Quadrupole Alignment via the Vibrating Wire Field Measuring Technique

Written by:
Michael Jansz

Under Supervision of:
Alan Chen
Dave Hutcheon
Peter Machule

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Introduction

The DRAGON separator is a recoil mass spectrometer. It separates out reaction products (recoils) from the steady stream of beam particles. The physical parameters (reaction cross-sections) are then extracted by comparing the experimental data to models of the transmission though the separator. It is thus imperative that the models and experiments describing DRAGON's transmission agree. This requires that either a) the separator be perfectly aligned or b) the misalignments in the separator be measured precisely and incorporated into the models. Indeed, DRAGON is not perfectly aligned, nor have the misalignments been measured before this summer. Due to shifting of the concrete floor, the magnetic elements of the separator have moved, and according to a recent TOTAL survey, some of the magnets appear to be as much as 3mm out of position.

In particular, DRAGON contains 10 quadrupole magnets used to focus the beam and steer stray particles towards the beamline. These quadrupoles (quads) have field gradients on the order of 50G/mm, so even small misalignments can have drastic effects on the trajectory of the beam.

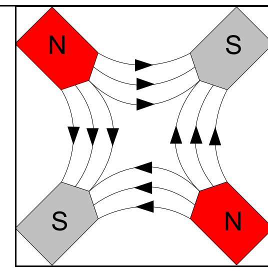


Figure 1: The field of a quadrupole magnet.

For this reason, the vibrating wire field measuring technique was employed to determine the locations of the magnetic centers of the quadrupole magnets with respect to the beam axis.

The first two arms of the dragon separator were measured, including quads 1-5. Some large discrepancies have been found, particularly in quads 1 and 2, suggesting possible adjustments that may increase transmission.

Presented in this report are a brief summary of the idea behind the vibrating wire field measuring technique, the practical information necessary to reproduce this work (including step-by-step instructions for setup and data acquisition), and a summary of the data on quads 1-5.

The Vibrating Wire Field Measuring Technique

The vibrating wire field measuring technique was developed by Alexander Temnykh, to align the CESR quadrupole magnets. Only a brief description of the theory will be given here, but a full explanation can be found in A. Temnykh, Vibrating wire field-measuring technique, Nuc. Inst., A 399 (1997) 185-194.

The vibrating wire technique operates on the principles of Fourier series, and Lorentz forces. You drive an alternating current through the wire, and the magnetic forces produce local, periodic forces. If the period of these forces match one of the fundamental modes of the wire, then a simple harmonic resonator results. By exciting one mode at a time, and adding the contributions of all of these modes, you can reconstruct the field profile along the wire.

The Apparatus and Materials

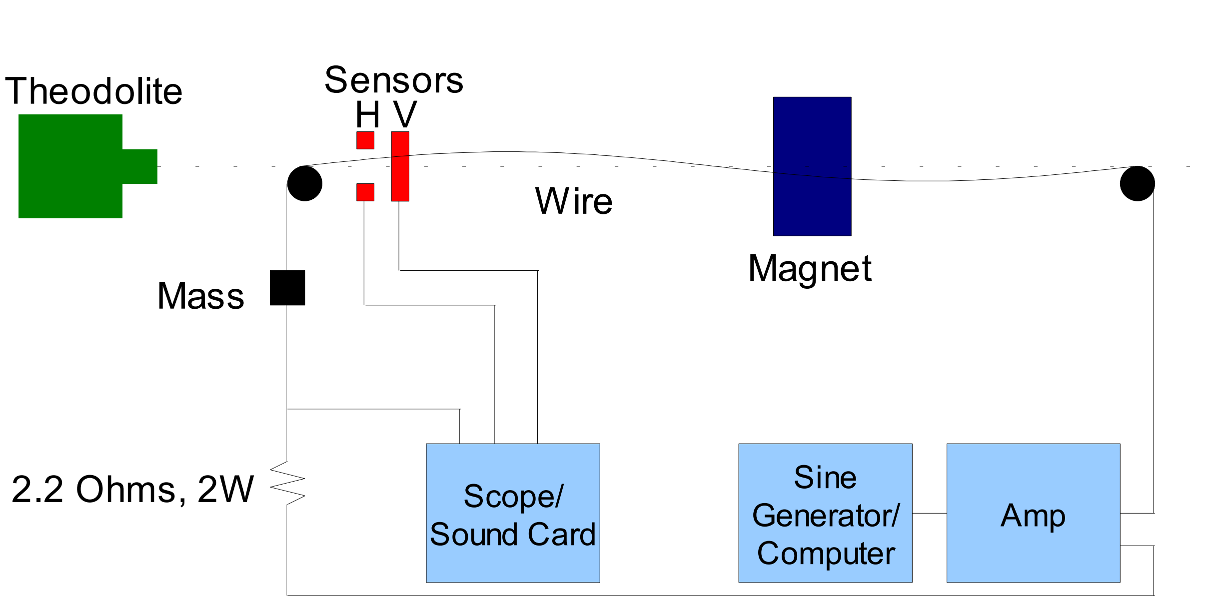


Figure 2: Diagram showing the physical setup of the vibrating wire.

<u>Some Pictures of the setup:</u>

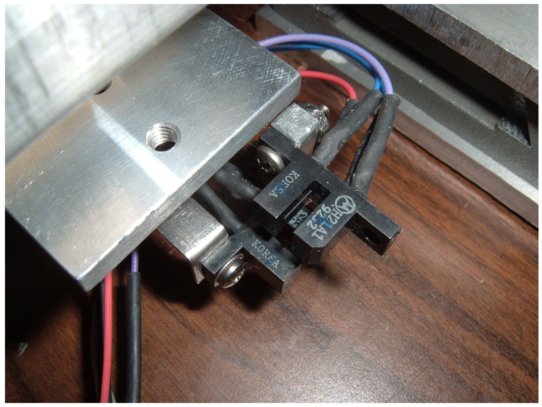


Figure 3: Picture showing the two photo-transistor assemblies mounted to produce the horizontal and vertical position sensor.

