiments.



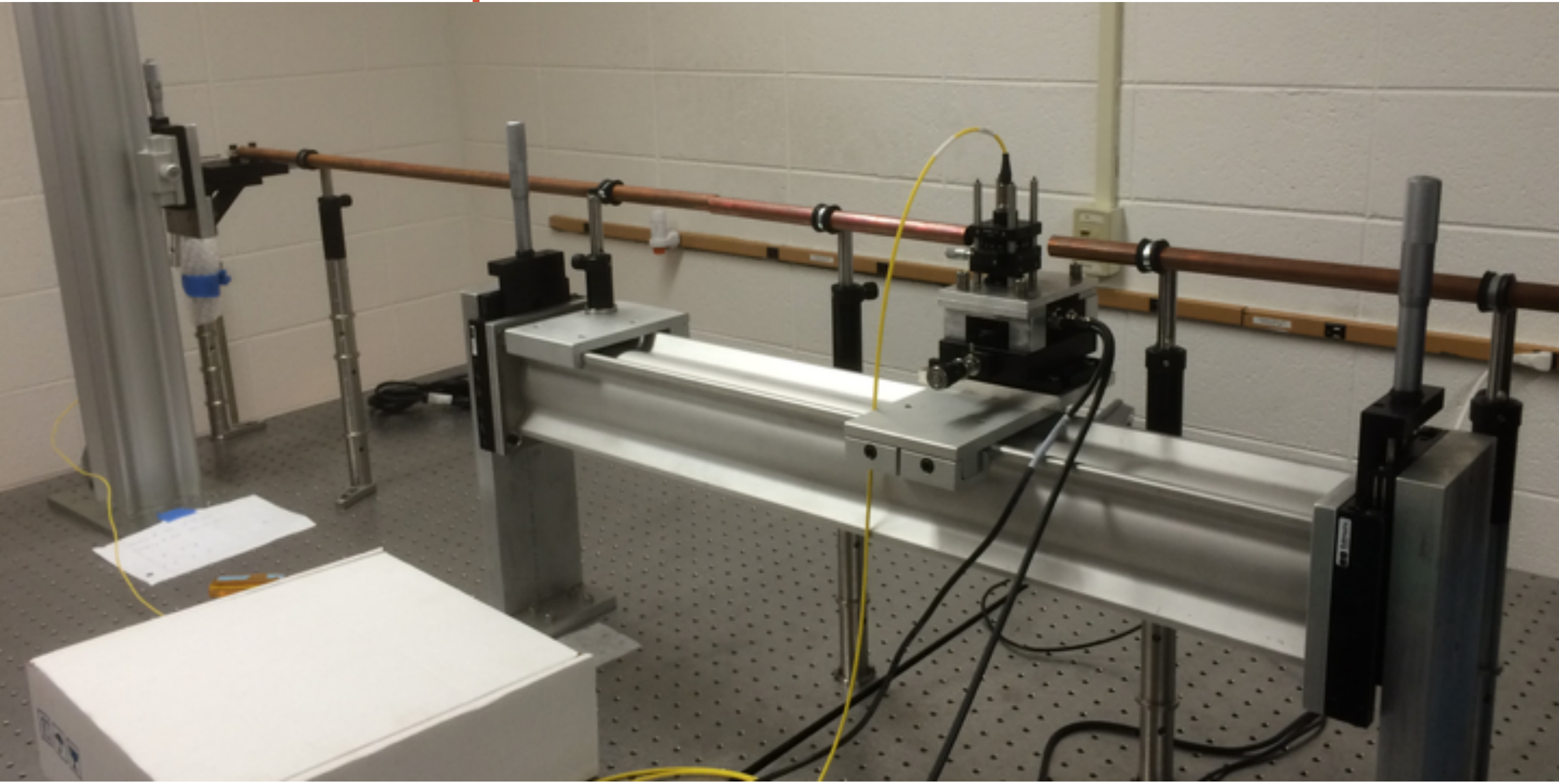


Setup: Wire Tension

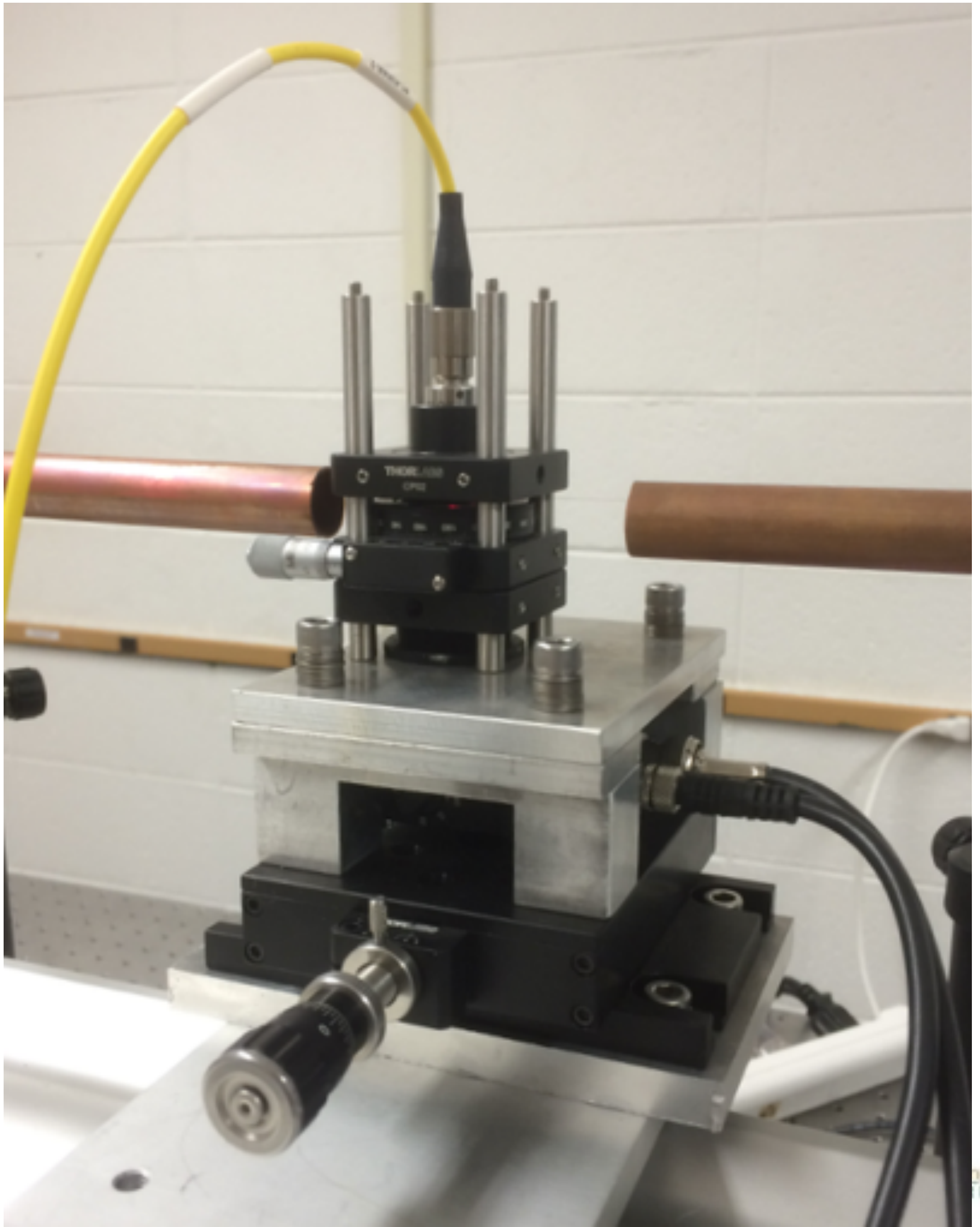
- **Weight**
  - Used 2.3N and 0.85N.
- **Higher tension reduces dispersive effects, increases wave speed, and decreases wire displacement.**



