SLAC-PUB-9353
December 2002

Generating, Detecting, and Analyzing High Frequency Acoustic Signals in Accelerator-Grade Copper

Elizabeth L. Greenwood
Office of Science, ERULF Program
Massachusetts Institute of Technology
Stanford Linear Accelerator Center
Menlo Park, California

August 13,2002

Prepared in partial fulfillment of the requirements of the Office of Science, DOE Energy Research Undergraduate Laboratory Fellowship under the direction of Josef Frisch in the Next Linear Collider Program at the Stanford Linear Accelerator Center.

Stanford Linear Accelerator Center, Stanford University, Stanford, **CA** 94309, **USA**

,

Abstract

Generating, Detecting, and Analyzing High Frequency Acoustic Signals in Copper. ELIZABETH L. GREENWOOD (Massachusetts Institute of Technology, Cambridge, MA, 02139) **J.** FRISCH (Stanford Linear Accelerator Center, Menlo Park, California, 94025)

One of the major limitations on the Next Linear Collider (NLC), a high-gradient particle accelerator in development, is that sparks form within the copper structure, damaging the material. The sparks also generate high frequency acoustic signals that can be used as diagnostics to solve the problem. First, however, the signals' location, attenuation, and propagation must be established, so an effective method for generating and detecting these signals in a simple copper block is necessary. Impact trials with ball bearings and a BB gun as well as tests with a grinder, a laser, and a sparker were conducted to determine how to produce the greatest ratio of high to low frequency acoustic signals. The laser had the largest ratio, but the sparker was chosen because it also had high ratios and was both more practical and more analogous to the actual signals in the accelerator. Further tests were then conducted to determine the best sensor; an International Transducer Corporation 9020 1N57 was chosen. Subsequent analysis of signals using this setup could establish the location and types of signals and, ultimately, how to solve the problem in the structure.

Table of Contents

Introduction

Under development for about 20 years, the Next Linear Collider is a longer, higher frequency, higher gradient version of the Stanford Linear Accelerator, a high-energy particle accelerator. When completed, it will allow physicists to detect and determine the properties of fundamental particles, some of which, such as the Higgs boson, are only hypothesized. The fact that the structure operates at a higher gradient, however, magnifies a technical problem that had not adversely affected the operation of the SLAC accelerator - sparks form within the copper accelerator structure, causing breakdowns that damage the material.

These sparks also produce acoustic signals of frequencies ranging from 100 kHz to 10 MHz. Being able to locate and analyze these signals in the structure is perhaps the most effective technique for finding out where the breakdowns occur, whether they are caused by electric or magnetic fields, and, most importantly, how they can be prevented. Although the theory behind the propagation of acoustic waves in solids is well developed, it is difficult to apply it to specific polycrystalline materials because unpredictable variations such as grain boundaries and other plane defects as well as individual point defects and differences in the amount of hydrogen present can have a major effect on wave propagation and frequency attenuation (Spencer, 1999). Before the properties of acoustic signals can be understood in the complex geometrical design of the accelerator structure, they must first be established through the analysis of a simple copper block.

Essentially, acoustic waves are generated mechanically and travel at the speed of sound; they are entirely different from electromagnetic radiation, which includes x-rays and microwaves as well as the visible spectrum and which travels at the speed of light (Guinier, 1987). The methods for creating and detecting these waves in a copper block therefore seem somewhat unconventional. Any type of mechanical jostling creates acoustic signals; the challenge is finding a method that produces a relatively high ratio of frequencies in the 100kHz to 10MHz range.

After establishing a way to generate and detect high frequencies, the next step is to figure out where they propagate and what specific types of waves they correspond to. The three classifications, pressure, shear, and surface, primarily differ in the direction of atom displacement – if the atoms displace in the direction of propagation, they create a pressure, or longitudinal, wave, whereas if they displace perpendicular to the direction of propagation, they form a shear, or transverse, wave. Sound propagates through air and other gases and liquids almost entirely in pressure waves because shear waves attenuate very quickly in those phases. Additionally, a surface wave is technically a different classification, occurring only at the surface of a sold, and it can be thought of as a combination of pressure and shear waves (Cracknell,1980).

One long-term goal of this analysis is to determine the predominate type of wave generated by the signals; the other is to determine the location of the signals to the precision of a millimeter. Because of point and plane defects in the material as well as the complex shape of the structure, this task could prove to be very difficult or even impossible, but determining this limitation to be definitely the case would be an equally useful conclusion. This project was essentially to create a set-up for analysis of high frequency acoustic signals and therefore consisted of various experiments to find the most effective method of generating and detecting them in accelerator copper. This setup could then be used to determine more detailed information about the propagation of these signals in the accelerator structure itself.

Methods and Materials

Throughout the project, a number of methods were used to establish the optimal way to generate and measure high frequency acoustic signals in copper as well as the attenuation of these frequencies and the speed of sound propagation in the material. To maintain a maximum level of consistency, the same accelerator-grade, 4’’ by 4’’ by 2’’ copper block was used for all the trials, and all data was collected with a 250 MS/s oscilloscope, usually set at 25.0 MS/s. For the first segment of the project, before the best sensor had been determined, a Pacific Acoustics Corporation (PAC) Microdot 100 sensor took the data.

Determining the most effective method of generating signals

The initial trials dealt with determining the signals produced by different types of impacts. Ball bearings of the same composition and three different sizes were thrown by hand at the block at approximately the same speed to determine the effect the mass of a projectile has on the signal produced. Then, a ball was launched down a ramp starting from 79 cm, 57 cm, 38 cm, and 19 cm to determine whether the speed of a ball had a greater effect on the frequencies produced by a collision than did its mass. Under the assumption that the speed of a projectile and the frequency it produces have a positive correlation, the block, placed in a protective box, was shot at close range by a BB gun.