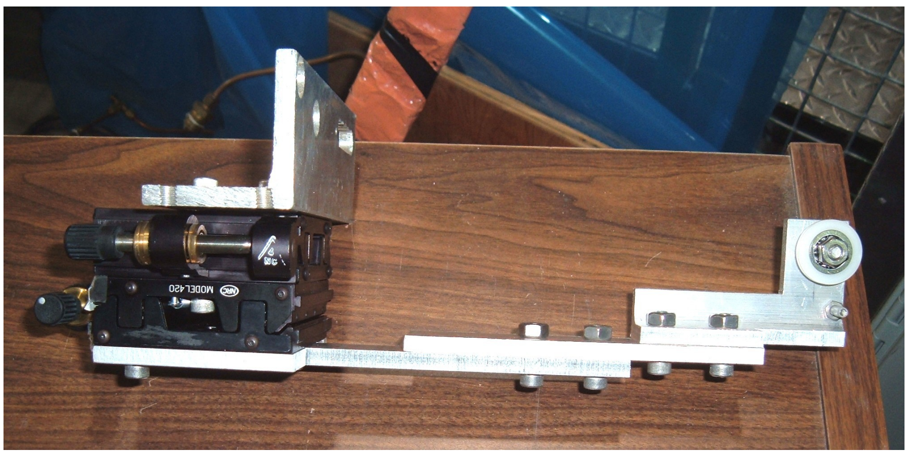


Figure 4: Picture showing on of the wire end mounts. The XY stage, aluminum adapter piece, and the v-groove pulley are visible.

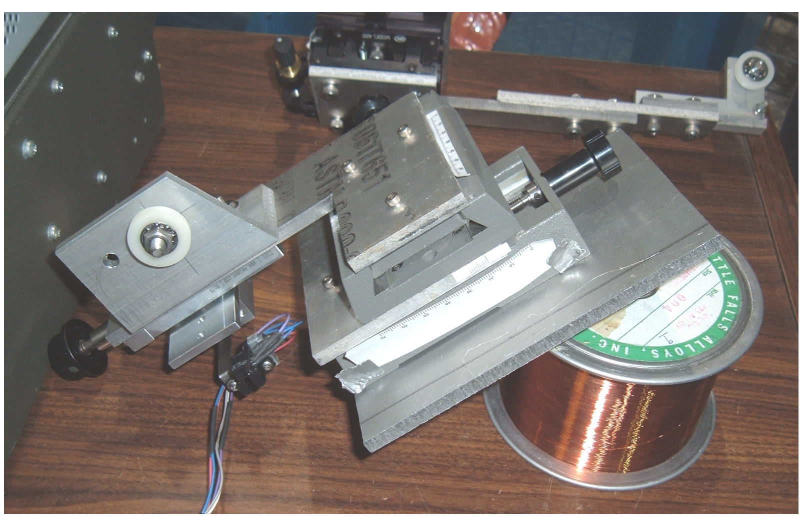


Figure 5: Picture showing the wire spool and the second wire mount. Also visible are the paper verniers used to measure the wire position.

Materials:

Item	Use	Source
HP 6286A DC Power Supply	Current Source for Amplifier.	Peter Machule
Car Stereo Amplifier	Amplify sinusoidal current through wire.	Peter Machule
H21A1 Photo-transistor Assembly (x2)	Used as a sensor to measure the vibrations in the wire.	Peter Machule
Dell Computer	Data acquisition (recording sound, function generator).	Dragon
Creative Sound Card	Data acquisition card (2 ch ADC in, 1 ch DAC out).	Konstantine
RC DC Blocking Filter	Remove DC component from position sensors .	Stores
Tektronix TDS 3034 Scope	Used to find modes, evaluate maximum mode, the 'product of signals' function was used for rudimentary data acquisition.	Dragon
Agilent Arbitrary Waveform Generator	Used to scan frequencies to fin fundamental.	
75um CuBe Wire	Strung through magnets.	Wayne Faszer
100 g Mass	Provide known tension.	
XY Stages (x2)	To translate wire ends.	Matt Pearson (2) Peter Machule (1)
Paper Verniers (x4)	To quantify displacement from aligned position.	Printed
Insulating V-Groove Pulleys	Alignment by theodolite, align 90° grove with cross hairs of theodolite.	Wayne Faszer
Kern Theodolite	Provides the optical axis for aligning pulleys.	Beamlines Group

Table 1: Lit of the items, uses, and sources used with the vibrating wire.

Custom Pieces:

There are several fixtures, mostly cut from 1/4” aluminum scrap, that act as adapters between the different pieces. These fixtures are shown in the pictures above. They also act as extenders, providing the necessary separation between the xy-stages, sensors, and pulleys. There are various adapters allowing the end pieces to be mounted in different locations along DRAGON. All pieces were designed with standard imperial measurements.

