Automation and Testing of a Drift Chamber Wire Tensionometer

by

James Haus

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Approved by:

Dr. Sebastian Kuhn (Advisor)

Dr. Lawrence Weinstein

Dr. Alexander Godunov

ABSTRACT

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James Haus
Old Dominion University, May 2010
Advisor: Dr. Sebastian Kuhn

An automated, PC-based method for the testing of wire tensions is described. The technique is proposed to measure tensions of the constituent wires in the new CLAS 12 Drift Chambers (detectors) to be built for Jefferson Laboratory's 12 GeV upgrade.

ACKNOWLEDGMENTS

Special thanks to Professor Kuhn for letting me investigate multiple ideas while making sure I stayed on the right track.

Additionally, I would like to thank my predecessor James Graves for taking the time to bring me up to speed on the hardware involved in this project.

Finally, I must thank everyone whose advice and/or assistance I solicited along the way: Chris Cuevas of Jefferson Lab, Tom Hartlove and Michael Moore of ODU's Nuclear/Particle Lab, and ODU Professors Dr. Larry Weinstein, Dr. Stephen Bueltmann, and Dr. Robert Bennett.

CHAPTER 1

A Brief History

Jefferson Laboratory's CLAS 12 is an updated detector for tracking and classifying the products of high-energy nuclear interactions. The detector is designed to be used after the lab's Continuous Electron Beam capabilities are upgraded from 6 GeV to 12 GeV. When the electron beam interacts with a target, a shower of subatomic particles will emerge from the collision region, and CLAS 12's three regions of Drift Chambers will trace the path of said particles through the detector. Magnetic fields of known intensity will bend the particles' trajectories in inverse-proportion to their momenta, allowing for identification of any particle passing through the chambers.

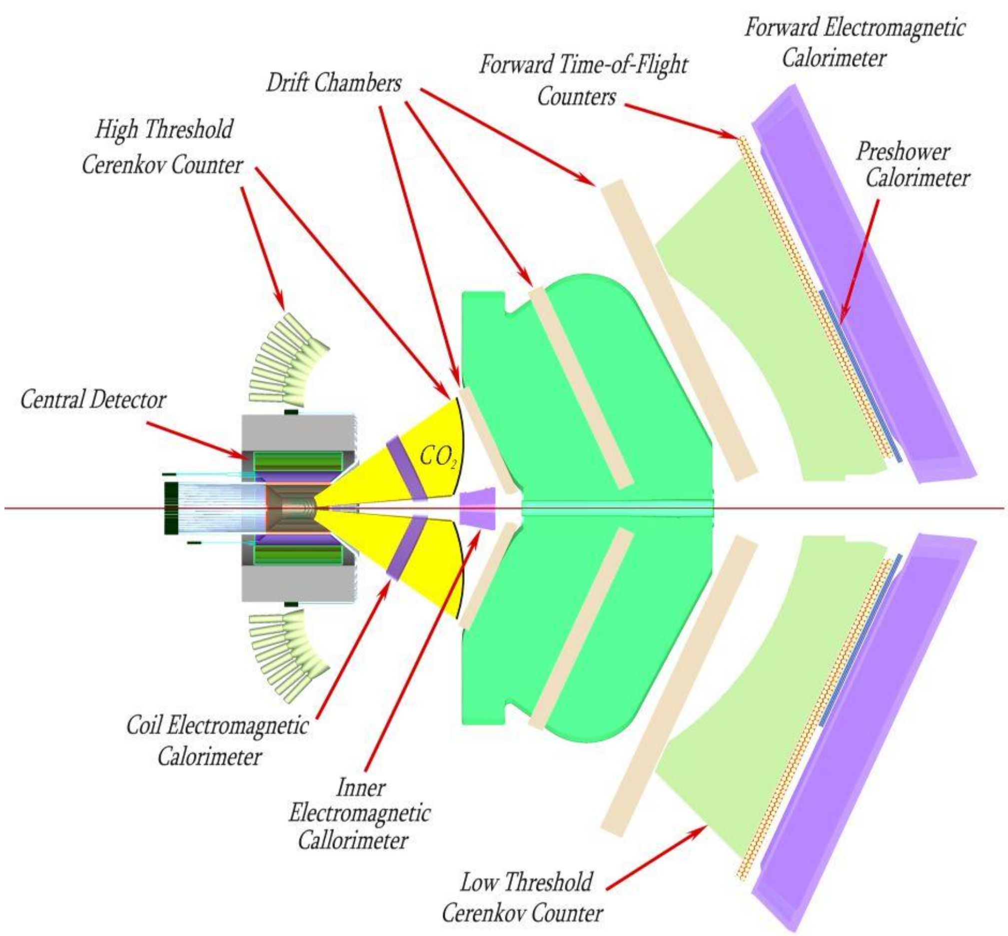


Figure 1: CLAS 12 Detector (short for "CEBAF Large Acceptance Spectrometer"). Contains 3 regions of Drift Chambers.

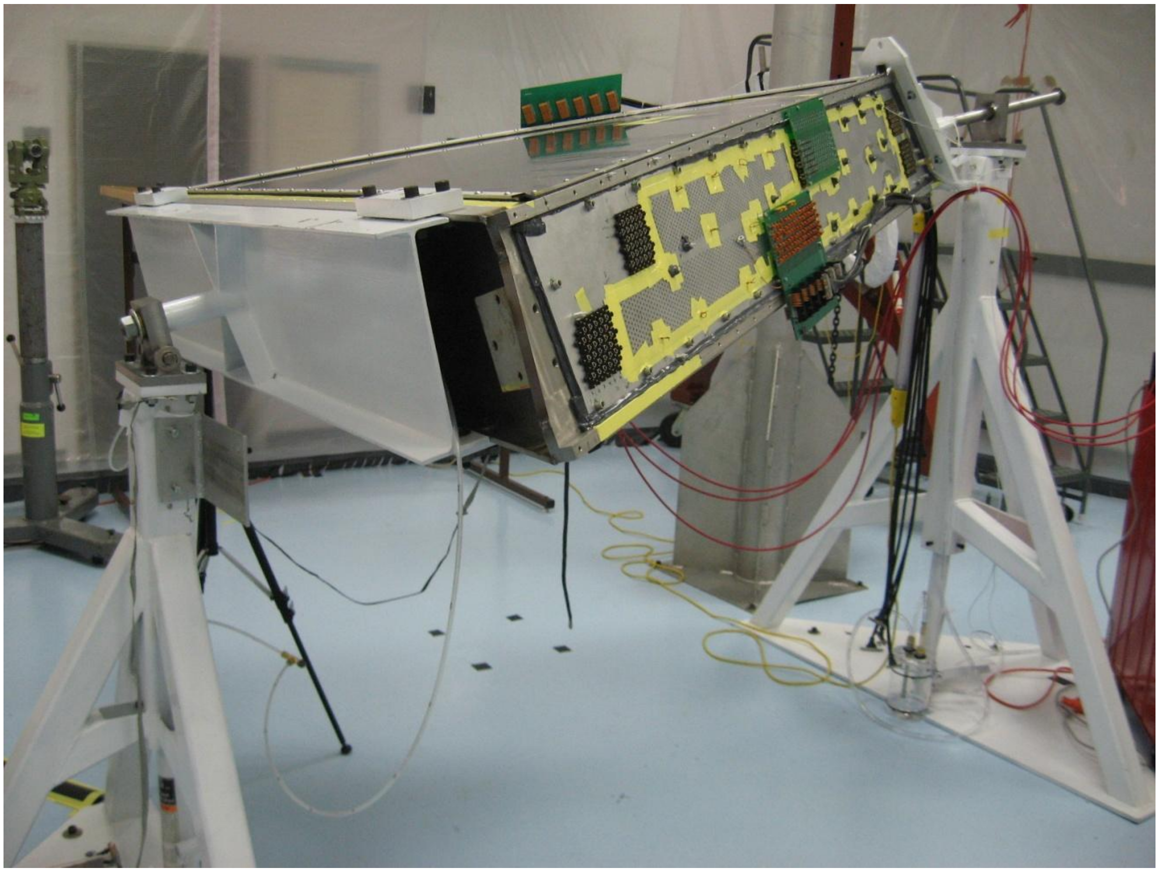


Figure 2: A single Drift Chamber under construction.
Six of these triangular "wedges" form one circular region.