In addition to the impact trials, tests were also run using a grinder (*********) with a few different types of drill bits, a method that also allowed for an informal comparison of signals generated at different locations on the block when the grinder was applied to its side, back, and corner. A laser beam was then directed onto the block to test the effectiveness of electromagnetic radiation. Finally, since sparks cause the breakdowns in the structure itself, a high voltage sparker was tested to see if it would best emulate the actual signals.

These tests established that the overall most effective way of producing high frequency acoustic signals in copper for analysis was the sparker. The housing for the test sparker, however, allowed too much energy from the spark to be lost in the air (Figure 1) and used a connector that was not designed to withstand repeated voltage of up to 5 kV, so a new sparker had to be designed and machined (Figure 2). This sparker used a high voltage connector with some of the housing cut away to expose the pin and an aluminum block to house the connector and clamp to the copper block so that the pin was .73 mm from the block.

Figure 3 shows a circuit diagram of the setup. With the high voltage power supply set to 5 kV, the signal from the spark on the oscilloscope usually reached a maximum voltage of 1.4 volts. Since the voltage divider outputs a voltage .0003 times the input, this means that the spark was actually 4667 kV. Furthermore, since energy is one-half capacitance times voltage squared, the energy of the sparks can be calculated from the .5 microfarad capacitor and 5 kV outputted to be 6.25 Joules. Since a close look at Figure 4 indicates that the sparks last about 10 microseconds, the power of the sparks is $6.25 * 10^5$ Watts. The circuit was further improved by wrapping the connecting cables around ferrites to prevent current from returning the way it came and by adding an amp with a filter and a gain of 11 constructed for this project (Kunz, 2002). Figure 5 shows a photograph of the final setup.

Determining the most effective sensor for reading signals

The next step was to determine which of five sensors available in the lab detected the most frequencies consistently in the desired range. The sensors tested were a PAC Microdot 100, International Transducer Corporation (ITC) 9020 1 N57, PAC S9225 1 HF AA02, PAC HD2WD S/N AA36, and MATEC DP 2001 (Figure 6). The PAC Microdot 100 sensor had previously been calibrated on a network analyzer by clamping the faces of two of the same sensors together in a vice and seeing which frequencies were more present in the distribution than in the noise distribution, a method that is useful for rough estimates but not as effective as testing on the block itself. Each was positioned on the block directly across from the sparker either with a clamp and vacuum grease or with superglue and the block was sparked as before.

Calculations

The analysis of the data gathered from these tests required performing a Fourier transform to change the form of the data from pulses on an oscilloscope to frequency distribution. Basically, a Fourier transform of a function is not a different function but rather a new way of representing the same function using the concept of a Fourier series. Such a series is the infinite sum $a_o + (a_1 cosx + b_1 sinx) + (a_2 cos2x + b_2 sin2x) + \dots$, where the coefficients are determined by the function being represented and are known as Fourier's constants. Thus any continuous function is uniquely determined by its Fourier transform, allowing waveforms and other periodic functions to be represented in terms of frequencies. (Butkov, 1968). Although an infinite function such as a sine wave does not have a Fourier transform by the strictest theoretical definitions, any mathematical representation of a physical quantity can be assigned a transform (Bracewell, 1978).

Because the measured pulses in this experiment varied in shape and power depending on the method and were made up not only of the acoustic signals but also of background noise, electrical pickup, and other factors, MATLAB programs had to be written to generate the transforms using the language's fast Fourier transform capability and to display them in a manner useful for comparison.

The first analyzed one set of data by plotting the signal and its transform on separate graphs, dividing the signal into a designated number of color-coded slices, and overlaying the transforms of each slice on the other plot to give an idea of the frequencies present and their attenuations. A second function, useful for comparing multiple trials from the same experiment, displayed the overlaid transforms of the first 50 microseconds of multiple pulses. It also calculated the ratios of the powers of high (900 kHz – 1 MHz) to low (100 kHz – 200 kHz) frequencies for a data set. Both functions utilized a Hamming window to account for anomalies in the transform caused by slicing the waveform to look at specific sections of time. The windowing function essentially amplifies the middle part of the signal in time by multiplying by a predetermined array of numbers that if graphed in terms of time would form a parabola (Bracewell, 1978). A Butterworth filter for removing some of the effects from electrical noise to smooth the plot was also tested, but it proved not to be useful in this situation.

The third function was for comparing data sets taken under different conditions. To scale each data set to the same relative power, the frequency spectra were divided into

100 kHz slices in which the powers of all the frequencies were averaged and divided by the initial power. Then the logarithm of the powers was taken so that all frequencies could be compared on the same figure. The value for each slice was plotted at the lowest frequency in the range (e.g., 100 kHz – 200 kHz is plotted at 100 kHz), creating a line graph where a higher line indicates higher power over those frequencies. These plots, along with the ratios of high to low frequencies, were crucial in establishing the most effective method.

Results

Determining the most effective method of generating signals

The impact trials, in general, gave low ratios and had low powers at high frequencies (Table 1). The trials of size and speed had little relative variation; in all cases the ball bearings had very signals at higher frequencies. The BB gun test showed an overall increase in power relative to any other trial on the order of at least 10^4, but it did not have a better ratio of low to high frequencies nor peaks at higher frequencies on the transform (Figure 7). The grinder data was erratic, especially at low frequencies, creating a large variation in the ratios but not generally indicating a better performance at higher frequencies (Table 2).