Setup Instructions:

1) Have the beamlines group set up a theodolite at the proper position looking along axis of interest.
2) Vent DRAGON, and remove the BCM/Slits/Faraday Cup/Target where the wire mounts will go.
3) Choose the end pieces/adapters that work best at the given locations.
   1. Pick most convenient upstream/downstream orientation for the wire mounts.
   2. Pick extenders based on the size of the empty cavity.
4) Clamp the end pieces firmly into place with C-clamps.
5) String CuBe wire through beamline and attach one in end to weight and the other to the insulated pin. (May be useful to use measuring tape to pull it through.)
6) Configure computer sound card (in windows control panel, and attach cable to "Aux In."
7) Set up wiring.
   1. Computer "Line Out" goes to amplifier, via headphone jack to BNC adapter (positive and negative matter!!!).
   2. Power source to amplifier (12V, ~ 0.5A).
   3. Amplifier pink wire to +12V.
   4. Amplifier channel 1 positive out to Start of CuBe wire.
   5. Long, low-resistance wire from end of CuBe wire amplifier channel 1 negative.
   6. Establish common ground between 9V battery, amplifier channel 1 negative, and "Aux In" negative.
   7. Channel one into computer "Aux In" (or scope) connects through RC filter to the position sensor about the voltage dividing resistor (on whichever sensor is being measured). The leads coming from the sensor are labeled, ground is obvious.
   8. Channel two into computer "Aux In" (or scope) connects to the end of the CuBe wire.
   9. Connect 9V battery to position sensor.
8) Move position sensors away from wire.
9) Move front pulley away from axis.
10) Align back pulley with theodolite, record position.
11) Bring front pulley back to axis, align with theodolite, record position.
12) Bring position sensor back to wire, align vertically and horizontally using scope on DC mode. Use the middle of the linear regime that is closer to the bottom of the 'U' of the sensor. (See 'H and V Sensor Calibration.ods' for calibration plot.)
13) Scan for fundamental frequency. To find precisely, measure the frequency of a higher mode and divide by the mode index.
14) Find the strongest mode, and scale the sine amplitude to maximize the wire current without saturating the position sensor (200mV P-P) at resonance.
15) Take data. (While taking data it is helpful to cover the position sensor with a folded sheet of paper to block ambient light from the photo-transistor, which is a major source of noise—especially in the 120Hz range).
16) Remember to disconnect 9V battery when done.

Calibration:

Sensors:

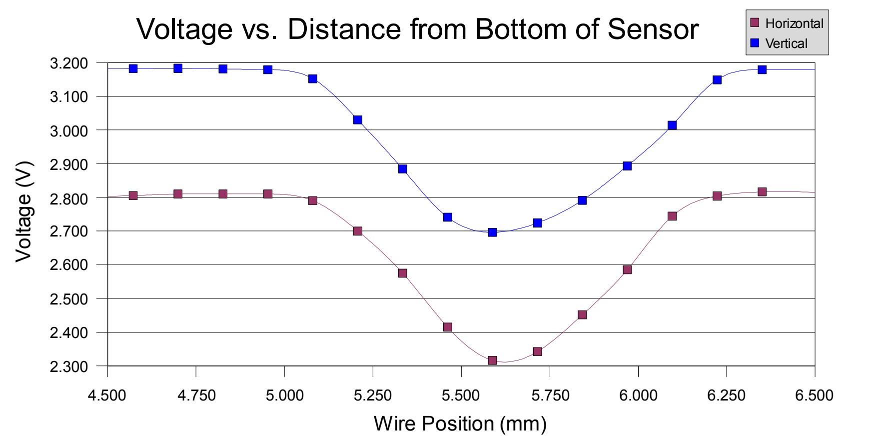


Figure 6: Plot of voltage as a function of wire position for the sensors.

To calibrate the position sensors, the voltage across the drop-resistor in the photo-transistor assembly was plotted as a function of position. There is a nice linear regime with the wire located at about 5.3mm from the bottom of the sensor (the bottom of the 'U'). Here, both sensors have a slope of roughly -1.1mV/um, and range of 0.3mm. The sensors have been mounted to each other such that they are perpendicular with the linear regime located near the center of the other sensor. With this arrangement, the there is almost no cross-talk between the sensors, and the full 0.3mm range can be used. Typically the computer data acquisition can resolve vibrations as small as 1um, and the sensors saturate at vibrations of roughly 150um—providing a large range of detection. As the sensors have been permanently fixed, and should not change with time, this calibration should never need to be redone. It is important, however, at every use the sensors be placed such that the wire is located at the very middle of the linear area to prevent distortion of the waveform.

Frequency Dependence:

Due to wide range of frequencies used, one must consider the frequency response of the apparatus. The sound card output and amplifier both attenuate low frequency signals. It was found that this attenuation was small (> 75% of max amplitude), even at the lowest frequencies used. Also, the current amplitude is measured subsequently, so any attenuation is known and accounted for. The photo-transistor is quotes as have an 8us turn-on time and a 50us turn-off time. Given that the sensor is essentially remaining on, the time delay in reacting to changes in wire position should be significantly less than 8us. Thus, there should be no appreciable phase shift of frequency response for the range of frequencies used (<1KHz). Finally, the ADC in the sound card presents two challenges: frequency response, and a time delay between the two channels. The frequency response is canceled because we measure two signals at the same frequency and then take their quotient. Thus, any attenuating factor is present (and equal) in both measurements, and is then canceled in the division. The time delay caused by the alternating channels was measured (with the sample rate at 44100 S/s, which is used in the data acquisition) to be 7ms and is subtracted off from the second channel to synchronize the two channels. With this correction in place, the phase of a single signal measured through both channels agrees to 0.01rad over the range of frequencies used.