Isolation required

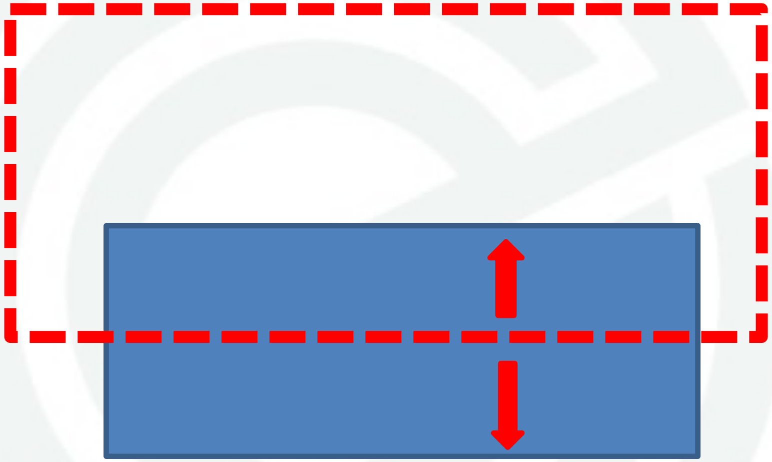


Detector region



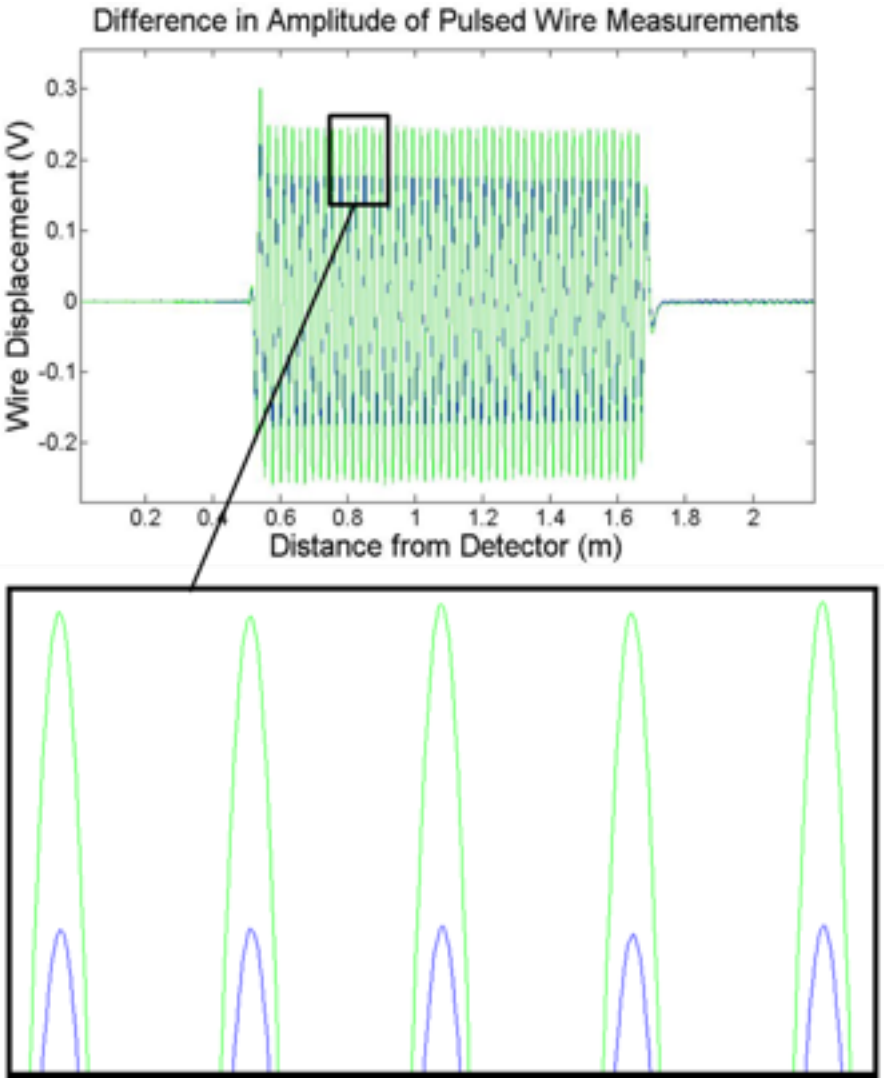