Giving a relatively higher power at high frequencies than any sort of impact, however, were both the laser and the spark tests. Only one trial could be run with the laser, but both the transform (Figure 8) and the ratio, 6.3103, indicated a clear improvement over the impact trials. The sparker gave very consistent ratios (Table 3) and peaked through 2 MHz in the transform (Figure 9), an improvement over every other method besides the laser. Table 4 gives the ratios for all methods before and after all outliers had been removed, and Figure 10 shows the normalized line graph comparing typical data samples for each method.

Determining the most effective sensor for reading signals

After choosing a method and setting up a controlled experiment, the next step was choosing a sensor. The MATEC DP 2001 was not sensitive enough at the desired frequencies and produced only electrical signals on the oscilloscope, but the other four sensors gave relatively equivalent ratios and transforms. Table 5 shows the ratios of high to low frequencies for the different types of sensors. The transforms for the sets of data (Figures 11-14) indicate that the ITC 9020 1 N57 and PAC S9225 1 HF AA02 sensors are sensitive at slightly higher frequencies, and the normalized plots at lower and higher ranges of frequencies (Figures 15-16) also show the effectiveness of those sensors.

Discussion and Conclusions

Determining the most effective method of generating signals

Considering the typical data sets for each method, the laser is clearly the most effective, as shown by both Table 4 and Figure 10. It has by far the highest ratio of high to low frequencies without outliers, and it is the most powerful at almost all frequencies. In Figure 10, however, the spark is not significantly less powerful for most frequencies. Furthermore, other factors are important in choosing the most effective method for generating high frequency acoustic signals. The method should be reproducible, giving similar levels of ratios and Fourier transforms every time, and it should be practical for multiple tests. Tables 1-3 indicate that most of the trials are relatively consistent with the exception of the grinder, which spans a range of almost 10^4.

The advantages and drawbacks of each method became evident after running a few trials. The ball bearing trials were very difficult to replicate; it was nearly impossible to hit the block in the same dent every time, even with a pendulum. The BB gun was much easier to aim and was therefore slightly more reproducible but created large dents in the block that would have changed the structure of the impact area on the block and therefore would have had a very major effect on subsequent trials. Although the grinder did not change the shape of the block, it made a lot of noise that often triggered the oscilloscope, making data acquisition a difficult process and affecting the signal as well.

The laser, by contrast, was extremely replicable since the beam could be aimed and fixed, but it was very expensive and required either specialized training or supervision by someone with training, rendering it extremely impractical for use over a short period of time. Since the only laser time available prior to the conclusion of the test rendered one complete data set, it was difficult to justify its use. The spark generator, on the other hand, offered both consistency and practicality. The sparker can be aimed and fixed, and it leaves a mark on the block where the spark hit to determine exactly where the signal originated. In addition, it was by far the best way to emulate the actual signals in the accelerator. The plots and ratios indicated that the sparker was almost as effective as the laser mathematically, and once the amplifier with a filter was added to the circuit for subsequent trials, it produced ratios on the level of the laser's (Table 5). Thus the sparker was selected as the most effective method.

Determining the most effective sensor for reading signals

Table 5 indicates that the difference between the sensors is not entirely clear-cut. Again, consistency is an important factor in determining effectiveness; although the PAC

S9225 1 HF AA02 sensor has the highest average ratio, its ratios vary much more than those of any of the other sensors, making it somewhat suspicious. The ITC 9020 1 N57 and PAC Microdot 100 sensors seem relatively similar at lower frequencies, but Figure 16 demonstrates that the ITC 9020 1 N57 is more effective in a range up to 3 MHz, the approximate frequency to which the Fourier spectra indicate the sensors are sensitive. An added benefit is that it is inexpensive and plastic, so that it can be superglued to a block, detached, and reattached multiple times. The ITC 9020 1 N57, which is currently in use on the NLC test accelerator, is the most effective sensor.

Further considerations and implications

This study established an effective way of generating and measuring high frequency acoustic signals in copper and took some preliminary data based on this setup. Other methods of generating signals, such as induced currents from other wires in a magnetic field, are currently in the process of being tested. Additionally, many more tests could be run using this setup to determine more properties of accelerator-grade copper, including comparing signals in the copper block to signals in another material such as aluminum, comparing signals generated different distances from the sensor by moving the sparker around on the block, looking for surface waves by testing blocks of different dimensions, and seeing how they behave in magnetic fields. The signals could then be used to determine the locations of the accelerator sparks to the precision of a millimeter and the types of waves produced, which would lead to a better understanding of the problem and potentially to a solution as well.

Acknowledgements

My first thanks go to Carmen Kunz and Anna Bershteyn, my partners on this project, as well as the other incredible summer students in the ERULF program and Taxi House. Thanks also to the other scientists in the NLCTA lab, Marc Ross, Douglas McCormick, Tonee Smith, R. Keith Jobe, Janice Nelson, Simon Jolly and Gavin Nesom. Thanks to Lucky Charms for giving me a reason to get up every morning. And extremely special thanks go to my mentor, Josef Frisch, for working so hard to make sure the rest of his students and I had a great experience this summer and for being an incredible person.

I also thank Erin Smith, Sekazi Mtingwa, and Helen Quinn for all their hard work in organizing and running such an excellent program, as well as the Stanford Linear Accelerator Center and Stanford University for hosting. Finally, thanks to the Department of Energy and the National Science Foundation for funding this program.

The research described in this paper was performed at the Stanford Linear Accelerator Center.

References

Bracewell, Ronald N. (1978). *The Fourier Transform and Its Applications*. San Francisco: McGraw-Hill Book Company.

Butkov, E. (1968). *Mathematical Physics*. Menlo Park, California: Addison-Wesley Publishing Company.

