Multi-Straw and Single Straw Prototype Detectors: Tension Measurements

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Abstract

The following report explains the development of a tension-testing device for the conducting wires in a new particle detector under the name of Straw Chamber Detector to be installed at location B0 in the Tevatron. It also explains some of the advantages of this detector over the Wire Chamber. Some remarks on Straw Detectors manufacturing and the approach taken to evaluate the tension of the wires in the diverse Straw Prototypes presently used by means of vibration mechanics and harmonic excitation are introduced.

Introduction

In the particle physics field, the use of particle accelerators equipped with reliable and precise detectors has become a necessity. Studies involving conservation of energy and momentum on collisions of fundamental particles require accurate experiments to determine the properties of such particles.

One of the most widely used detectors is the Wire Chamber. It consists of a chamber containing many individual wires, properly arranged in planes and under high voltage. The chamber is then filled with a gas, most of the times hydrogen, which is able to ionize with relative ease after being excited by a controlled beam passing through the detector. As a consequence of the electric potential difference of the wires, particles produced by the ionization of the gas and their interactions with the beam are attracted to the wires and their tracks can be detected and interpreted. In order to make such calculations, some parameters precisely defined such as concentration of gas and tension of the wires must be met by every single part of the detector, for any undesired or even miscalculated condition results in erred measurements – and loss of valuable time and resources. Unfortunately, there is a major problem concerning the operation of this detector: whenever one wire is broken it curls, and as a consequence of this it touches and sometimes gets tied to other wires. Under such circumstances the detector cannot be operated due to the negative effects that this event has on the neighboring wires. Most of the times, many wires and their circuits are damaged, forcing an exhaustive search for the originally broken wire, the affected wires and the replacement of every single element affected by such incident, which leads to a major postponement in the studies to be performed.

Presently, Fermilab is developing a new kind of detector. Under the name of "BTeV

Project" a new collision detector will be incorporated to the Tevatron at B0, where Straw Detectors are to be used in preference to Wire Chambers. A Straw Detector is one in which every single wire passes inside a conductive straw, hence isolating it from the rest of the wires. It is made of Au-coated, 25-μm diameter W wires; and Low Resistivity Kapton-Al-Kapton, 4-mm inner diameter straws. With the capacity of operating under high voltage conditions and severe radiation effects, this new detector has one more advantage: if one of its wires breaks, it will not interact with any other wire. As a result of such condition, the sole broken wire can be deactivated from the detector operation, ensuring the correct functioning of the rest of the elements of the system whose data acquisitions can continue without interruption for a while until such problem is fixed. Thanks to this, the operation of the detector as well as the maintenance of the circuits and its parts become easier, which can still perform satisfactorily and with reasonable precision even with the presence of some broken or faulty elements, due to the unique feature of individual deactivation that this detector embraces.

In reality, the design is a bit more complex: the actual detector contains not one, but two wires per straw, coming from the ends of the straw, opposite to each other and brought together – not in direct contact though – by a nonconductive glass fiber bead located in the center of the straw. Due to this exceptional characteristic no current can flow through the wires, since the discontinuity of the circuit and the presence of insulation by means of the glass fiber bead do not allow the current to do so. However, the manufacturing of prototypes where continuous individual wires are present is acceptable to study the operation of the detector.

Among many of the properties that need to be ensured is the tension of the wires. Such characteristic is critical for an acceptable performance of the detector. Although the possibility of using conventional tension tests is null, the use of indirect measurements as an alternative is not only necessary, but in some occasions more suitable to fulfill the expectations for accuracy in such measurements.