Setup: Wire Vibration Detection

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



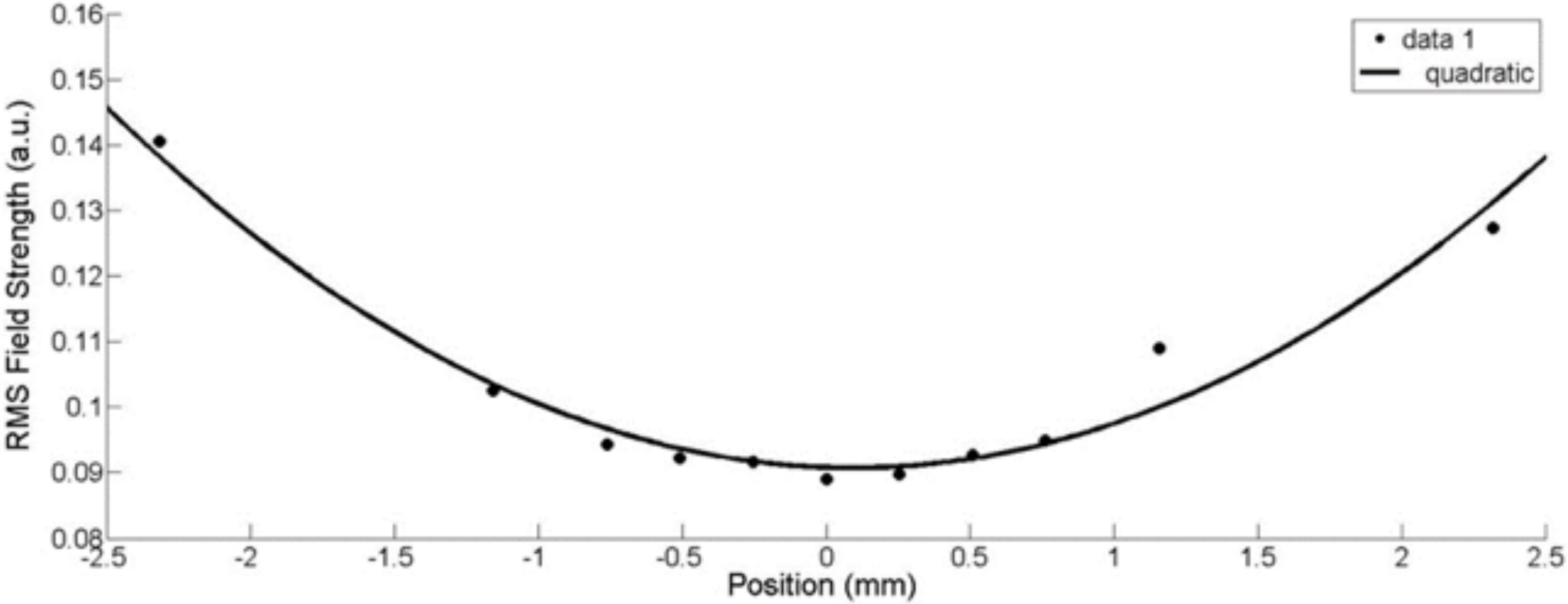