Eighteen Drift Chambers are arranged into three circular regions, each 50% larger than the region before it. When the chambers are filled with an Argon-CO_2 gas mixture, these gas atoms will be stripped of electrons (ionized) whenever traversed by an incoming particle. As a chamber contains thousands of field wires (gold-plated aluminum) and sense wires (gold-plated tungsten), biased at negative and positive high voltages respectively, the negatively-charged electrons from the ionization will drift toward the positively-charged sense wires, further ionizing the gas along the way. When this avalanche of electrons strikes a sense wire, a pulse of electric current is generated across the wire that is then sent to the data-acquisition system. The trajectory of the incident particle can thus be mapped-out via these induced currents on sense wires.

A third type of wire, the guard wire, is also employed in the Drift Chamber, but only to shape the overall electric field provided by the sense and field wires. In all, every Drift Chamber contains about 5000 wires.

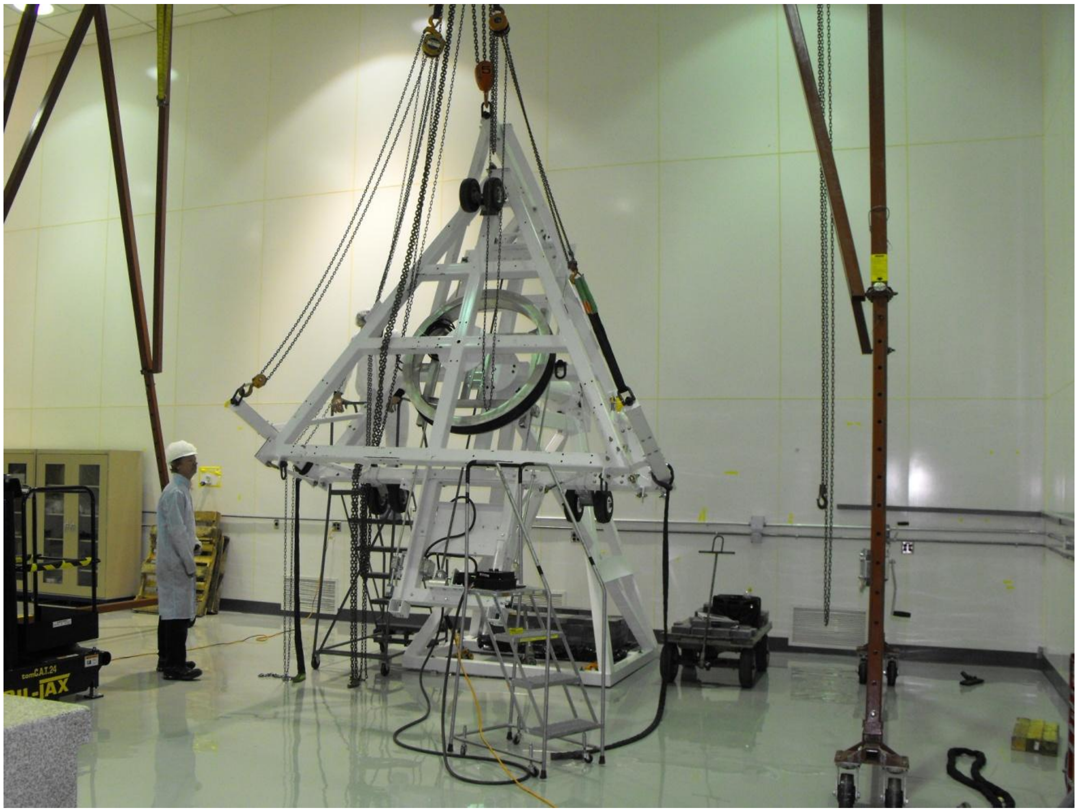


Figure 3: Rig to lift Drift Chambers into position. Note the circular Coil Magnet in center.

Because the resolution of the detector is directly impacted by the positioning of each and every sense and field wire, the amount of allowable 'sag' on the wires due to gravity must be carefully considered. Each wire is methodically strung, then tightened by attaching a weight of known mass. The tension on the wire is then just $F = mg$, i.e.,:

$$\text{Tension (N)} = (\text{tensioning mass})*(9.81\ \text{m/s}^2)$$

Once tightened, the wire is crimped into place, and the tension should (theoretically) remain the same indefinitely. However, this is not to be left to chance, and so a method for measuring whether the optimal tensions have been achieved (and have held up over time) is a must.

This is accomplished via a well-established process that relates the tension on a wire to its fundamental frequency. A wire is said to be vibrating at its fundamental frequency when there is only one standing wave on the wire. If two waveforms (crests) are seen on the wire, then the wire is said to be oscillating at its second harmonic (and, by extension, three crests corresponds to the third harmonic, etc.). So, in other words, the fundamental frequency is merely the first harmonic.

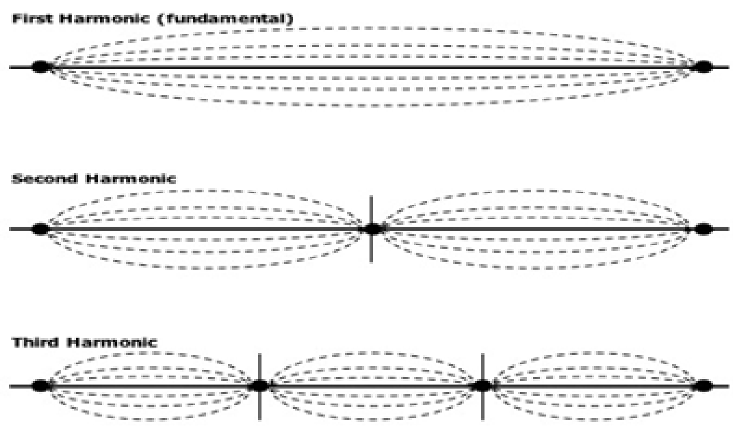


Figure 4: Standing Waves on a Wire

The relationship between the wire's fundamental frequency and its tension is as follows: the fundamental vibrations of a plucked string are such that their wavelength is twice the string's undisturbed length. In other words, the wavelength **λ** of standing waves on a string (i.e., a wire) is simply:

$$\lambda = 2L$$

By the universal wave equation,

$$\overset{\lambda}{\text{(wavelength)}}*\overset{f}{\text{(frequency)}} = \overset{v}{\text{(Velocity of wave)}},$$

we can say that the resonant (or fundamental) frequency of the string, f, is:

$$f = \overset{v}{\text{(Velocity of wave)}} / \overset{\lambda}{2L}$$

As the velocity of the wave can be expressed as

$$v = \sqrt{T/(\frac{m}{L})}\ ,$$

where T = tension and m = mass, the fundamental frequency f can be rewritten as

$$f = \sqrt{T/(\frac{m}{L})}\ / 2L$$

After rearranging terms and making the substitution $\rho = \left(\frac{m}{L}\right)$, our final equation for the tension on a wire, in terms of its fundamental frequency is:

$$T = \rho(\ 2Lf)^2$$

[It should be noted that, in practice, the linear density ρ is calculated by:

ρ = (Wire Density) * π(½Wire Diameter)^2,

where the Density and Diameter of the wires are provided by the manufacturer.]