Whenever tension tests are done in either Multi-Straw Prototypes (MSP), containing many straws and wires, or Single Straw Prototypes (SSP), with only one wire and straw, the presence of continuous wires is a helpful feature. Since current can be induced, in opposition to the real detector, many tests

involving current flow can be done and the effects of wire vibration in the electric signal behavior that is obtained from the wire-straw couple can be observed using an oscilloscope. Such test is known as *Function Generator Test (FG)*, and it works by placing the wire-straw couple in a magnetic field, generally using a magnet. Then, an AC current with known frequency is flowed through the wire with a function generator oscilloscope – from here the name given to the test. Such event induces a vibration of the wire. The power output is then read with an oscilloscope and the effect on the signal can be seen. A major signal output change is observed when the wire starts to be driven to resonance, which is proportional to the tension of the wire, as will be demonstrated later. However, since the range of resonance is relatively large – the resonance effects with this test are seen in an approximately 6-7 Hz interval – and due to the impossibility of performing such test in the real detector, neither the accuracy nor the aptness of such test are ensured. Therefore, and following the same approach of vibrating the inner wire and driving it to resonance, the use of sound frequencies to produce vibration has been considered. Such test is known as the *Tone Generator Test (TG)*. The objective of this report is to further explain the operation and development of this new test and its components, along with the results obtained from its performance.

TG Operation: Hardware and Software

The Tone Generator Test has been developed to produce vibration in the wire inside the straw using sound. The development of this new system started in summer of 2001, and has improved due to many modifications done in its structure since. In previous acquisitions, for example, the very first data acquisition – that is, the data produced when the whole system was just connected – was accurate, but the subsequent results obtained from the computer were a copy of the first result. For this reason, not only the test became unable to work in other wires – as mentioned, the readings were a copy, and no new data were acquired –, but also the repetition of the test would give the impression of being statistically consistent and accurate when done in the same wire. Also, the massive repetition of the test would increase the uncertainty of the results, since error from the approximations done by the system would be accumulated. This problem represented a reason to suspect the significance of previous experiments done in Single Straw Prototypes,

where many single acquisitions are done in the same wire. Fortunately, this detail has been solved.

The Tone Generator Test uses the possibility of interaction between a computer that a user can control and the acquisitions done by instruments arranged for that purpose. The device created for such purpose operates in both MSP and SSP, and potentially in other sorts of prototypes, and consists of:

- Voltage Source (~81 V)
- Amplifier
- Loudspeaker
- AC signal circuit
- Oscilloscope (Tektronix TDS 350, two channel, 200 MHZ, 1 Gs/s)
- *Tone Gen 1.1* (Lab VIEW)

The test procedure is depicted in Fig. 1. After a prototype has been constructed, either a MSP or a SSP (see Appendix I for prototype manufacture), the wire is connected to an AC circuit with a constant potential source (~81 V), and the system is grounded to the frame of the prototype. Due to this potential difference, the wire-straw couple becomes a coaxial cylindrical capacitor. A sound blast is produced in the loudspeaker – regulated by the amplifier and coordinated by Lab VIEW VI *Tone Gen 1.1* –, which is used to vibrate the wire. The signal produced by the change in the capacitance due to the vibration of the wire inside the straw flows through the AC circuit, which is converted to an electrical power signal that is read by the oscilloscope and displayed in our VI, *Tone Gen 1.1*. This program, developed in Lab VIEW, resembles an oscilloscope able to display the power output of the wire-straw couple due to the change in capacitance of the system. In addition, the program helps the user to define which sound frequencies are to be individually produced by the loudspeaker in the prototype, to determine the frequency range, and to choose the step size to use in increasing the frequency every single time.

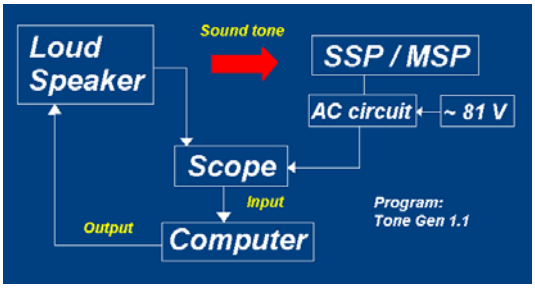

Figure 1. Tone Generator Test Operation.

Once the total data acquisition has been done, the maximum power output can be clearly identified in the chart: it corresponds to the resonant frequency. Then, the program

calculates a 2nd-degree polynomial approximation for the highest power output value and relates it to its corresponding frequency value (in Hz), which is also converted to tension (in grams).

Such calculations are done based in the assumption that the vibration of the wire must be harmonic, due to the fact that the wire is fixed and under certain tension presumably constant.