Cracknell, A. P. (1980). *Ultrasonics*. New York: Wykeham Publications Ltd.

Guinier, A. & Jullien, R. (1987). *The Solid State: From Superconductors to Superalloys.* New York: Oxford University Press.

Kunz, C. (2002). *Amplifying High Frequency Acoustic Signals*.

Spencer, J. N., Bodner, G.M., & Rickard, L.H. (1999). *Chemistry: Structure and Dynamics*. New York: Wiley.

Tables

	Small	Medium	Large	79 in.	57 in.	38 in.	19 in.	BB Gun
Trial 1	.0064	.0095	.0027	.0184	.0067	.0028	.0008	.0059
Trial 2	.0039	.0065	.0032	.0061	.0281	.0035	.0082	.0040
Average	.00515	.0080	.00295	.0122	.0174	.00315	.0045	.00495

Table 1. Ratios of high to low frequencies for the impact trials. Note little clear correlation between ratios and mass or speed; the ratios are all on the same order regardless of impact.

	Front	Side	Back	Corner
Trial 1	.8002	87.1394	.1052	.1022
Trial 2	12.4983	.0722	.1618	.2609

Table 2. Ratios of high to low frequencies for the grinder trials. Note that despite a few anomalies the ratios are generally lower than for any other trial.

	Ratio
Trial 1	.8564
Trial 2	.8543
Trial 3	.2037
Trial 4	.8905
Trial 5	.2570
Trial 6	1.7739
Trial 7	.8690
Trial 8	.6016
Average	.7883

Table 3: Ratios for the sparker trials. Note the overall consistently high ratios.

Method	Average with Outliers	Average without Outliers
Ball Bearing (sizes)	.0054	.0054
Ball Bearing (heights)	.0093	.0150
BB Gun	.00495	.00495
Grinder	12.64	.2504
Laser	6.3103	6.3103
Spark	.7833	.7833

Table 4: Average ratio for all six trials, with and without outliers. Outliers are defined as data points greater than ten times the median of the data.

	PAC Microdot 100	PAC HD2WD S/N AA36	PAC S9225 1 HF AA02	ITC 9020 1 N57
Trial 1	2.7845	1.8064	3.2049	9.6514
Trial 2	11.3650	2.4845	60.5554	9.8794
Trial 3	4.4652	3.4586	11.1452	7.1630
Trial 4	10.0845	3.6524	10.7525	5.5926
Trial 5	3.7892	3.4407	5.7173	4.9263
Average	6.4977	2.9685	18.2748	7.4425

Table 5: Ratios of high to low frequencies and averages for the four working sensors. Note that all are generally consistent except for the PAC S9225 1 HF AA02.

Figures

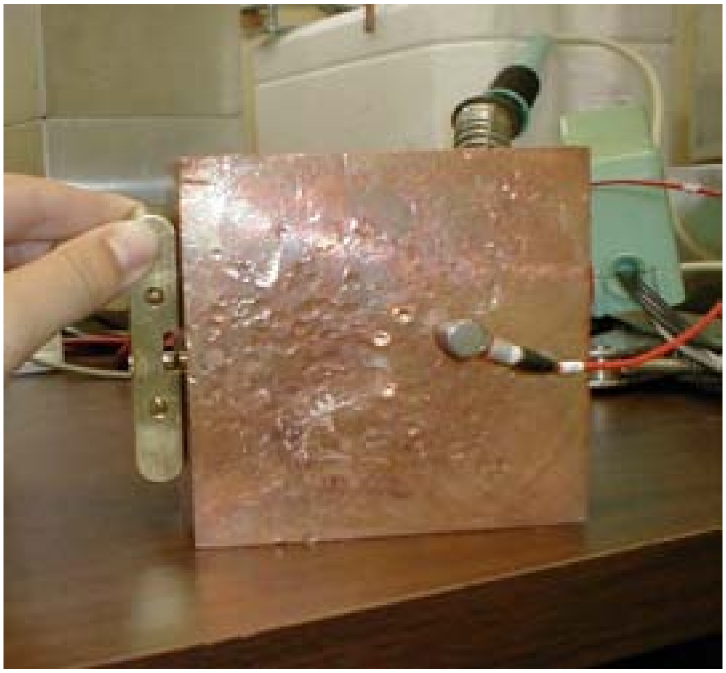

Figure 1. Original design for the sparker housing. Note the gap between the housing and block, through which energy was being lost.

Figure 2. The new housing for the spark, clamped to the block.

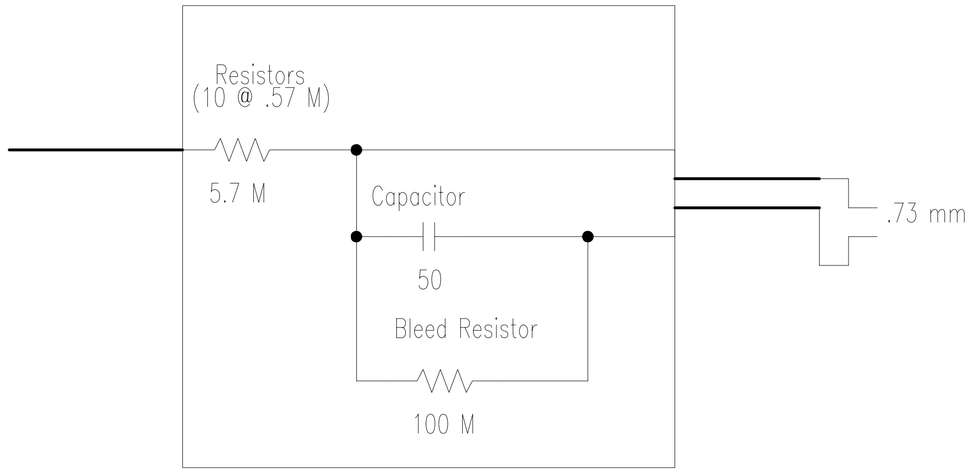

Figure 3. Diagram of the circuit for the sparker and resistor divide. The items in the square are all contained inside a box, with cables coming from both sides.