Commercial tension-meters detect a wire's fundamental frequency in a variety of ways, but all require the user to input the length, and nearly all require that the wire be manually "strummed." However, since Drift Chamber wires are so densely packed (and sealed off with a Mylar sheet to hold in the gas), the wires cannot be directly manipulated. Only the outermost tips of a chamber-wire are accessible after stringing, and so a non-contact method for determining a given wire's fundamental frequency is needed.

Enter the fact that Drift Chamber wires are conductors. Constructing a low-amperage circuit through a wire (simply by attaching a negative electrode to one end, and a positive electrode to the other end) allows us to take advantage of the fact that the Force on a wire of length ***L*** carrying a current ***I*** through a magnetic field ***B*** is:

$$\vec{\boldsymbol{F}} = \boldsymbol{I}(\vec{\boldsymbol{L}}\ X\ \vec{\boldsymbol{B}})$$

This vector-product implies that if an upward-pointing magnetic field causes a current-carrying wire to bend to the left, then if we reverse the current (or field) direction, the wire will begin to bend to the right. By continually reversing the direction (via Alternating Current), the wire will swing between right and left at any frequency the operator desires. The wire's fundamental frequency will hence be detectable (i.e., whenever the oscillations are at a maximum), although it requires the operator to vibrate the wire at multiple different frequencies until the correct one is found (and to repeat this process for every subsequent wire).

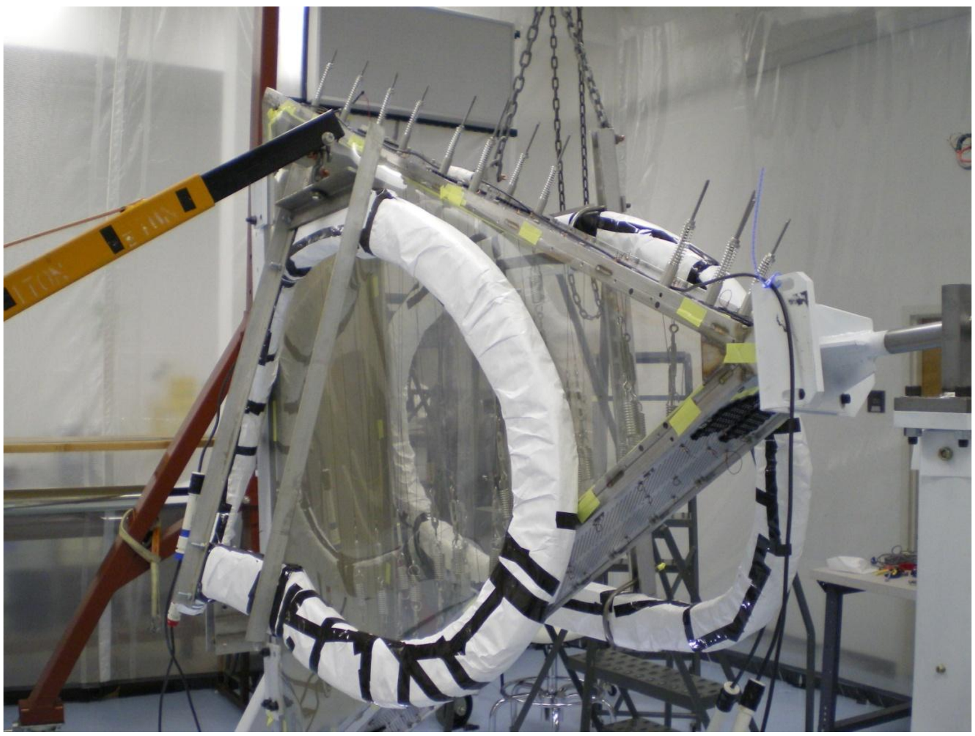


Figure 5: Drift Chamber set for wire stringing.
Magnetic Field is supplied by the two Coil Magnets (wrapped in white plastic).

Not surprisingly, finding the Tension from the Fundamental Frequency, by this method, can take several minutes per wire. But, in 1996, Princeton University's Mark R. Convery published a greatly streamlined version of the scheme. From his paper, "A Device for Quick and Reliable Measurement of Wire Tension":

> "Our method eliminates the need to scan a range of frequencies by, in effect, plucking the wire with a brief (3 ms) pulse of current and then observing the oscillating voltage induced by the wire's vibrations."

In other words, Convery's technique is to use a pulsed current, allowing a wire to vibrate nearly back to rest before being "strummed" again. When the wire oscillates in a magnetic field ***B***, Faraday's Law of Induction tells us that an electromotive force ***ε*** (measured in Volts) will be generated across the wire that is equal to the time rate of change of the magnetic flux Φ:

$$|\varepsilon| = \left|\frac{\Delta\Phi}{\Delta t}\right|$$

Since flux is the magnetic field ***B*** through an Area ***A***, it follows that

$$\frac{\Delta\Phi}{\Delta t} = \frac{\Delta(BA)}{\Delta t} = \frac{\Delta(BLx)}{\Delta t} = BL\,\frac{\Delta x}{\Delta t} = BLv,$$

where ***L*** is the wire's length and ***v*** is its velocity. This simply tells us that the faster our wire vibrates, the greater its induced voltage (energy per unit charge) will be. As the wire vibrates back down to near-rest, these decreasing voltages can be turned into a digital signal by any standard oscilloscope.[1]

Convery then makes use of oscilloscopes' Fast Fourier Transform algorithms to convert these periodic voltage-oscillations into information about the wire's harmonics. Fourier Transformation re-expresses "Voltage ***V*** at Time **t**" as "Voltage ***V*** at Frequency ***f***" by way of Fourier's Theorem, which tells us that if the time domain repeats at 100 cycles per second (100 Hertz), the frequency domain will contain a first harmonic at 100 Hz, a second harmonic at 200 Hz, a third harmonic at 300 Hz, and so on.

1) Strictly speaking, the middle of the wire will vibrate more quickly than the portions of the wire near its fixed ends, so the full equation is $\varepsilon = \int_0^L B(\frac{dx}{dt})dL$. However, the idealized "uniform velocity" version suffices to convey the general effect.

The frequency with which the time domain repeats itself, then, is our fundamental frequency. Because the frequency domain is only defined at the harmonics, our Fourier-Transformed voltage-signal "spikes" at the location of the fundamental frequency. Hence, the "f" term in the equation

$$T = \rho(2Lf)^2$$

can be quickly obtained with any conventional scope. This allows for the calculation of a wire's tension as rapidly as one can type its measured fundamental frequency value into a spreadsheet (i.e., a sheet pre-loaded with the wire's length $\boldsymbol{L}$ and linear density $\boldsymbol{\rho}$).

Although this cuts the testing-time down to about one wire per minute, it is desirable to make the process even less labor-intensive still. Entering many thousands of frequency values by hand is sure to result in some overlooked typos, and because tension is proportional to the fundamental frequency squared, even modest errors in data-entry could result in unacceptable errors in the final calculations. Convery goes on to suggest that a fully-computerized version of his system should be possible, although he does not illustrate how it might be done. Just such a system (based upon the Convery approach, but further reducing operator-involvement) is the ultimate goal of this project.