Theory

A fixed string, according to vibration mechanics theory, represents a continuous system, with an infinite number of degrees of freedom. Particularly, as stated by stationary waves theory, wave interference exists due to the difference of individual vibration of both sides of the string, wherever it is plucked. As a consequence, the interference of these waves produces a new wave that vibrates at maximum amplitude when it reaches resonance, producing a unique phenomenon called *harmonic vibration*. These waves are called stationary because they do not seem to travel, since interference makes them appear to oscillate transversely only. The points of the string, periodically located through the length of the wire, that do not move in such vibration are called nodes, and represent locations of destructive interference. The opposite of these are the antinodes, where constructive interference is manifested as the maximum amplitude locations in the wire.

In order to allow vibration of the system, a difference in the tension between both ends of any section of our vibrating string must exist, as shown by Fig. 2. The string element position can be defined by a function *y(x,t)*, obeying a deflection curve equation.

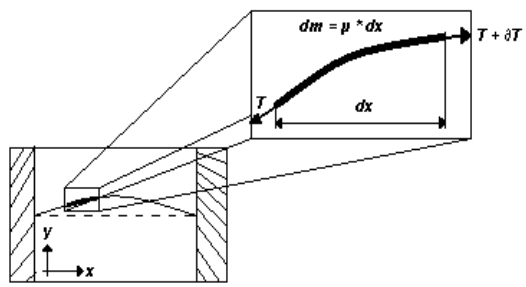

Figure 2. Harmonic string vibration.

The vertical component of the tension in the left side of the section shown is

$$-T\frac{\partial y}{\partial x}$$

In the right side of the string section,

$$+T\frac{\partial y}{\partial x}+\partial\left(T\frac{\partial y}{\partial x}\right)$$

From Newton's Second Law of Motion, and considering the differential mass element,

$$-T\frac{\partial y}{\partial x}+T\frac{\partial y}{\partial x}+\partial\left(T\frac{\partial y}{\partial x}\right)=dm\cdot\frac{\partial^2 y}{\partial t^2}$$

$$\because \quad dm = \mu \cdot dx$$

$$T\frac{\partial^2 y}{\partial x^2}dx = \mu \cdot dx\frac{\partial^2 y}{\partial t^2}$$

$$\therefore \quad T\frac{\partial^2 y}{\partial x^2} = \mu\frac{\partial^2 y}{\partial t^2}$$

In order to satisfy the assumption of harmonic vibration, the solution must be of the form

$$y(x,t) = y(x)\sin\omega t$$

Our partial differential equation is then reduced to a form similar to an undamped time independent vibration differential equation:

$$T\frac{d^2 y}{dx^2} = -\mu\omega^2 y$$

$$\therefore \quad \frac{d^2 y}{dx^2} + \frac{\mu\omega^2}{T}y = 0$$

For this differential equation, the general solution is of the form

$$y(x) = C_1 \sin\omega_n x + C_2 \cos\omega_n x$$

where $\omega_n^2 = \dfrac{\mu\omega^2}{T} \therefore \omega_n = \omega\sqrt{\dfrac{\mu}{T}}$

Boundary conditions for this equation are $y(0) = y(L) = 0$, where L represents the length of the fixed string.

For $y(0) = 0, \quad C_2 = 0$

$$\therefore \quad y(x) = C_1 \sin\left[\omega x\sqrt{\frac{\mu}{T}}\right], \text{ where } C_1 \neq 0$$

For $y(L) = 0$, and under the condition that $C_1 \neq 0$,

$$\omega L\sqrt{\frac{\mu}{T}} = n\pi, \text{ where } n = 1,2,3...$$

The existence of periodic frequencies - multiples of a fundamental frequency - is an evidence of harmonic vibration. In addition,

$$\because \quad f = \frac{\omega}{2\pi}$$

$$\therefore \quad \boxed{f_n = \frac{n}{2L}\sqrt{\frac{T}{\mu}}\ ;\ n = 1,2,3...}$$

The subscript *n* represents "harmonic vibration".