Magnetic Center

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

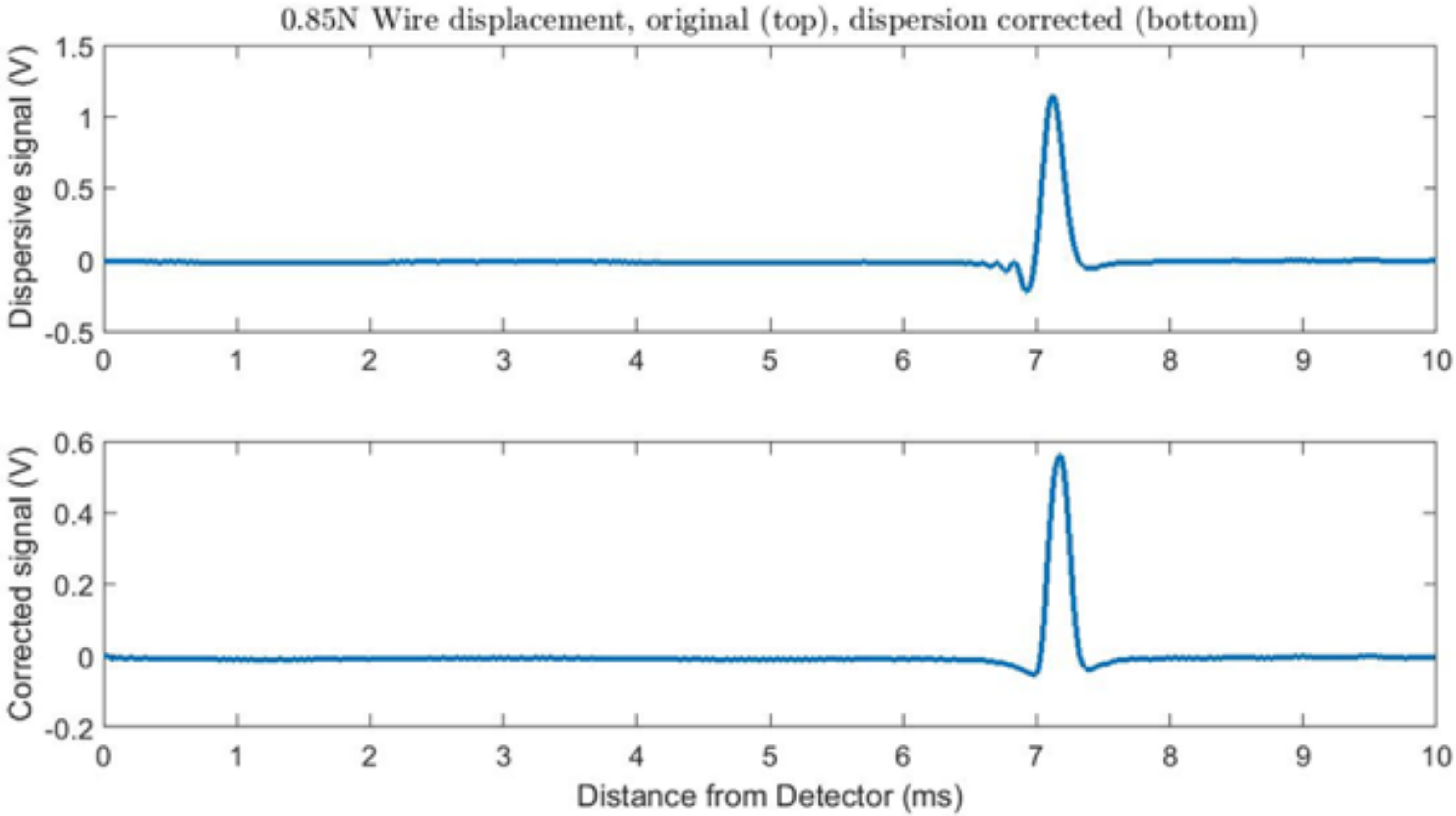


Magnetic Center