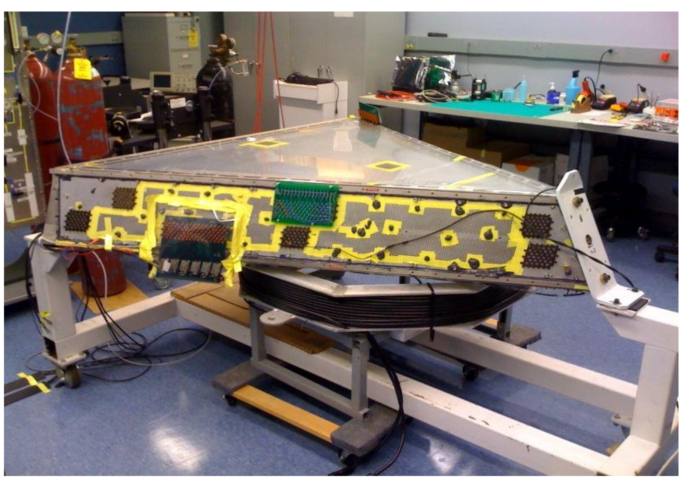


Figure 6**:** Drift Chamber sealed with Mylar, ready for Wire Testing.
Coil Magnet is centered underneath Medium-Length Wires.

Chapter 2

Tensionometer Development

Upon inheriting this project from Mr. James Graves, much of the hardware for the proposed Tensionometer was tentatively in place. A circuit-board to provide a 5 millisecond pulsed current to the wires had been constructed (its circuit diagram is included as Appendix 1), as had a new Helmholtz coil magnet capable of a 50 gauss magnetic field (directly in the center) using 77 Amperes of current. Mr. Graves and his advisors had also acquired a USB-based oscilloscope ("PicoScope 6") that connects to a PC, as an alternative to a traditional standalone oscilloscope.

As the three regions of Drift Chambers are being constructed at different facilities (Region 1 at Idaho State University, Region 2 at Old Dominion University, and Region 3 at Jefferson Lab), all Tensionometer data herein represent trials on the Region 1 Prototype Chamber at ODU. The chamber has already been strung with sense, field and guard wires of known tensions, allowing us to compare our results with the expected values.

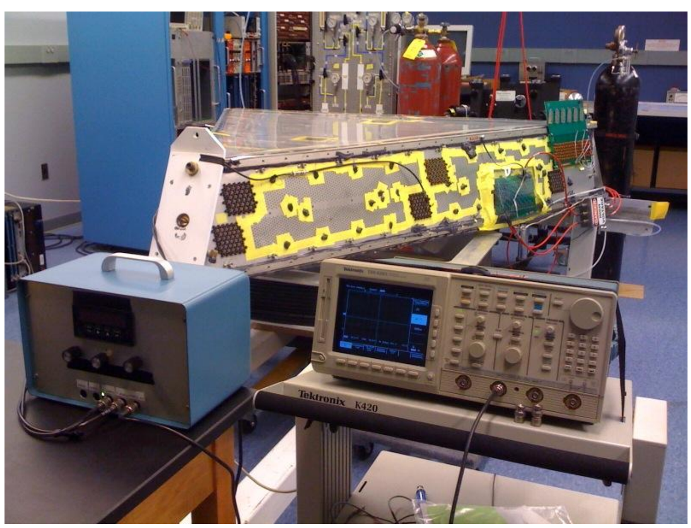


Figure 7: R1 Prototype Chamber at ODU.
Blue box in foreground is a circuit board to provide electric current to test-wires.
Beside it is a Tektronix Oscilloscope to display the corresponding signals.

Our first order of business was to verify that we could get fundamental frequency readings from the R1 Chamber with our magnet and a 5 millisecond-pulse circuit.

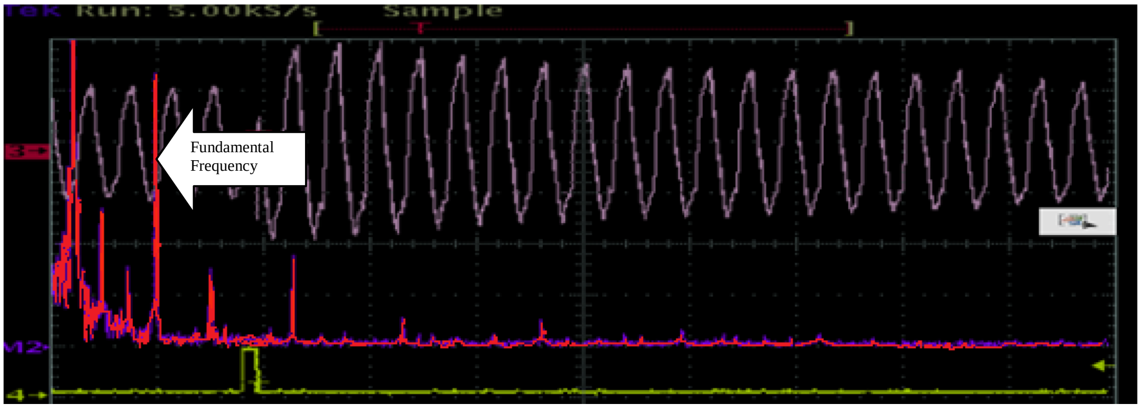


Figure 8: Medium-Length Field Wire (Tektronix Oscilloscope display).

Figure 8 shows the induced voltage on the wire as a function of time (in purple) from the vibrations of our electrically-pulsed wire in a magnetic field. Note how the wave decays until another pulse of current is delivered to the wire. The graph of the Fast Fourier Transform (FFT) is overlaid in red. Each red spike in the foreground is a wire-frequency where the voltage peaks. In this case, the fundamental frequency is the 2nd-highest peak. Figure 9 (below) is the output when the screen is saved to disk. Here, we zoomed-in on our 2nd-highest peak (the height of this peak increases with a stronger magnetic field).

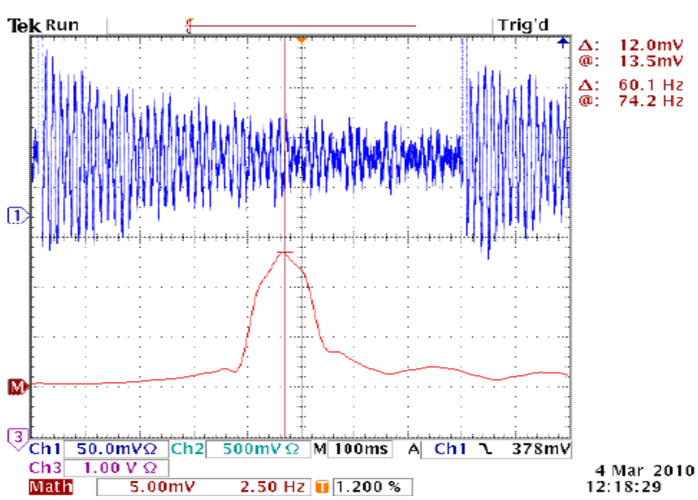


Figure 9: Medium Length Field Wire with Tektronix Oscilloscope
(Zoomed in on Peak @ Fundamental Frequency)

The location of the vertical red line in Figure 9 gives the value of our fundamental frequency in Hertz (74.2 Hz for this wire). It is important to note that the fundamental frequency's peak in Figure 8 will vanish when the coil magnet supplying the field is sufficiently turned down. Any remaining red peaks, then, are all 'fake' (e.g., electromagnetic noise from nearby devices and the power grid). This is the indicator of the true fundamental frequency, in the event that there is any doubt. One must beware not to confuse noise with a meaningful peak, especially when the magnetic field is weak. For example, a 60 Hz background noise source (corresponding to any nearby AC electrical devices) must not be mistaken for the wire's fundamental frequency. In principle, however, this problem can always be remedied by increasing the magnetic field until the fundamental frequency stands unmistakably taller than the 60 Hz peak.