Experiments

Two experiments were designed to test the effectiveness and accuracy of the TG Test, in order to evaluate the possibility of extending its use to more complex prototypes and actual Straw Detectors.

The first experiment consisted of a comparison between the nominal results obtained in the FG Test and those obtained in the TG Test. The MSP was wired in 34 different locations under different tensions, and the tension frequencies were evaluated with both methods. The differences between the readings from FG and TG were calculated and a statistical analysis was done. It is significant to note that

the readings taken with FG, as noted before, were estimated under some qualitative criteria such as the size of the wave shown in the oscilloscope within the range of 6 to 7 Hz of resonance present in this test.

The second experiment was developed to estimate the consistency and distribution of the measurements taken with TG. It used a SSP with an approximately known frequency. Under such conditions, twenty tests were made to calculate the mean value of the frequency – which was estimated to be approximately 250 Hz – and the variation of such readings.

Results

In the first experiment, the results shown in Table 1 were obtained. The distribution of the differences between TG and FG in the samples is not only a good sign, but also raises great expectations about the performance of both tests in prototypes. Even when TG is more accurate when determining a potential value of frequency due to the nature of the frequency calculation method – a polynomial approximation is more trustworthy than a subjective perception of a wave signal in an oscilloscope –, FG proves to approximate reasonably the values estimated by TG, with a slight tendency to a small difference rather than a large one, as Fig. 3 portrays.

Mean	**1.80**
Std. Dev.	**1.23**
Max	**4.67**
Min	**0.04**
Range	**4.63**
Number of Elements	**34**

Table 1. Distribution parameters for TG vs. FG experiment.

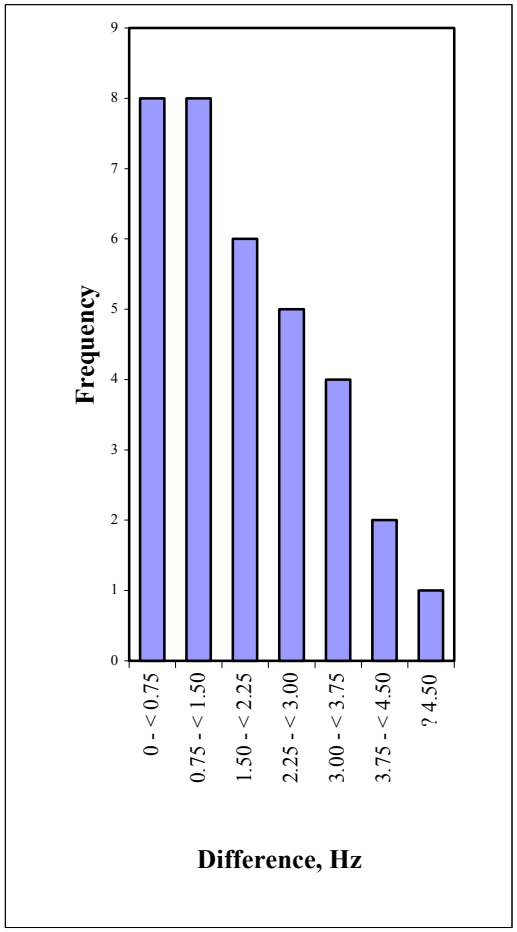

Figure 3. Distribution for reading difference between TG and FG.

However, the existence of such precision on both tests is not a guarantee for accuracy, besides the fact that FG is not an option when evaluating Straw Detectors as explained earlier.

The goal of the second experiment was to confirm the acceptable accuracy of both methods by checking that of TG readings, in case such accuracy existed. Table 2 shows the results of such experiment and Fig. 4 the distribution of its results – slightly skewed from normal distribution -, confirming that TG is accurate enough for prototypes such as MSP and SSP, and potentially for actual detectors and future complex prototypes. With an expected value of 250 Hz for the wire and a mean of 250.66 Hz from the statistical analysis, plus other positive parameters, the proper functioning of TG Test is ensured.

Mean	**250.66**
Std. Dev.	**0.42**
Max	**251.45**
Min	**249.85**
Range	**1.60**
Number of Elements	**20**

Table 2. Distribution parameters for TG accuracy experiment.