Field Magnitude:

The Fourier reconstruction only provides a description of the relative field strengths along the wire. In order to obtain actual field measurements, one must calibrate the plots, via a linear scaling factor, to achieve measurements in Gauss. In the first dataset, the field was calibrated to the residual field in a steering magnet along the wire which was measured with a hall probe to be roughly 3G. For the computerized reconstruction, a scaling parameter has been included to allow easy calibration. This parameter has been set at 63 (approximately 20π). It was determined by creating the Fourier reconstruction of an empty field, and scaling the background to the earths field. It is believed to be a reasonably accurate calibration (within a factor of 2 of the real value), and should be independent of wire length, so it should, in theory, not need adjusting. A new calibration to a stronger test field would certainly provide a more accurate scaling, making it easier to tell where the wire is relative to the center of the quad, however, the final goal is finding the zero, so scaling does not matter.

There is also the issue of defining the positive/negative sign convention for the field. In practice it can be accomplished by comparing the polarity one of the quads, and two Fourier reconstructions taken with the quad on and the wire translated a known direction. That said, it is often more useful to determine which direction horizontally and vertically corresponds to a positive field, and disregard the signs otherwise.

Data Acquisition:

Zero Finding:

The zero finding technique is the easiest way to find the center of a magnet, however it works only when one magnet is on, and only when there are no stray/residual fields. It involves simply finding two active modes, one with an antinode at the magnet of interest, and one with a node at the magnet of interest. This is done because the magnitude of the mode with the antinode at the magnet gives information about the magnet's shift, and the other mode gives information about the magnet's rotation, with very little cross over. The technique is to move the upstream end of the wire until the first mode is quite, then move the downstream end until the second mode is quite, and repeat. After a few iterations, you should arrive at a position where both modes are quiet. Then, simply scan through the rest of the modes (making tiny adjustments as necessary), to ensure that all modes are dead. It may be that the odd modes are never completely quiet due to the earth's magnetic field, however this is unavoidable. This technique works best using the oscilloscope, showing both the horizontal and vertical vibrations simultaneously, while triggering from the current. It is recommended that this technique not be used to measure final results as it is not as sensitive as other methods. Also, the computer can be used as a function generator using the “Signal Generator.vi” program. A 'discrete' mode has been included making it easier to access particular modes.

Manual Fourier Reconstruction:

For the first round of tests (quads 3,4, and 5), the data was acquired manually. The current was measured via the voltage drop across a long, low-resistance wire on one oscilloscope channel, and the wire position was measured on another via AC coupling. The digital scope includes a 'math' function, which was used to multiply these two channels. It also includes a 'mean' function in the 'measurements' menu, that was used to obtain the time average of this product. Roughly 12 modes were used, and 11 data points were taken at each, to provide a reliable fit. The driving frequency was set manually on the function generator, a few seconds were given to allow the wire to reach equilibrium, and the measured quantity was recoded from the scope. The data was then fit manually, one index at a time, in gnuplot. A typical data set would take about a day to acquire and fit.

Automatic Fourier Reconstruction:

For subsequent measurements, a LabVIEW program has been written to allow for automatic data acquisition. This program requires the user to enter various parameters to start, but will then complete the process (scanning each mode, acquiring data, fitting the data, plotting the field) on its own. This program should be run with the sound record option set to 'Aux in', and the sensitivity set to maximum. Also, the *computer* volume should be set to the minimum possible value to minimize noise and keep the current at an appropriate level! Due to the lack of an AC coupling option, an RC DC-blocking filter should be used with the wire position input. The data acquisition program is called “Data Acquision.vi”.

Input	Typical Value	Description
Output Sample rate	44100	Sample/s to DAC.
Number of output Channels	1	This indicates that the sound output is mono.
Output Bits per sample	16	Should be set at maximum of 16, for cleanest sire wave out.
Output Device ID	0	Picks the output device (which sound card to use).
Input device ID	0	Picks the input device (which sound card to use).
Amplitude	85	Ranges from 0-100. Used to set the driving current amplitude. Must be scaled to compensate for strong/weak fields.
Seconds to wait	3-6	Second of output, before input sampling. Allows transients to die.
Data points	11-15	Number of data points taken at each mode.
Number of modes	12-30	Number of modes examined.
Resolution	0.1-0.25	Spacing between data points at a given mode.
Wire length	2-4	Wire length in meters.
Current Resistor	2.2	This is the resistance of the resistor over which the current is measured. This converts volts to amps.
Fundamental frequency	15-40	Frequency of first mode in Hz.
Sensor	Vertical/ Horizontal	Pick horizontal or vertical, depending on which sensor is being used.
Amplitude cutoff	0.002	A pre-fitting cutoff, that discards modes of very low amplitude.
Damping cutoff	0.1	A post fitting check, to ensure that the parameters are reasonable. Typical damping values are in the 0.2-0.7 range, so anything lower than 0.1 is rejected.
Scaling factor	63	An empirically determined number that scales the output to Gauss.
Path	\Desktop\Data	The path of the folder the data will be saved into.

Table 2: List of the input parameters for the data acquisition program.

The program works by producing a continuous sine wave that is sent to the amplifier and then to the wire at high (50mA) current. The program will then wait 'seconds to wait' seconds for the wire to settle, and will then simultaneously sample the current (via the voltage across the resistor) and the wire position (via the photo-transistor assembly) for one second. It subtracts off the time delay between the two channels, removes the first half of the sampled data, employs a narrow band-pass filter centered on the frequency it generated, and then Fourier transforms the signals. It will then determine the frequencies, amplitudes, and phases of the two signals. It scales the two voltages to get vibration and current, and then computes vibration/current*cos(phase difference). The program will then do this 'Data points' times (at several frequencies centered on the resonant frequency) and stores the computed values to file and temporary memory. The program will then examine the data, disregard data sets that are of inconsequentially small magnitude, generate guesses for the fitting parameters, perform the fit (saving an image of the fit to file), evaluate the quality of the fit (disregard modes with poor fits), and save the fitted parameters to file and memory. Once this has been completed at all modes, the program will plot the field along the wire as a function of position (also saving this image to file).