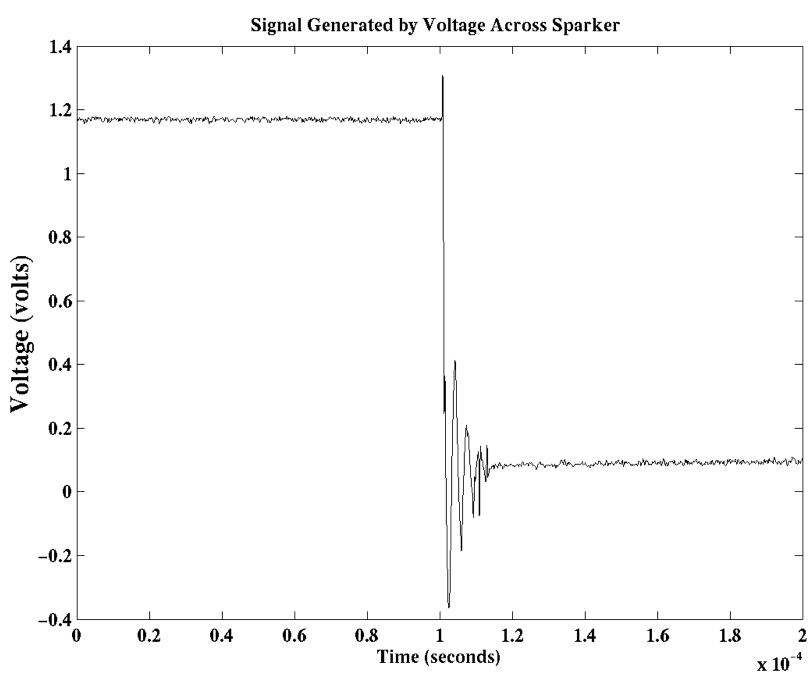

Figure 4. Note the duration and maximum voltage of the signal.

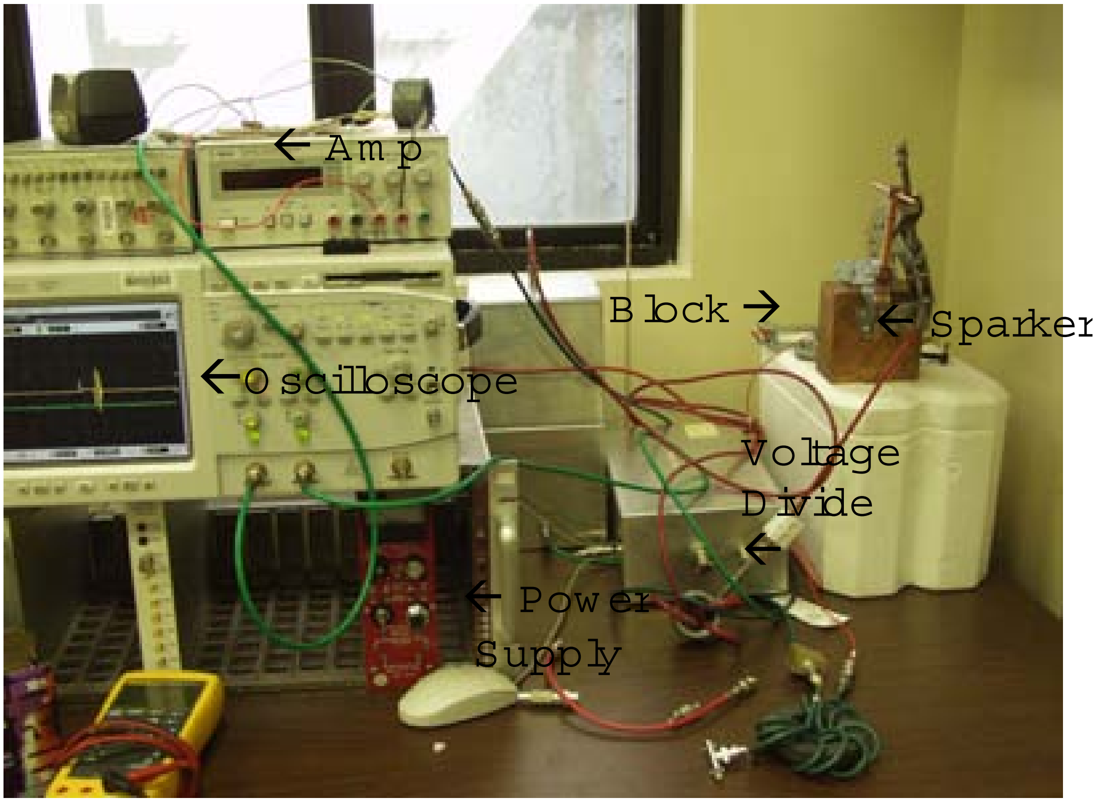

Figure 5. The entire setup of the sparker.