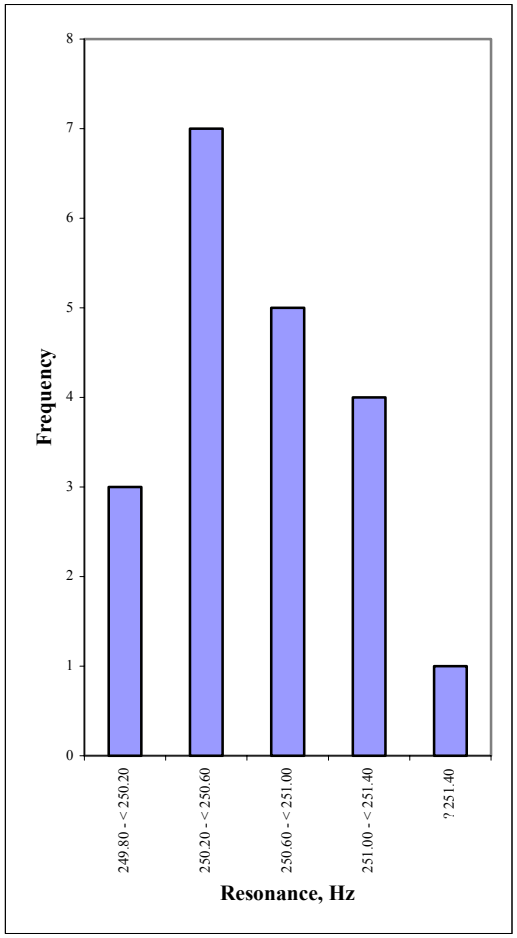

Figure 4. Distribution for TG Accuracy Experiment.

Conclusion

The development of a device capable of testing the tension of the conducting wires in a Straw Detector has been a major challenge since summer of 2001. It is a pleasure to report that a device accurate enough for such purpose has finally been calibrated and developed. Many changes may be still needed. In previous acquisitions the average time it took to

accurately test a single wire was about 3 minutes in a range of 20 Hz with the Tone Generator, which accounts to excessive amounts of time for a single acquisition. Now, it takes the same amount of time when working with a range of 100 Hz, obtaining much more accuracy than before and a more uniform distribution of the results – not to mention it takes only 1 minute per wire when the range of resonance location is better known, within 20 Hz and smaller frequency steps. However, it is not fast enough if considering a detector with more than 80,000 wires. But it is a good start.

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Finally, I'd like to thank my family and God, because they are responsible of my existence. I will never be grateful enough for that.

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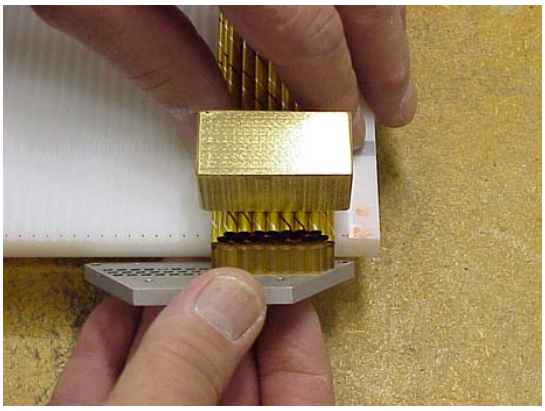
APPENDIX I