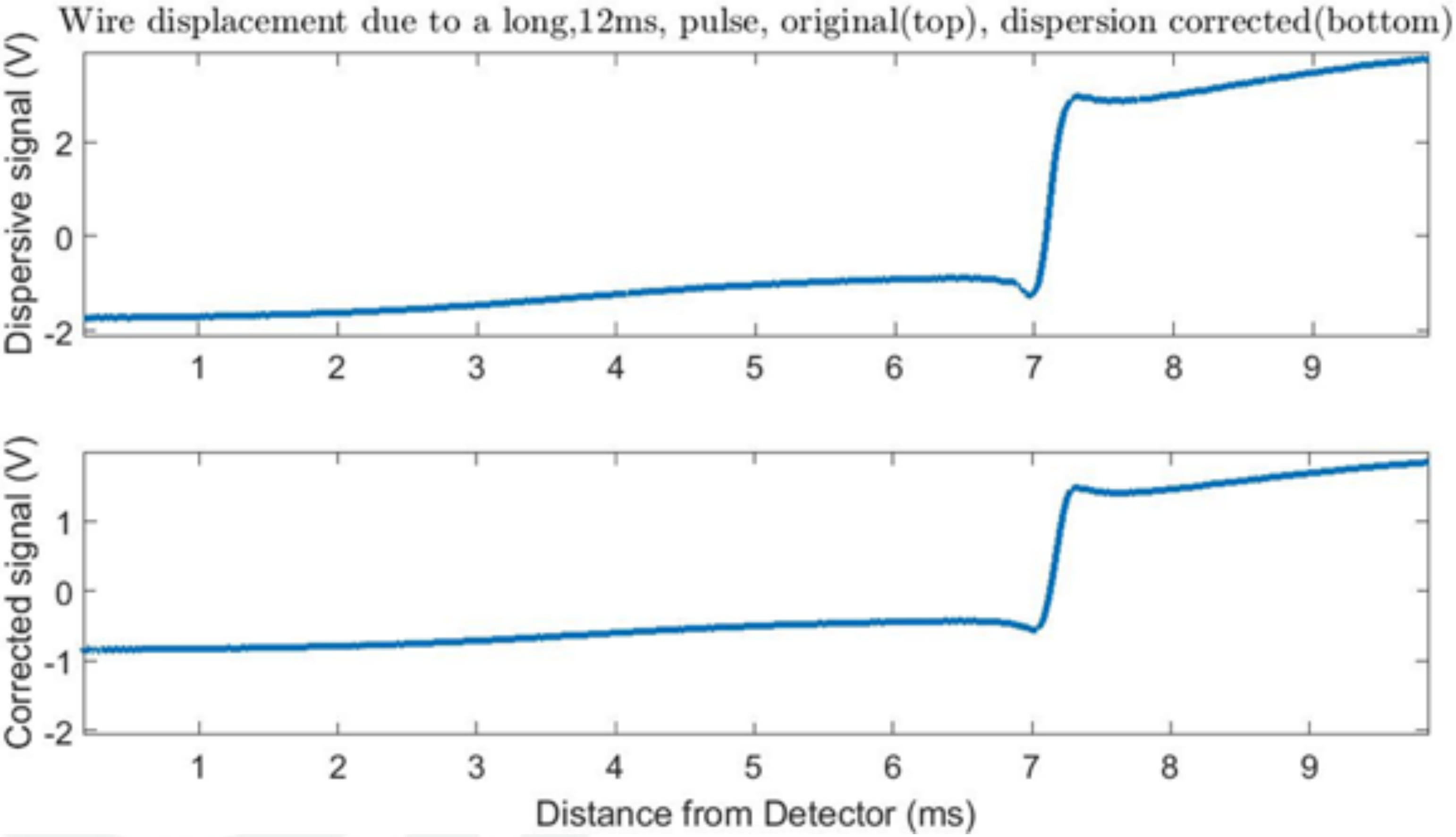
- RMS values of the field strength within the undulator at various locations within the gap.