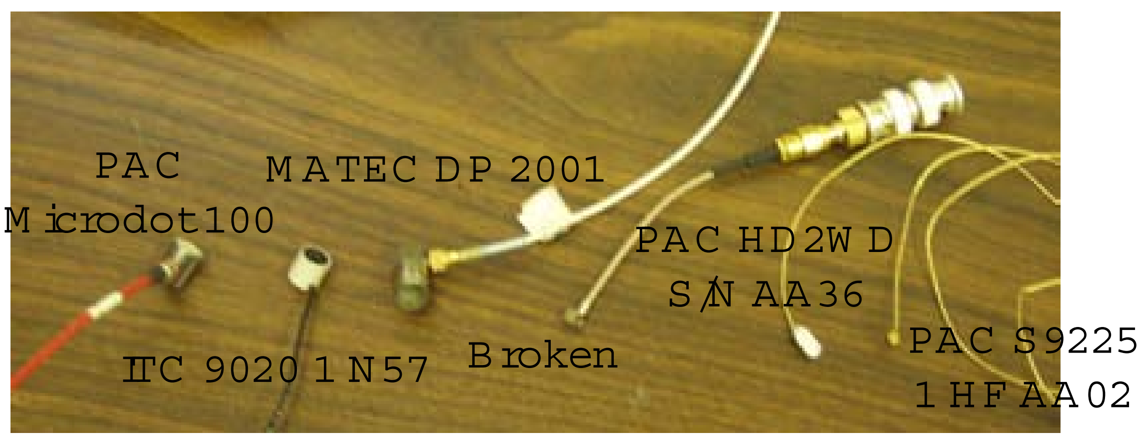

Figure 6. The sensors tested in the experiment.

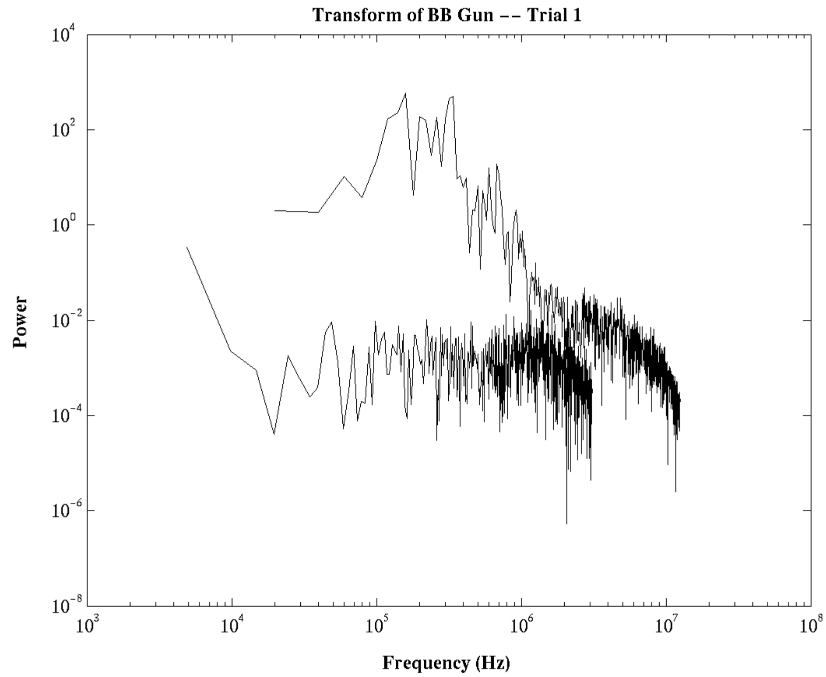

Figure 7. Note the peaks through around 1 MHz and the overall high power.

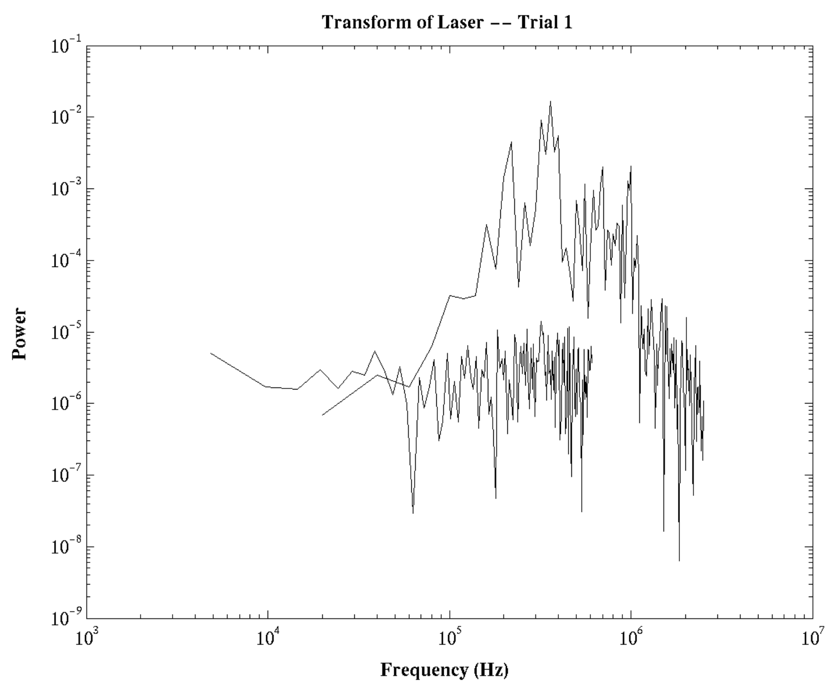

Figure 8. Note the large peaks through 1 MHz.