<u>The approach:</u>

From experience, the best technique is to begin by producing a Fourier reconstruction of the field with all of the magnets ON and the wire on the optical axis. This will give a rough idea of the scaling on the magnitude of the fields (because the sag will offset the wire from the magnet centers so the field should not be zero). Then, move the wire vertically and horizontally and reconstruct the field again. This will help determine the scaling, and will allow you to determine the positive/negative sign conventions (also, the polarities of the magnets are all known (they alternate), so if one magnet is knows, they are all known). Finally, with only one magnet on at a time: reconstruct the field, estimate the needed change in wire position; move the wire; and repeat. Once you have found the center of the magnet, turn the magnet off and reconstruct the background field. This method is quite time consuming, however it gives a reliable measurement of the location of the center of the magnet, and is far more precise than the zero-finding technique. With some practice, and the knowledge of how far from each end of the wire the magnet lies (to do a linear interpolation), guessing in which direction and by how much the ends must be moved becomes much easier and it only takes a few iterations to converge. Also, it should be noted that moderate field strength/current combinations tend to work best as high currents/fields cause uncontrollable, sharp resonance at high harmonics making data acquisition difficult; and low currents/field strengths decrease the signal to noise ratio and decrease the sensistivity of the technique. Generally currents around 25-50mA, and field gradients of 10-20G/mm seem to work best.

Note: Remember that vertical vibration are due to vertical forces, which are caused by the horizontal field. The nature of the field in a quadrupole is such that a vertical offset changes the strength of the horizontal field, so vertical motion affects vertical vibration. So the vertical sensor measures horizontal fields and vice versa.

Data Processing:

Fitting:

Referring to A. Temnykh's paper, the proper model to describe the data is $a_n \frac{(f-b_n)}{f(4(f-b_n)^2+c_n^2)}$, where a describes the strength of the resonance, b the frequency of the resonance, and c the damping. Also, the subscript n's denote that these parameters are unique to each harmonic. In practice it was found that there were small offsets in the two amplitudes due to noise, which resulted in a vertical offset in the final data points (the quotient of these amplitudes). For this reason, the model $a_n \frac{(f-b_n)}{f(4(f-b_n)^2+c_n^2)}+d_n$ was used for fitting to improve fits by subtracting this figment of the daq process. Typically the d parameter was three or four orders of magnitude smaller than the a parameter, and thus did not alter the fit much. When measuring weaker harmonics, however, subtracting this small offset allowed for more reliable fits.

Accounting for sag:

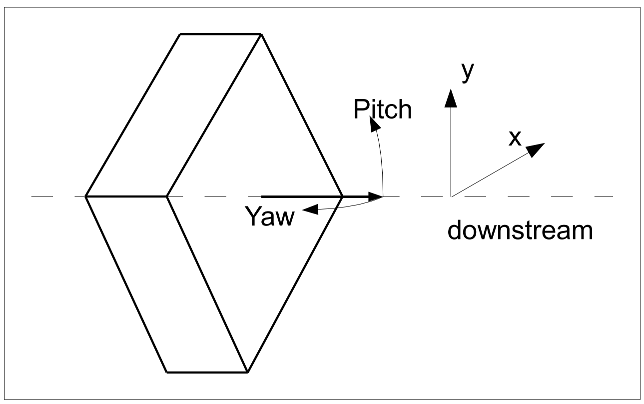
The wire is considered to be a perfect catenary with equal tension on both ends. The ends are allowed to differ in height, but the force applied is assumed to be approximately equal at both ends nonetheless. Due to the small linear density of the wire, with respect to the 100g weight providing the tension, this is a good approximation. The catenary is translated vertically and horizontally with two degrees of freedom to align the ends of the wire with their recorded locations. This is done in a spreadsheet ("Wire Magnet Centers") that will then automatically translate the catenary and subtract off its contribution to the offset and slope at each of the magnets. Assuming the same mass and wire are used, the spreadsheet requires only the total length of the wire, and the locations of the magnets to make these calculations. The linear density (μ) of the wire was estimated as 6.895E-5Kg/m, based on the diameter or the wire, the composition of the metal, and the densities of copper and beryllium. The tension (T) was estimated to be 0.9967N. This estimate was made by assuming that the mass was exactly 100g, and the making very small adjustments to the mass such that the predicted value of the fundamental frequency (given by $f=\frac{1}{2\mathrm{L}}\sqrt{\frac{T}{\mu}}$) agrees with the measured value. These parameters have then been used to predict the fundamental frequencies of wires of different lengths to an accuracy greater than 0.1Hz.

Data:

	Position Along Wire (mm)	Difference (mm)		Shift (mm)		Yaw (mrad)	Pitch (mrad)
		x	y	x	y		
Quad 1	1110	6.7	-2.4	1.52	2.05	4.71	4.42
		-3.1	6.7				
Quad 2	1660	6.5	2.5	0.15	1.23	3.85	-0.21
		-1.5	1.2				
Quad 3	1110	0.2	1.7	0.09	0.54	0.10	-0.67
		-0.1	0.5				
Quad 4	1660	-0.2	2.7	-0.25	0.29	0.03	-0.89
		-0.3	-0.3				
Quad 5	2210	0.5	3.5	-0.23	0.55	0.33	-0.58
		-0.5	0.3				

Table 3: The final results from the two application of the vibrating wire.

It is important to note that quads 1 and 2 (light gray) belong to one set of measurements, and quads 3, 4, and 5 (dark gray) belong to a second set. The systematic errors are different for the two data sets, so relative shifts and rotations are only reliable within a single dataset.