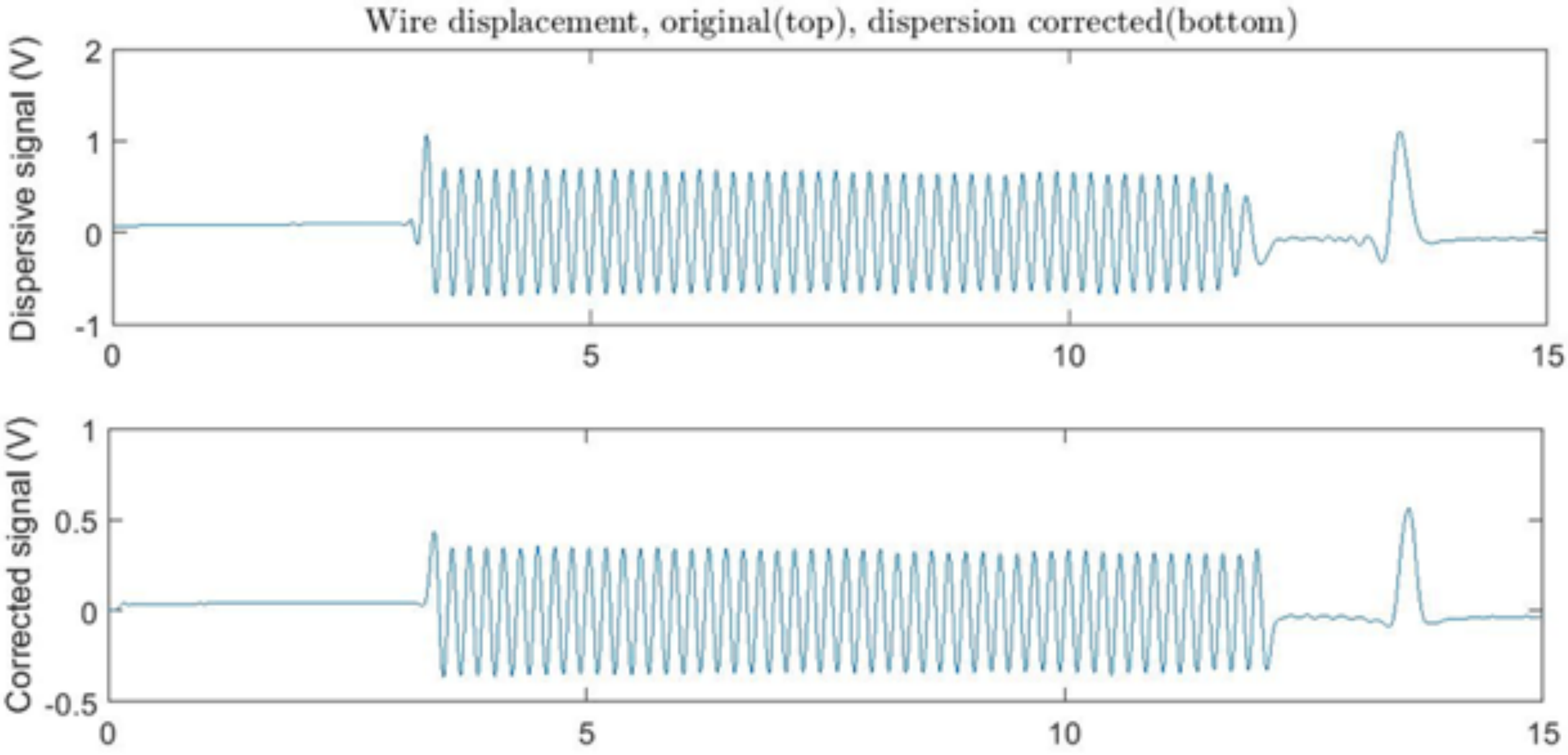
Dispersion Corrected: Short Pulse (1st Integral)