To recap, this is the Convery method in a nutshell-- Find the fundamental frequency with an oscilloscope, then type its value into a spreadsheet that calculates the tension. However, it is not immediately obvious how to fully automate such a system. First, the length of every wire is different, and the tension equation depends on length. Also, if it takes a trained eye to spot the fundamental frequency from the background peaks (and/or the harmonics), then how can a computer tell the difference? A partial solution is to drown out the noise by increasing the magnetic field, as stated above, but the desired peak will still never overtake the peak at the origin (See Figure 8-- the tallest peak in the red FFT graph is always to the left of the fundamental frequency peak, since the induced voltage surges at the beginning of every pulse). One would have to chop off the first few FFT data points to ensure that the fundamental frequency stands out from the other peaks in any practical way.

This is where the PicoScope comes in. We were initially skeptical that an inexpensive, PC-based oscilloscope could yield data with anywhere near the same accuracy as its more expensive Tektronix counterpart, so we opted to compare the two.

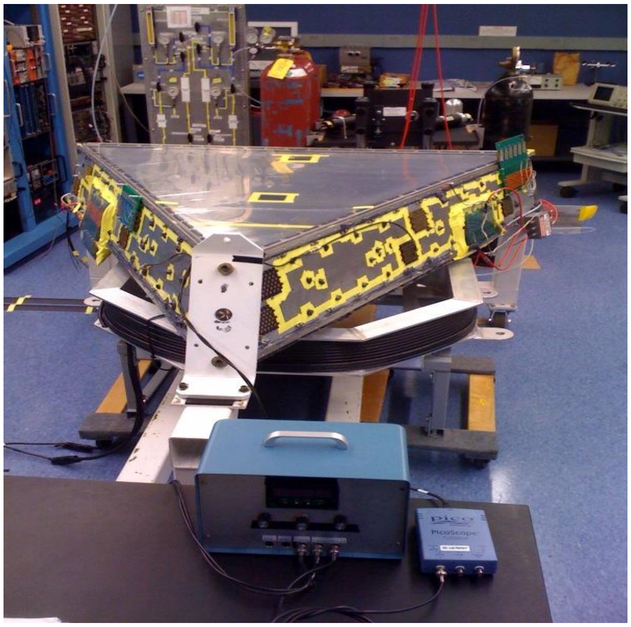


Figure 10: Same setup, now with PicoScope instead of Tektronix Oscilloscope.

After trials with several different lengths and types of wire, it appears that the PicoScope gives results that are in good agreement with the Tektronix Oscilloscope. Table 1 (below) is a quick comparison of fundamental frequency readings on the same 5 medium-length field wires, first with Tektronix, then with PicoScope:

Medium Field Wire #	***Tektronix Oscilloscope***	***PicoScope***
1	71.0 Hz	70.04 Hz
2	71.0 Hz	71.08 Hz
3	70.8 Hz	71.07 Hz
4	74.9 Hz	74.80 Hz
5	75.1 Hz	74.80 Hz

Table 1

The differences in all other cases were also on the order of one percent, so we concluded that the PicoScope meets our needs.

Visually, the PicoScope software shows the expected “ringing down” waveform (Figure 11), as well as the anticipated voltage peaks in its FFT (Figure 12).

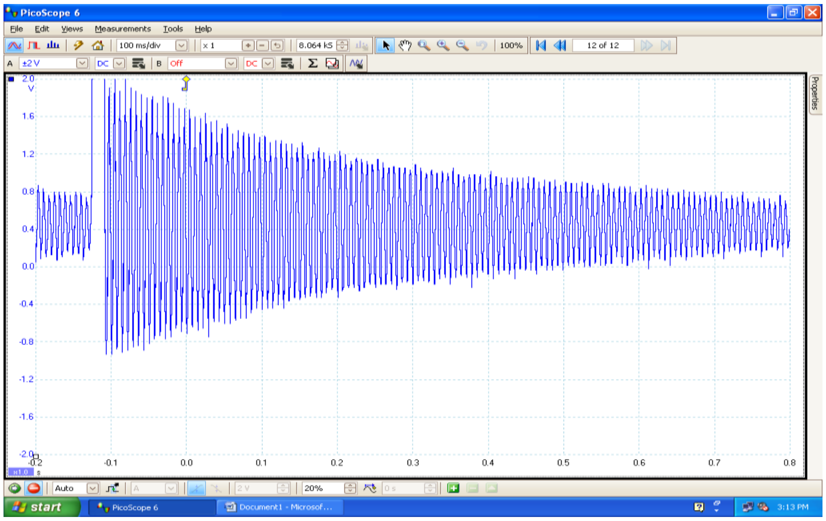


Figure 11: PicoScope display (voltage oscillations from plucked wire)

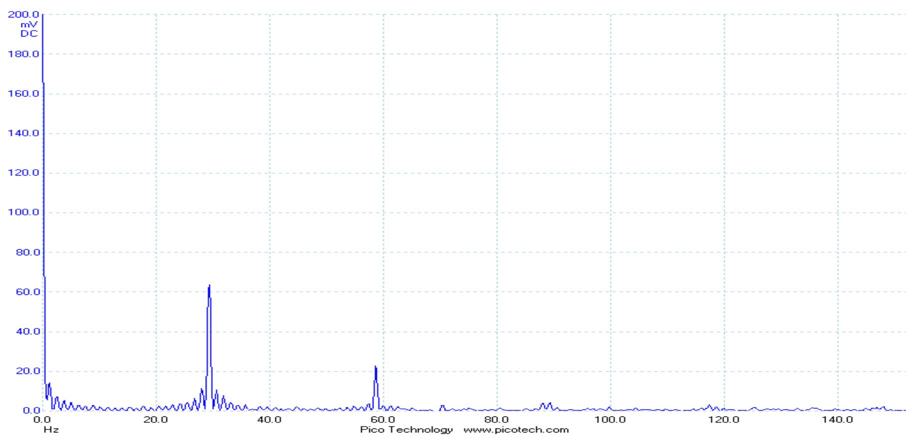


Figure 12: PicoScope FFT for Long Sense Wire.
Note that the fundamental frequency peak (30 Hz) is much higher than 60 Hz noise peak.

Compare and contrast Figure 12 now with Figure 13 (next page). Figure 12 shows the FFT for a long-length sense wire, whereas Figure 13 is the FFT for a medium-length field wire. The fundamental frequency of the long sense wire is at 30Hz, whereas the fundamental frequency of the medium field wire is at 70 Hz.

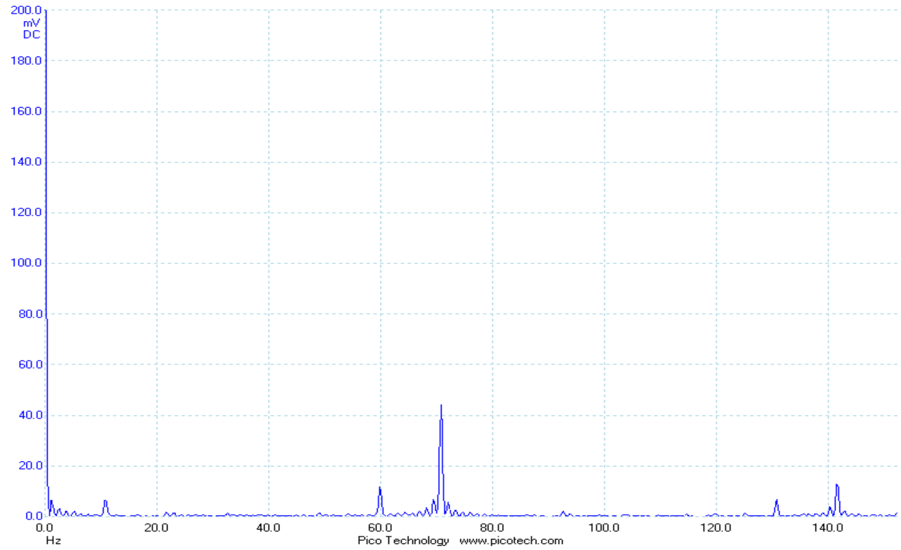


Figure 13: PicoScope FFT for Medium Field Wire.
Fundamental Frequency of wire @ 70 Hz.