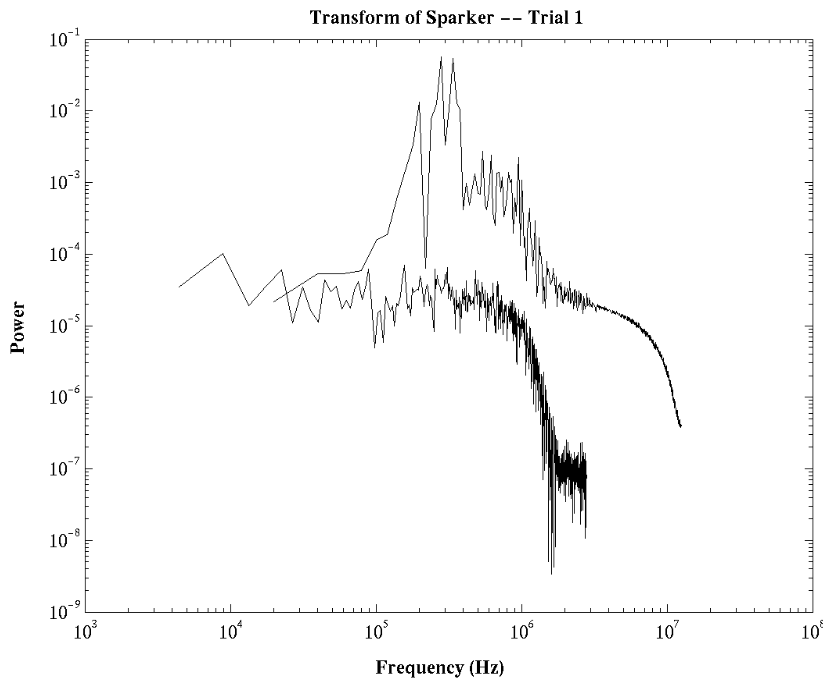

Figure 9. Note the very large peak between 200 and 400 kHz and the signal continuing through 3 MHz.

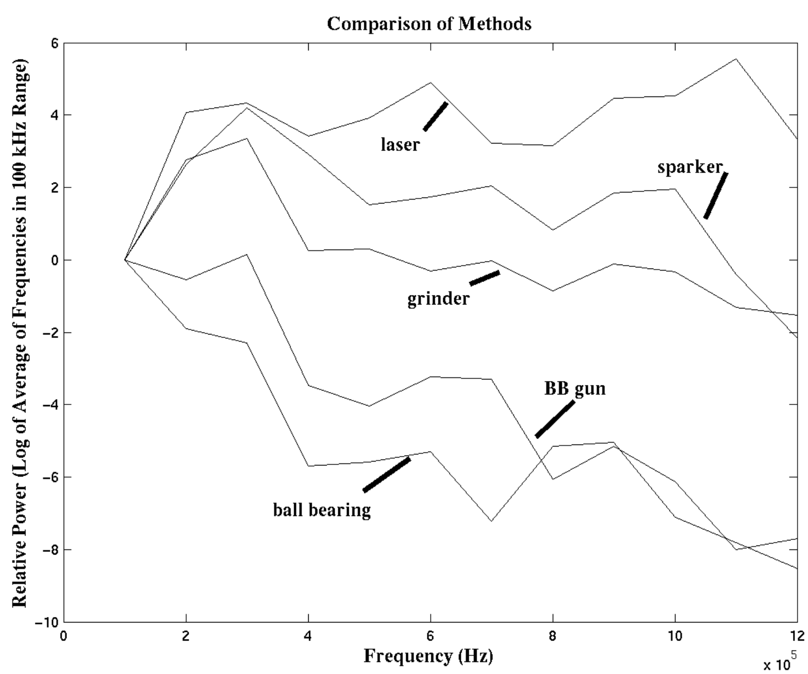

Figure 10. Note the weakness of the impact trials and the effectiveness of the laser.

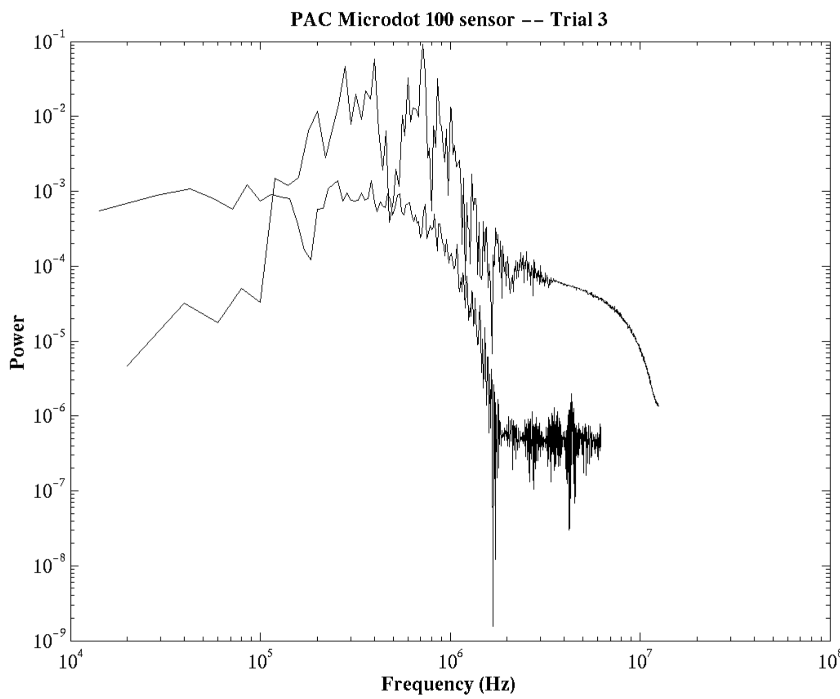

Figure 11. Note that the signal contains frequencies through at least 3 MHz.