Drawing 1: Diagram showing the coordinate system in which the measurements were made.

The following plots show Fourier reconstructions of different features observed when aligning the wire with the quad centers. When quads were on, the field was set such that the gradient was approximately 10G/mm.

1) A translation of the wire can be identified as a symmetric peak centered at the location of the quad. Due to the fact that the quads are placed in pairs and triples with alternating polarity, a translation of the wire should produce alternating positive and negative peaks. To consecutive peaks of the same sign indicate a rotation of the wire. The peaks may have different magnitudes due to a) misalignments of the magnets, b) different field strengths/gradients, or c) the sag in the wire may appreciably change the wire location at each magnet.
2) A rotation can be identified as an antisymmetric pair of peaks, with the zero separating them centered at the magnet center.
3) Often, one with observe a combination of the above two features. These features seem to obey a linear superposition, so the combination can be decomposed back into a sum again. In general, with two antisymmetric peaks, the average of the maximum and minimum values gives the field due to the translation, and the difference between the maximum and minimum values gives the field due to the rotation.

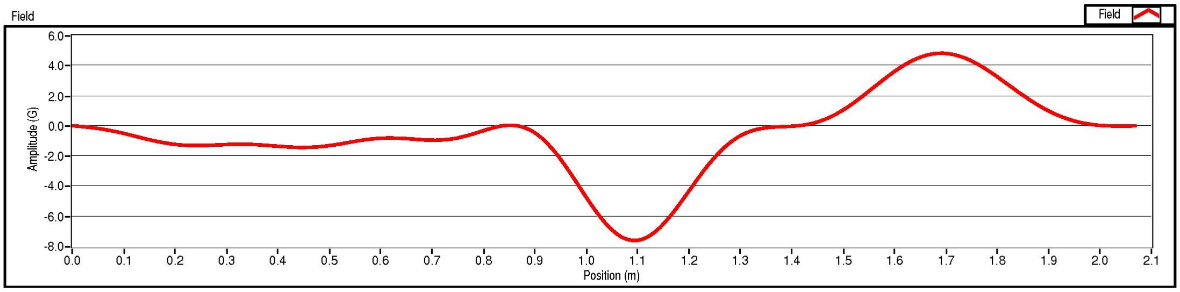


Figure 7: Plot of horizontal field with Q1 (middle of wire) and Q2 (4/5 along wire) ON and the wire shifted roughly 1mm.

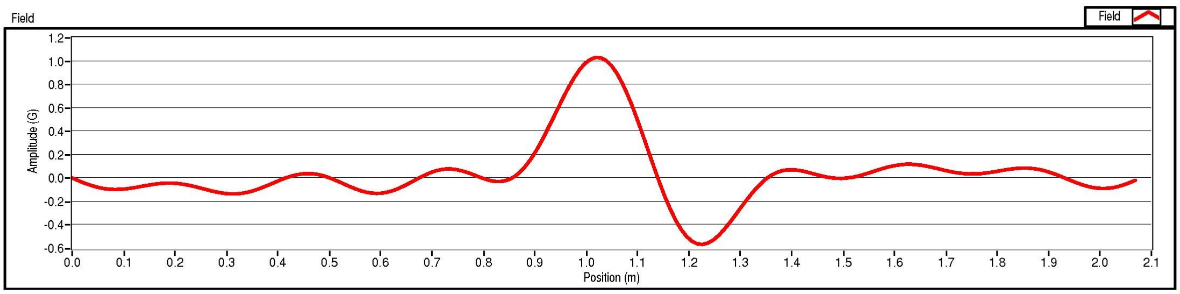


Figure 8: Plot of the vertical field with Q1 (middle of wire) ON and the wire rotated 1mrad and shifted 0.1mm.

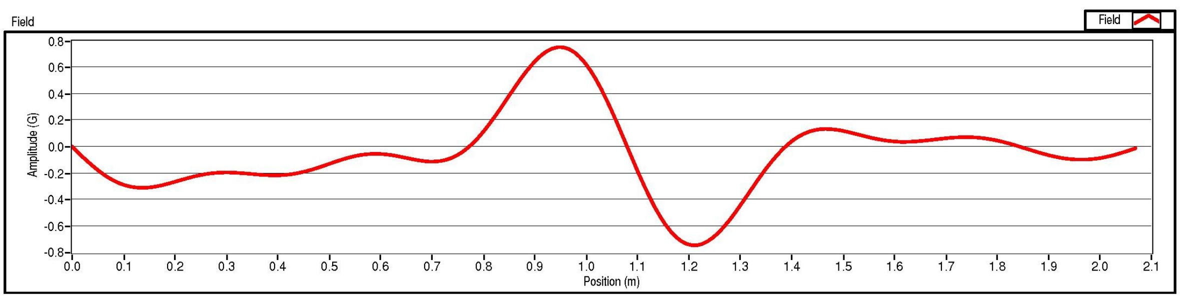


Figure 9: Plot of the vertical magnetic field with Q1 (middle of wire) ON and the wire rotated roughly 2mrad.