Ideally, the PicoScope's FFT should always look like this, in that the fundamental frequency's peak should be much larger than any others. Of course, this is not always possible, so it bears mentioning that what follows will still yield accurate results even if the fundamental frequency's peak is only slightly taller than the background noise.

As long as this condition is met, then automation of the tension-testing becomes possible because PicoScope has the convenient ability to output its waveform data as text files (Figure 14 below)

Time (Hz)	Channel A (mV)
0.00000000	414.47930000
1.19209300	137.21120000
2.38418600	11.43695000
3.57627900	1.64918900
4.76837200	1.05049000
5.96046500	1.07373500
7.15255800	0.94982000
8.34465100	1.22470800
9.53674400	0.75600770
….	….

Figure 14: Sample PicoScope Text File (portion)

The first few lines of the file are deleted in order to remove the tallest FFT pulse peak at zero (refer back to Figure 8).

From here, we simply import this text-file data into MS Excel, highlight the Voltage Column, and run "Sort Descending." This feature will find the largest of the remaining voltages (recall we chopped off the first few). The highest voltage's accompanying frequency will now be in the uppermost cell on the left. This frequency value is, of course, the fundamental frequency we are looking for. Pre-loading the spreadsheet with the wires' other parameters enables us to simply copy the contents of the first "Time (Hz)" cell into our "Frequency (Hz)" column (see Figures below) to get our final tension measurement:

		Wire ID	Wire Length (m)	Frequency (Hz)	Diameter (cm)	Area	Density (g/cm^3)	Linear Density (g/cm)	Linear Density (kg/m)	Tension (N)	Expected Tension (N)	% Difference
		F111	0.901		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
		F113	0.887		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
		F115	0.873		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
		F117	0.859		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
		F119	0.845		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100

Figure 15: A Spreadsheet waiting for Frequency-values from PicoScope.
The "Tension (N)" Column automatically calculates $T = \rho(2fL)^2$ based on values from other cells.

A	B	C	D	E	F	G	H	I	J	K	L	M
Time (Hz)	Channel A (mV)	Wire ID	Wire Length (m)	Frequency (Hz)	Diameter (cm)	Area	Density (g/cm^3)	Linear Density (g/cm)	Linear Density (kg/m)	Tension (N)	Expected Tension (N)	% Difference
		F119	0.845	73.90977	0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	1.11169031	1.093815	1.63421693
		F111	0.901		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
		F113	0.887		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
		F115	0.873		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
		F117	0.859		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
73.90977	23.972352											
69.92847	20.893732											
70.87365	12.827257											
71.82944	8.937454											
64.93625	7.928364											
65.17396	5.937353											
70.78354	5.062537											
141.5611	4.629414											

Figure 16: Spreadsheet after PicoScope's ".txt" file has been imported and processed.
Wire F119's measured Fundamental Frequency (Column E) is at 73.9 Hz.
Tension (Column K) is 1.11 Newtons.

Though this may seem convoluted, it can actually be achieved by the push of a single button. The key was to create an Excel macro that performs the following steps:

1. Erases the first five data points from the text-file (Columns A & B)
2. Highlights the remaining entries in Columns A & B
3. Goes to the "Sort" menu and selects "Sort by Column B" (Largest to smallest)
4. Copies the contents of the first Cell from Column A (the Time (Hz) Column)

5. Pastes into the *Last Empty Cell* in the Column designated for the fundamental frequency (in the case of Figure 15, this is Wire F119's "Frequency (Hz)" Cell)
6. Grabs this entire final row and Cuts (<u>does not "Copy"</u>)
7. Clicks on the first row of wire-data (in this case, Wire F111's Cell) and presses "Insert Cut Cells."
8. Saves the spreadsheet

This continually updates the sheet with the latest measurements, putting each new fundamental frequency reading into its proper cell, and it inherently allows operators to pick up wherever they left off. For example, Figure 17 follows immediately after Figure 16. Two wires, F119 and F117 have now been tested, with wires F115, F113 and F111 left to go (for convenience, we always go in reverse order, so that the most recent wire tested is always at the top of the list).

Time (Hz)	Channel A (mV)	Wire ID	**Wire Length (m)**	Frequency (Hz)	Diameter (cm)	Area	Density (g/cm^3)	Linear Density (g/cm)	Linear Density (kg/m)	**Tension (N)**	Expected Tension (N)	% Difference
		F117	0.859	72.71767	0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	1.112072082	1.093815	1.66911972
		F119	0.845	73.90977	0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	1.11169031	1.093815	1.63421693
		F111	0.901		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
		F113	0.887		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
		F115	0.873		0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	0	1.093815	100
72.71767	23.2354											
70.82634	18.68005											
70.52558	11.64251											
70.22755	8.31816											
68.84337	7.578353											
67.73649	5.385742											
71.71767	4.186343											

Figure 17: Wire most recently tested is always the first entry on the list (F117 here). Next wire to be tested is always at the bottom of the list (F115 in this case).

When all five of the wires in this sheet have been tested, the spreadsheet will look as it did when it began (Figure 18, next page), but all wires will have their measured fundamental frequencies and tensions in place.

Time	Channel A	Wire ID	**Wire Length (m)**	Frequency (Hz)	Diameter (cm)	Area	Density (g/cm^3)	Linear Density (g/cm)	Linear Density (kg/m)	**Tension (N)**	Expected Tension (N)	% Difference
(Hz)	(mV)											
		F111	0.901	70.92953	0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	1.164046815	1.093815	6.42081291
		F113	0.887	70.03546	0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	1.099891666	1.093815	0.55554786
		F115	0.873	72.71767	0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	1.148616625	1.093815	5.01013652
		F117	0.859	72.71767	0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	1.112072082	1.093815	1.66911972
		F119	0.845	73.90977	0.0102	8.17E-05	8.72	0.000712536	7.12536E-05	1.11169031	1.093815	1.63421693
70.92953	22.83344											
70.33349	20.68005											
71.52558	12.25643											
71.22755	8.424339											
68.84337	7.145398											
69.73744	5.328864											
72.71767	5.084443											

Figure 18: Testing completed for this row of wires (F111 through F119).
Note that all wires have returned to their original ordering.

Of course, to fully automate this process, a Windows macro had to be written that executes the following steps:

1) Stops the PicoScope's recording (recommended, but not mandatory)
2) Saves its data into the same rewritable text file every time
3) Opens the text file and Selects All (Control-A), then Copies (Control-C)
4) Opens the macro-enabled Tension Spreadsheet in Excel
5) Pastes the contents of the text file into the first two empty columns
6) Calls up the Excel macro

To this end, sophisticated programs such as LabView could certainly be employed. For the R1 prototype, AutoHotkey was implemented, as it is free software that accomplished all of our goals with a minimum of code-writing. An operator can, in fact, record the steps they want their main macro to perform, then view the source-code that the recording generated. Some minor tweaking (for instance, inserting "Run" statements to initiate the text file and spreadsheet, as well as changing the "Sleep 100" statements to "Sleep 1" to speed up the commands) was all that was needed to produce a macro that can now be called-up by the push of a button.

If, at any time, an operator wants to add more wires to the spreadsheet, the main macro does not need to be re-recorded. All that is required is to change two lines in the

Microsoft Visual Basic code for the Excel macro (e.g., telling it to put the Fundamental Frequency into a different starting cell, then to Cut & Insert that whole new row into the next desired location).