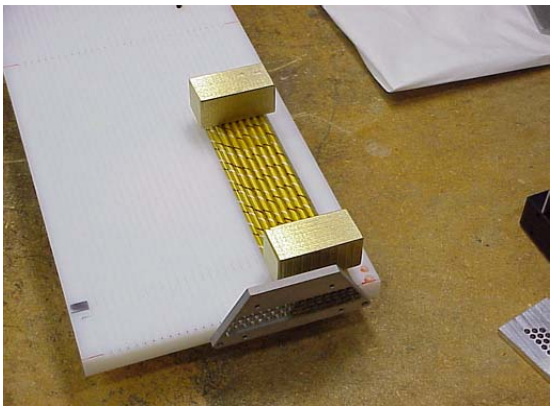
Prototype Manufacturing

Module

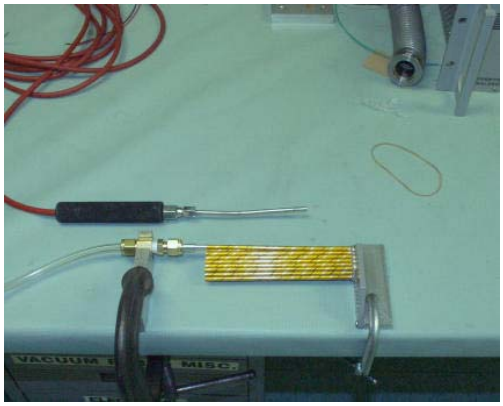
A module (or unwired prototype) starts to be manufactured by gluing with conductive epoxy the end plugs of the straws, whose twisters have been previously placed inside the straws.

Next, the straws are glued to the end frame, and pressed to allow proper attachment without defects in the arrangement of the straws.



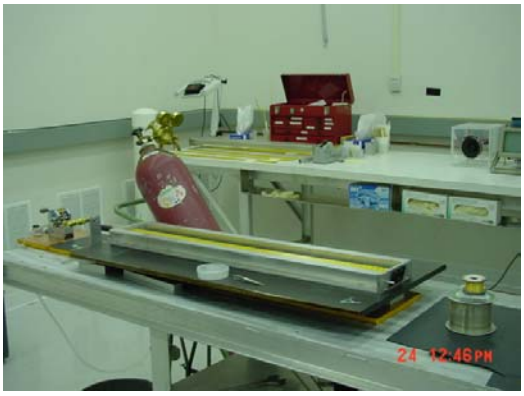


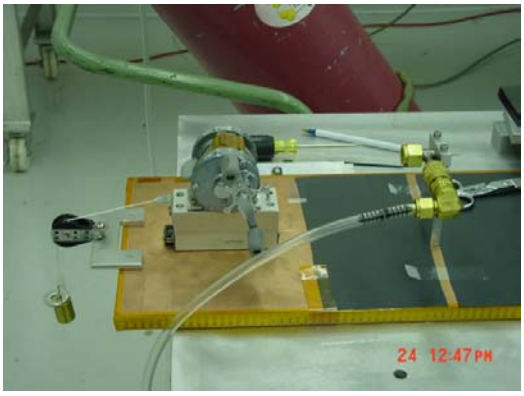
The pressure that the straws must tolerate is checked (next page). After that, the straw structure is put on a frame (not shown).

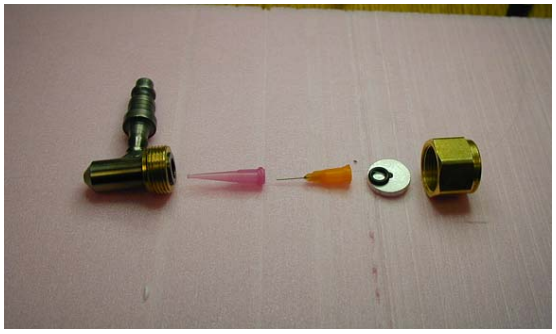


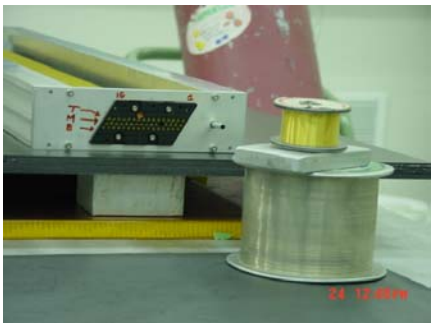
Wiring

A reeling system is used to pass a lead wire through the straw, which is tied to the W wire in the other end and reeled back to pass the W wire through the straw. The portrayed pulley in the reeling system is used to generate the desired tension after the opposite end of the W wire has already been passed through the straw and fixed to the frame by pinning it; then, the wire is pinned with the desired tension. The wire is dragged inside the straw using some gas (generally N_2), and guided with a needle system. The gas helps the wire to find the hole in the twisters faster by vibrating it rapidly.