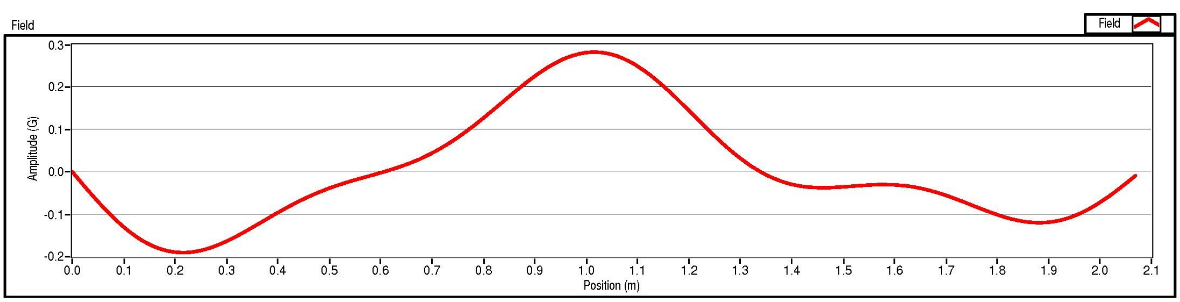


Figure 10: Plot of vertical field with Q1 (middle of wire) ON and the wire shifted roughly 0.05mm.

Discussion of Uncertainties:

There are several sources of error in the measurement and computation of these shifts and rotations. The sources of systematic error include setting up the theodolite and aligning the pulleys with the optical axis. The sources of random error include reading pulley positions from the vernier scales, computing the sag, and finding the exact magnetic center of the quads.

The theodolite is, by far, the most significant source of systematic uncertainty, and it contributes significantly to both the error in the angles and the shifts. The theodolite is aligned with the scribe lines on the flood and wall that describe the axis along which the quads should lie and provides the optical axis for aligning the pulleys. Theodolites are not designed to be set at a particular height or location, but are designed only to measure angles. Thus, aligning the theodolite with the scribe lines is a matter of guess-and-check that has a large uncertainty. Also, the theodolite has a small uncertainty in leveling which is magnified by the distance between the theodolite and the scribe line, and again by the distance between the theodolite and the pulleys. The beamlines group at TRIUMF has estimated the uncertainty in the position of the theodolite as ±0.5mm. Also, there is an uncertainty of roughly ±8 seconds seconds in the leveling.

The next source of systematic uncertainty is aligning the pulleys optically. This has been estimated by attempting to reproduce alignment, as having an error of ±0.2mm on each pulley. Since this is used as the central location from which all displacements are measured, this uncretainty propagates into both the angle and position measurements.

The sources of random error are, in general, quite small. There is a small uncertainty due to the parallax in reading the vernier scales that has been estimated at ±0.1mm. This uncertainty is further minimized if the same person makes all the measurements as their height (which is constant) determines this parallax.

There is also a small uncertainty in modeling the wire as a catenary. The tension and linear density of the wire are not exact quantities, so the calculated position of the wire based on these physical parameters has some uncertainty. The sag in the wire is typically on the order of 0.5mm, and the parameters are believed to be accurate to at least two decimal places, making the uncertainty in the sag negligible.

Finally, there is an uncertainty in where the actual center of the located. Typically, the quads have field gradients on the order of 50G/mm near the center. Given that the vibrating wire has been shown to be able to resolve fields as small as 0.5G acting over the length of a quad, this corresponds to an uncertainty of 0.01mm in the location of the center. This value is negligible compared to the other uncertainties present in these measurements. In terms of rotations, this 0.01mm discrepancy over the typical effective length of a quad (30 cm) results in an uncertainty of roughly 0.1mrad.

<u>Other problems to consider:</u>

There are several issues that make the vibrating wire Fourier reconstruction less straightforward than it otherwise seems. These include the background field, the dependence of the height/width of peaks on the number of modes in the reconstruction, and the inclusion of weak modes.

The background field presents several interesting problems. The first, and most straightforward, is the fact that a strong background field make the zero-finding technique impossible. There is simply no way around this, except to eliminate the field by reversing currents through elements with residual fields. It is not recommended that the zero-finding technique be used for any final measurements so this does not present much of a problem. The second problem is that the background fields may make it difficult to resolve misalignments of the magnets. This can be overcome by simply increasing the quad field strength to overwhelm the background. The final problem the background presents is an unusual tendency to scale large with larger peaks. This is believed to be a 'piggy-backing' effect where the strong peak excites many harmonics, including higher modes, and the background simply makes its small contribution to these harmonics. Without the peak to provide the base excitation, the background cannot excite the modes to a measurable level so they are assumed to be zero and the contribution from the background is lost. Also, the fact that only a finite number of modes are used causes incomplete cancellation in zero-field areas producing fictitious background.

The finite number of modes used also impacts the shape and height of the peaks caused by the quads. Typically, a sharp peak is caused by the superposition of many harmonics in that one location while those same harmonics cancel elsewhere. Thus, taking only a few modes severely decreases the height of the peak. Also, the resolution of the reconstruction depends on the number of modes used, so the width of the peak will appear much broader if too few modes are used. In terms of finding the magnetic centers, these facts merely make the process more difficult as you are not seeing a true representation of the field, however the zero, once located, should appear as a zero.

The last complication is the inclusion of higher harmonics to improve the reconstruction. Because of the smooth and finite nature of the field, the strength of the harmonics should decay at least as fast as $1/x^2$. While this means that only a relatively small number of modes need to be measured to get a reasonable representation of the field, it also means that higher harmonic are quite difficult to measure. When the harmonics get increasingly weak, the signal to noise ratio in the data acquisition get increasingly worse. This poses problems for the fitting, because poor data gives poor fits, and poor fits allow the parameters to have unreasonable values, causing false contributions to the reconstruction. To combat this problem, two logical checks have been implemented: one to discard very weak modes, and one to discard very poor fits. Discarding higher harmonics of weak amplitude inevitable decreases the quality of the reconstruction, so the parameters that control these checks must be adjusted carefully to save as many meaningful modes as possible while still discarding all erroneous data.