In practice, our 'macro within a macro' takes about four seconds to execute, from the time we press 'T' in PicoScope (or whatever "hotkey" the Windows macro is assigned to) until the time we see a tension measurement in Excel. Therefore, if two operators are attaching the electrodes to the wires, with a third running the computer, it is not unreasonable to expect that several wires a minute could be tested with this approach.

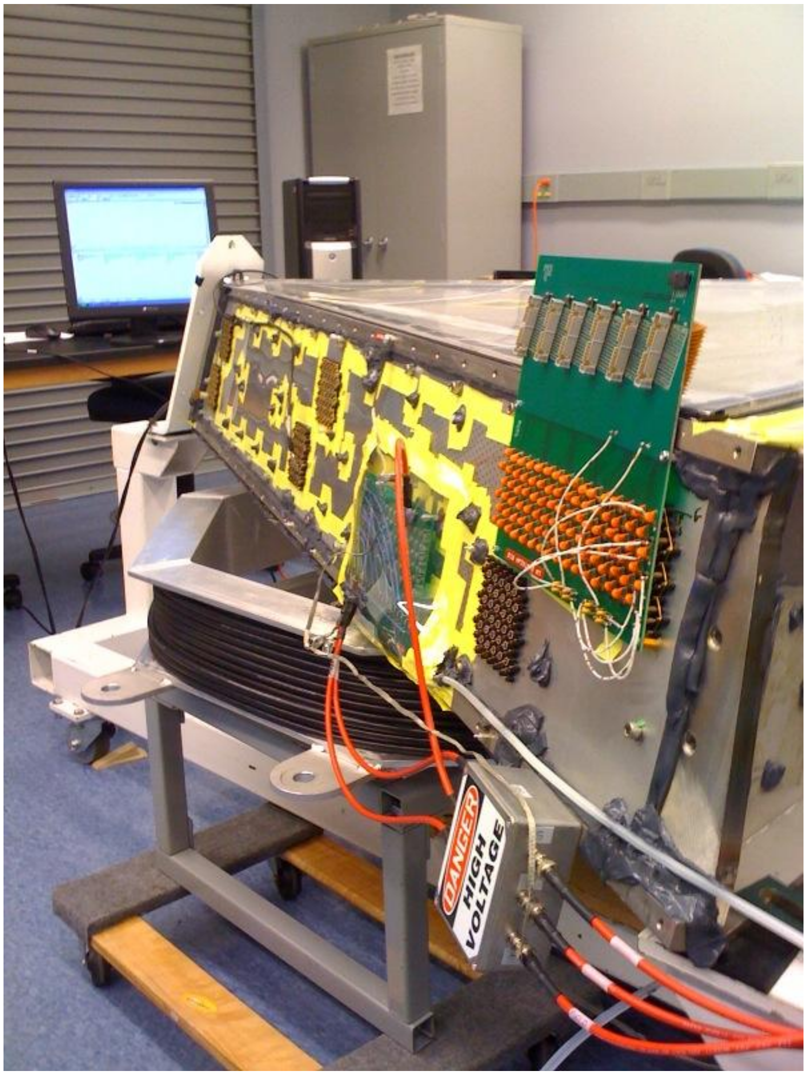


Figure 19: Connected to PC

Chapter 3

Testing and Results

With an automated system now operational, testing the wires themselves was a relatively simple matter. Figure 20 is another sample spreadsheet generated by this method, now with two different types of wire included.

Wire ID	Wire Length (m)	Frequency (Hz)	Diameter (cm)	Area	Density (g/cm^3)	Linear Density (g/cm)	Linear Density (kg/m)	Tension (N)	Expected Tension (N)	% Difference
D111	0.901	69.43941	0.00283	6.29E-06	21.34	0.000134232	1.34232E-05	0.2101739	0.20601	2.021212913
D113	0.887	72.12163	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.21973309	0.20601	6.661371303
D115	0.873	73.61174	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.22173784	0.20601	7.634503205
D117	0.859	75.99593	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.22881482	0.20601	11.06976474
D119	0.845	73.61174	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.20774221	0.20601	0.840836854
F111	0.901	70.92953	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.16404682	1.093815	6.420812914
F113	0.887	70.63151	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.118693	1.093815	2.274425216
F115	0.873	73.31372	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.16752369	1.093815	6.738679665
F117	0.859	73.31372	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.1303776	1.093815	3.342667304
F119	0.845	74.50581	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.1296929	1.093815	3.280070313

Figure 20: Spreadsheet of wire properties for 5 Sense Wires, followed by 5 Field Wires

Figure 20 concludes with the measured tensions, the expected tensions from the mass suspended on the wire during stringing, and the percent difference. A quick glance at the final column shows that these R1 wires are all within the desired 15% of the expected values. In fact, wire D117 is the only wire out of these ten that showed a difference of more than 10%. In general, the tension measurements from the PicoScope's FFT are what we expected (and/or hoped) to see, and they show good reproducability (e.g., if someone tests the same wires the next day, they should expect to get the same data to within 2%). Appendix 2 shows results for even more wires.

Regrettably, we were not able to measure the tension of the guard wires, as a stronger magnetic field would be necessary in order to induce enough of a voltage to work with (the guard wires' higher density reduces the amplitude of their induced oscillations). Fortunately, the guard wire sag does not significantly affect the resolution of the detector, so their tensions need not be measured to the same degree of precision as the others.

It should also be noted that we tested this method most extensively on the medium and long-length wires, where it works best. Short wires are more difficult to measure, as the signal is small and can be overwhelmed by noise. To reduce this interference, the electrode cables should be as close to one another in length (and separation) as possible, even if it involves wrapping them around each other (reducing the gap reduces the area, thereby reducing the flux of the noise).

As such, the induced voltages of the shortest field wires were only detectable when tensioned with a heavier mass than usual. Adjusting the frequency of the current-pulse to 10-per-second (or more) for the short wires may be necessary, even if the use of two Helmholtz coils (i.e., doubling the magnetic field we used for this testing) is ultimately planned, as in Figure 5. Increasing the current of the pulse (presently 25 milliAmps) is also a possibility, as Mr. Graves demonstrated that the effects on the wires' tensions from the extra heat (due to coefficients of thermal expansion) are negligible. Like with the guard wires, though, the exact value of the fundamental frequency of the shortest wires is not absolutely necessary, as long as we can ascertain that they are tensioned at all.

In closing, we have shown that full automation of our tension-testing is possible (at least for the crititcal sense and field wires), although it will require a great deal of preparation beforehand. Someone will have to enter all of the available wire data (all of their lengths, etc.) into spreadsheets before testing can commence. Consequently, this will force the testers to "stick to the script" rigidly. If a wire is to be tested 'out of sequence' (or re-tested), it must be done without the aid of automation. Therefore, Tensionometer operators must still have some knowledge of how this technique actually works. They will have to be able to tell at a glance if the PicoScope is showing a good FFT waveform before they proceed with measurements. Furthermore, they need to be prepared to type the fundamental frequency into the spreadsheets manually if they cannot get a strong enough response for automation on the shorter wires. Nevertheless, with over 85,000 total wires to measure, even full automation for only the medium and long wires will still speed up the testing process considerably.