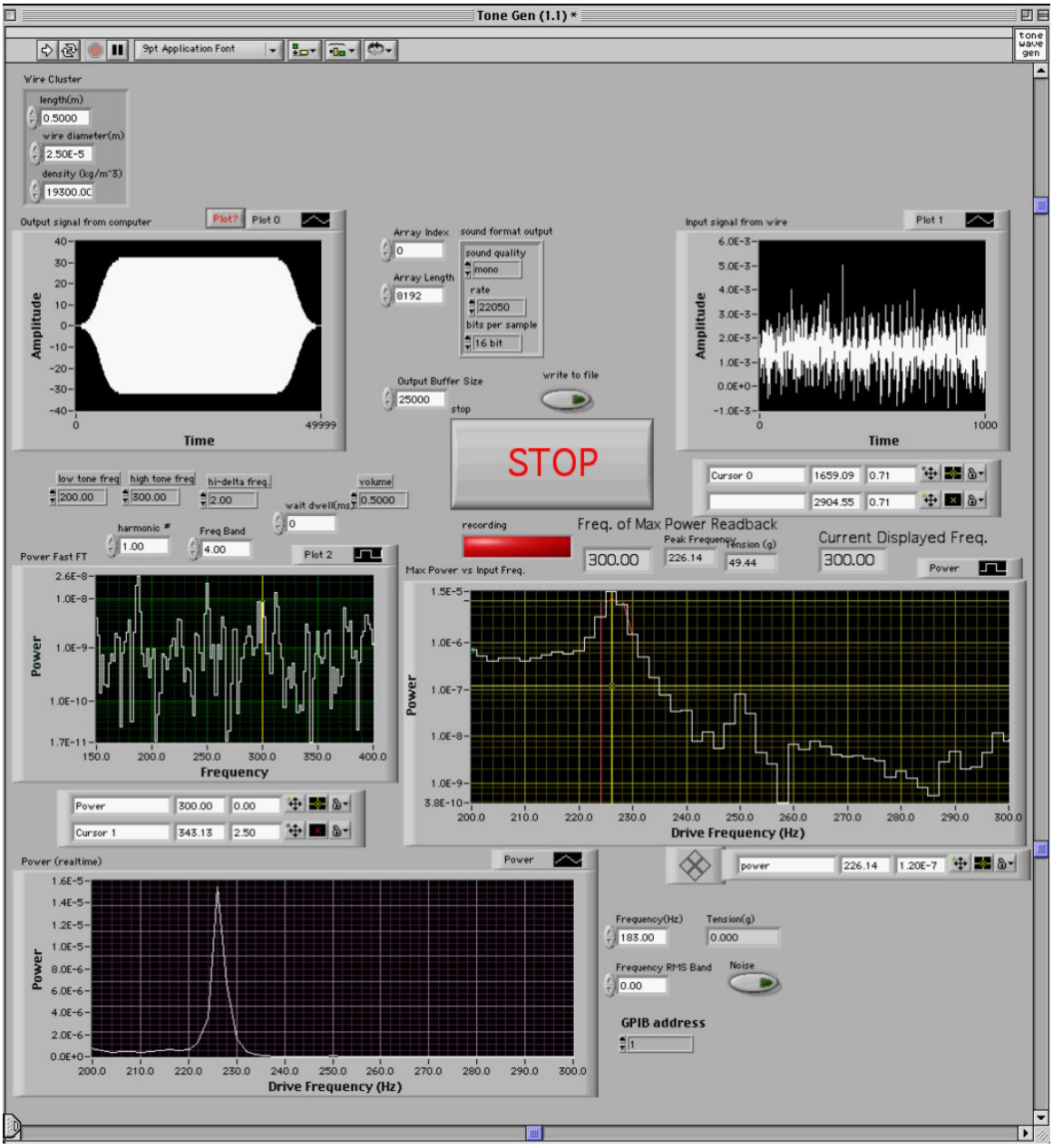




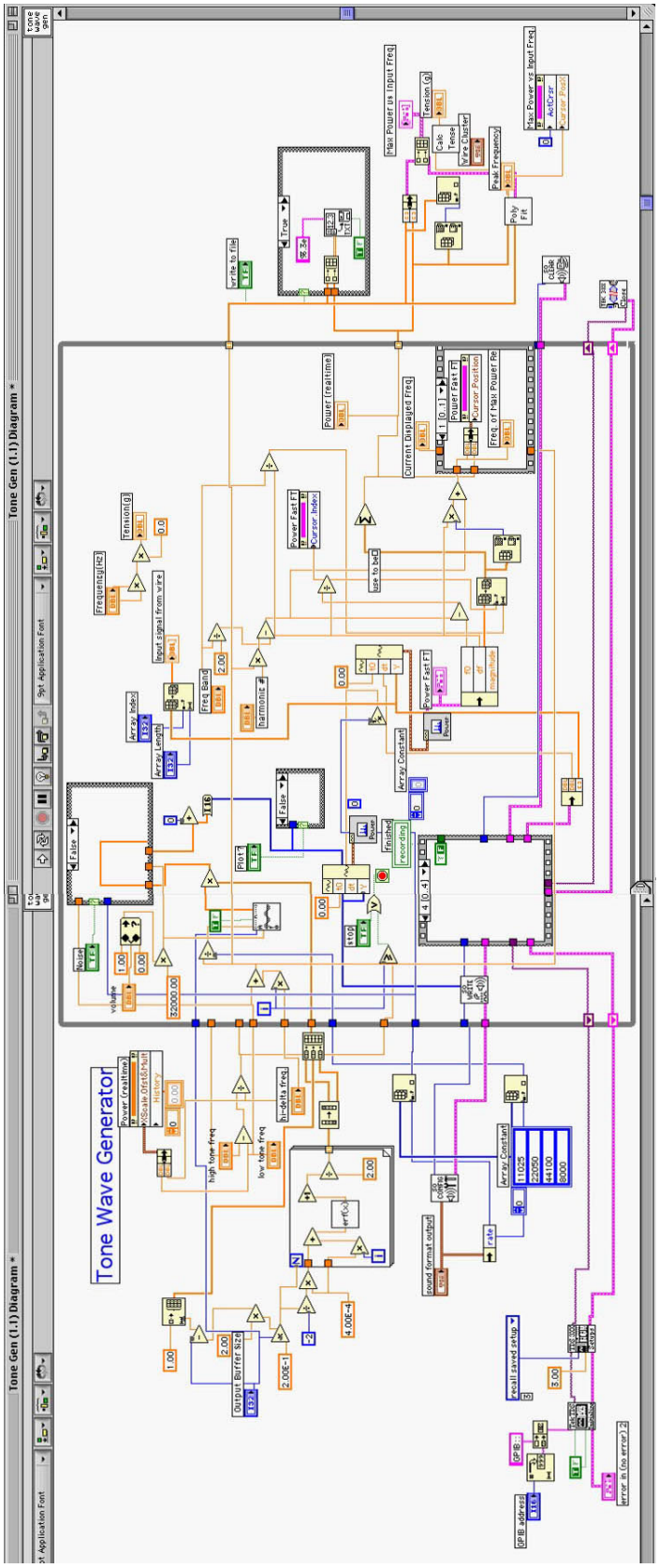
APPENDIX II

TG Software

VI Panel



VI Diagram


Tone Gen (1.1) Diagram *
Tone Wave Generator
Power (realtime)
Current Displayed Freq
Power Fast FT
Cursor Position
Freq. of Max Power Re
Max Power vs Input Freq
Max Power vs Input Freq
Tension (g)
Calc Tense
Wire Cluster
Peak Frequency
Poly Fit
write to file
True
Frequency(Hz)
Tension(g)
Input signal from wire
Freq Band
harmonic #
Array Index
Array Length
Array Constant
use to be
Plot
finished
recording
stop
Noise
volume
32000.00
high tone freq
low tone freq
hi-delta freq
Output Buffer Size
sound format output
rate
recall saved setup
GPIB address
error in (no error) 2