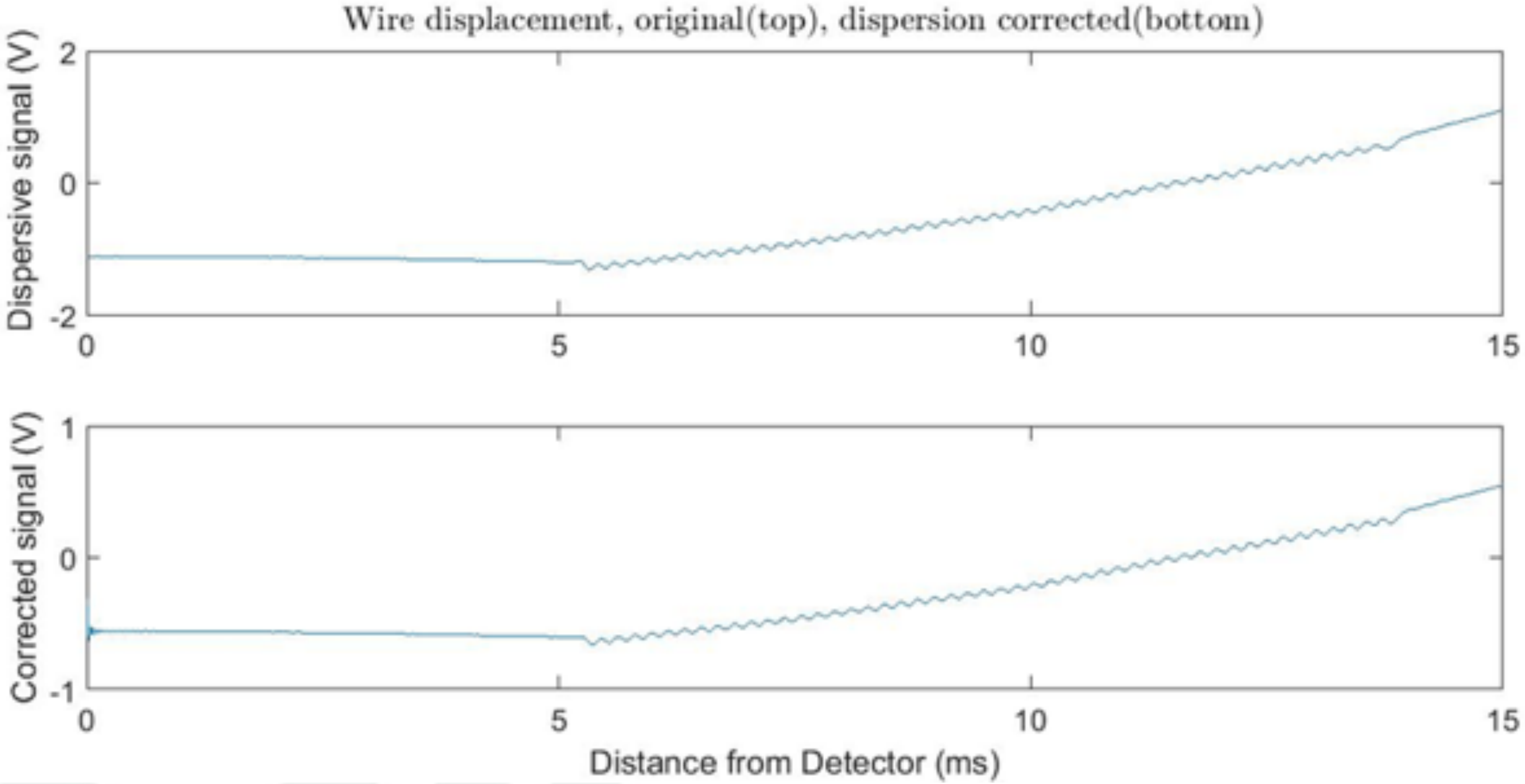
Dispersion Corrected: Long Pulse (2nd Integral)



1st Integral of the Undulator and Ref. Magnet



2nd Integral of the Undulator



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