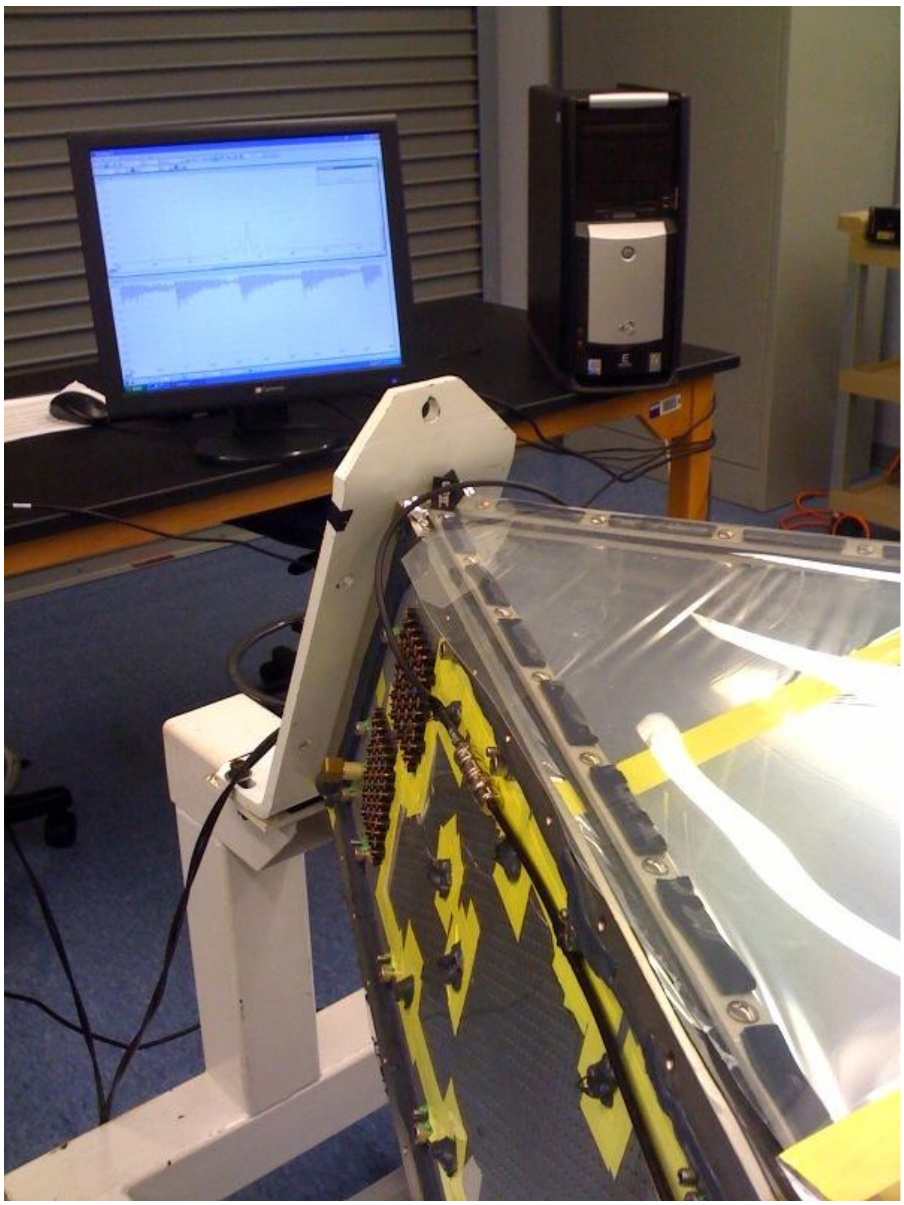


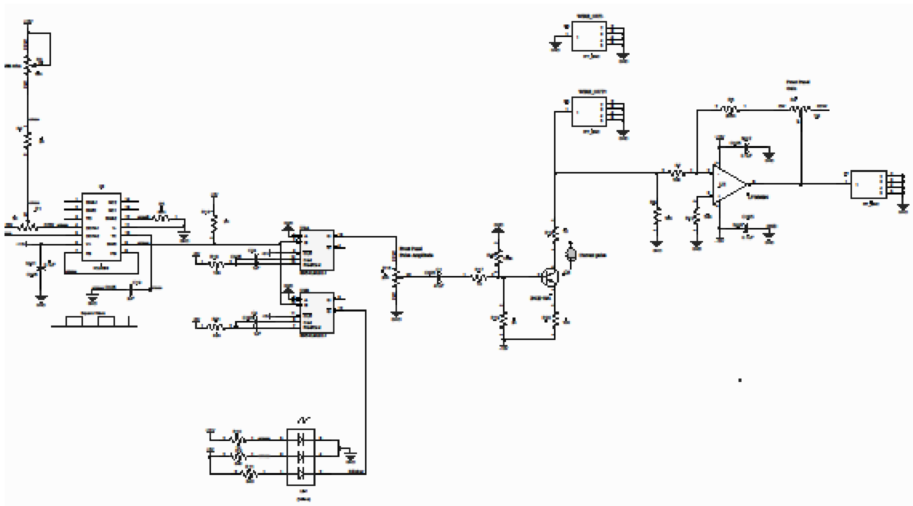
Figure 21: The two blocks of golden "studs" protruding from Chamber are the wire-tips that the electrodes connect to.

REFERENCES

Convery, Mark R. "A Device for Quick and Reliable Measurement of Wire Tension." Princeton, 1996.

Graves, James. "Development of Ring-back Tensionometer for Drift Chamber Wire Tension Testing." Senior Thesis, ODU, 2009.

APPENDIX 1



Circuit Diagram for Current-Pulser

APPENDIX 2

Wire ID	Wire Length (m)	Frequency (Hz)	Diameter (cm)	Area	Density (g/cm^3)	Linear Density (g/cm)	Linear Density (kg/m)	Tension (N)	Expected Tension (N)	% Difference
G6	1.5805	36.95488	0.00283	6.29E-06	21.34	0.000134232	1.34232E-05	0.1831681	0.203067	9.7991981
G8	1.5668	36.95488	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.1800064	0.203067	11.356168
G10	1.553	38.14698	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.1884432	0.203067	7.2014821
G12	1.5393	39.63709	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.199879	0.203067	1.5699128
G112	0.892	74.20779	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.2352588	0.20601	14.197754
G114	0.878	73.01569	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.2206676	0.20601	7.1149959
G116	0.864	71.8236	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.2067659	0.20601	0.3669392
G118	0.85	75.69791	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.2222915	0.20601	7.90324
G120	0.836	74.20779	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.2066468	0.20601	0.3091169
J111	0.901	70.63151	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.2174522	0.20601	5.5541761
J113	0.887	71.8236	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.2179208	0.20601	5.7816738
J115	0.873	73.01569	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.2181615	0.20601	5.8984811
J117	0.859	75.69791	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.2270237	0.20601	10.200347
J119	0.845	76.89	0.00283	6.29E-06	21.34	0.000134232	1.34E-05	0.2266576	0.20601	10.022623
I112	0.892	73.01569	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.2090069	1.093815	10.531209
I114	0.878	69.1414	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.0503452	1.093815	3.9741421
I116	0.864	71.8236	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.0975606	1.093815	0.3424382
I118	0.85	73.01569	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.0978347	1.093815	0.3674903
I120	0.836	77.18803	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.1868045	1.093815	8.5013882
N3	1.5943	28.90826	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	0.6054115	0.61803	2.0417224
N5	1.5805	28.90826	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	0.5949762	0.61803	3.7302047
N7	1.5668	28.90826	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	0.5847062	0.61803	5.391932
N9	1.553	30.39837	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	0.6351996	0.61803	2.7781151
N11	1.5393	27.71616	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	0.5187754	0.61803	16.059838
N111	0.901	70.33349	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.1445654	1.093815	4.6397621
N113	0.887	69.43941	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.0812497	1.093815	1.1487627
N115	0.873	74.80383	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.2154661	1.093815	11.121727
N117	0.859	78.38012	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.292007	1.093815	18.119337
N119	0.845	74.80383	0.0102	8.17E-05	8.72	0.000712536	7.13E-05	1.1387484	1.093815	4.1079543

Test results for three rows of Sense Wires (Long and Medium-Length) and three rows of Field Wires (Long and Medium)