Conclusions:

In conclusion, the measurement of the first 5 quads has been a big success. The vibrating wire technique has proved its sensitivity and effectiveness, and all the materials and software necessary for efficient measurement have been prepared. Several large misalignments have been observed, providing important insight into improving DRAGON's transmission. The large systematic uncertainties involved in defining the optical axis provide a significant hindrance to the interpretation of the measurements, however several of the misalignments observed were significant nonetheless. Refining the alignment procedure would greatly improve the technique, however the current procedure is still worthwhile nonetheless.

The results point conclusively to a major problem in the first arm of the separator. There is a significant vertical shift, which is consistent with the TOTAL measurements, and a large horizontal rotation and shift which are, unfortunately, very difficult verify through the total measurement. Simulations in RayTrace have confirmed the significance of these finding, and hopefully, once they are verified by determining the relative locations of the optical axes on the different arms of the separator, they can be fix mechanically.

Future Work:

Due to the successful measurement of the first 5 quads, it is definitely recommended that the last 5 quads be measured as well. Also, due to the improvements in the technique between the first and second applications, it might be beneficial to remeasure quads 3-5 using the slower, but more precise zero measuring technique.

More work would also be beneficial in defining the optical axis and relating the optical axis to the TOTAL survey completed earlier this summer. The optical axis may be improved by setting up the theodolite many times and averaging the pulley center locations. This will be quite time consuming, but not only will it improve the definition of the reference point from which the misalignments are measured, but it will provide an idea of the reproducibility of the theodolite setup, as well as allowing the misalignments in different parts of the separator to be compared. Tying the vibrating wire and TOTAL measurements together is as simple as positioning a reflector at the exact height of the scribe line, and completing one small survey that includes this new point and the points on the magnetic dipoles that define the TOTAL measurement axis.

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Appendix

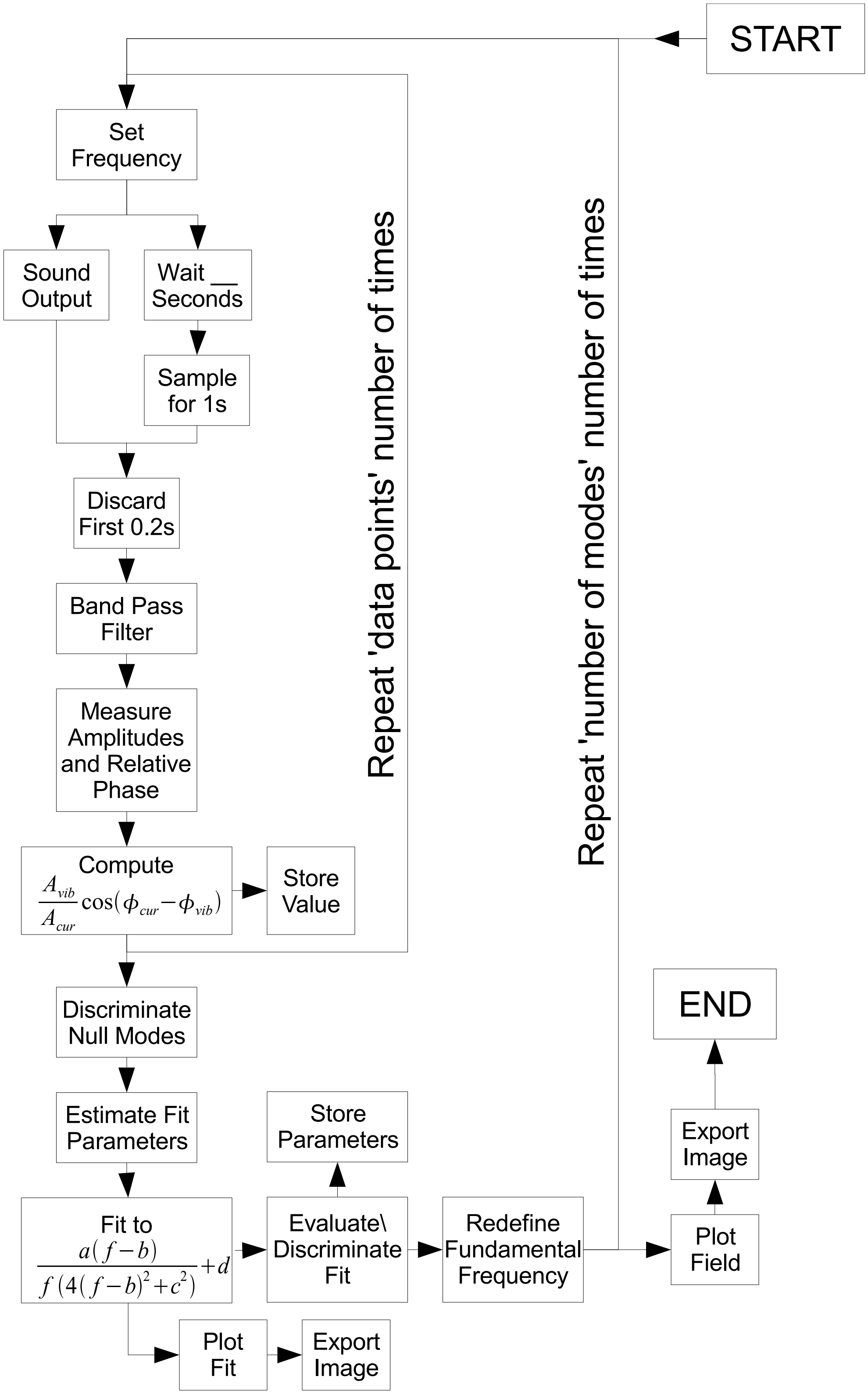

Figure 11: Flow chart showing the structure of the Labview data acquisition program.