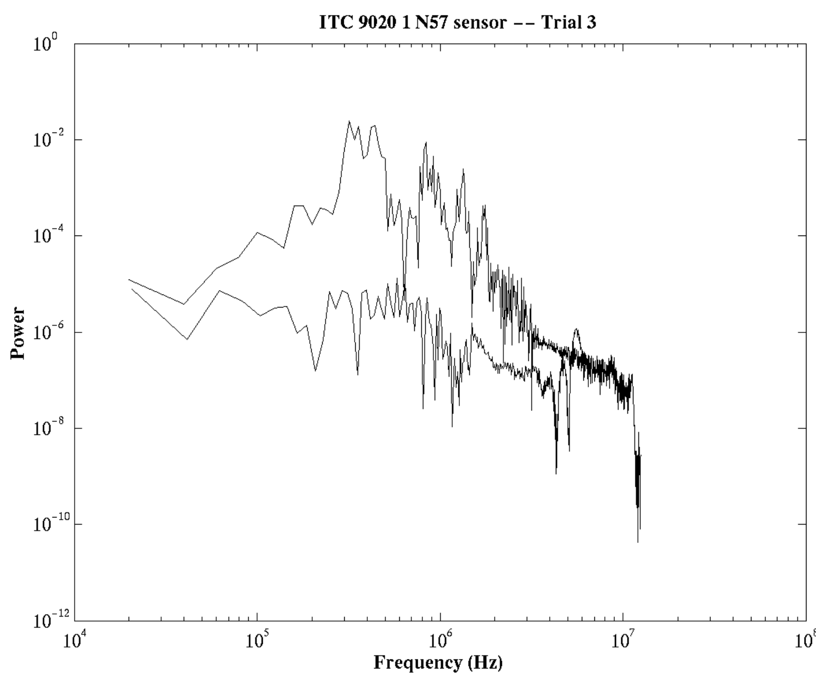

Figure 12. Note that the signal is separate from the noise and continues through 3 MHz.

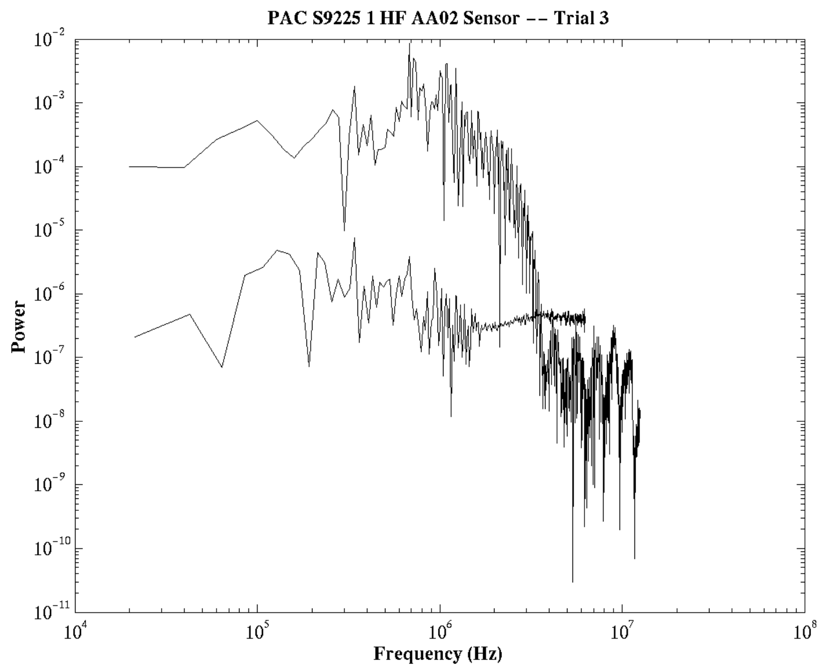

Figure 13. Note that the signal peaks around 1 MHz and dies off around 3 MHz.

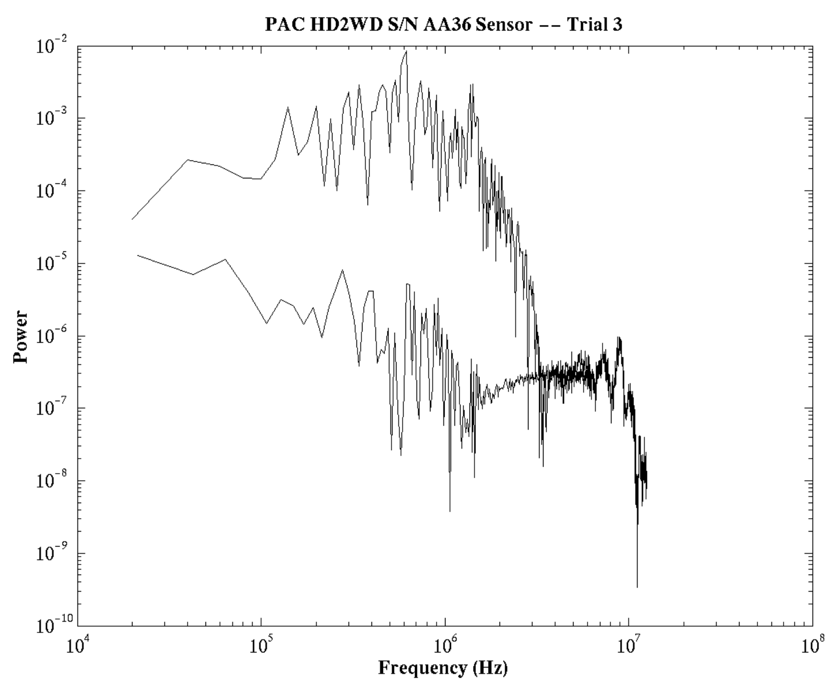

Figure 14. Note that the signal dies off sooner than the others.

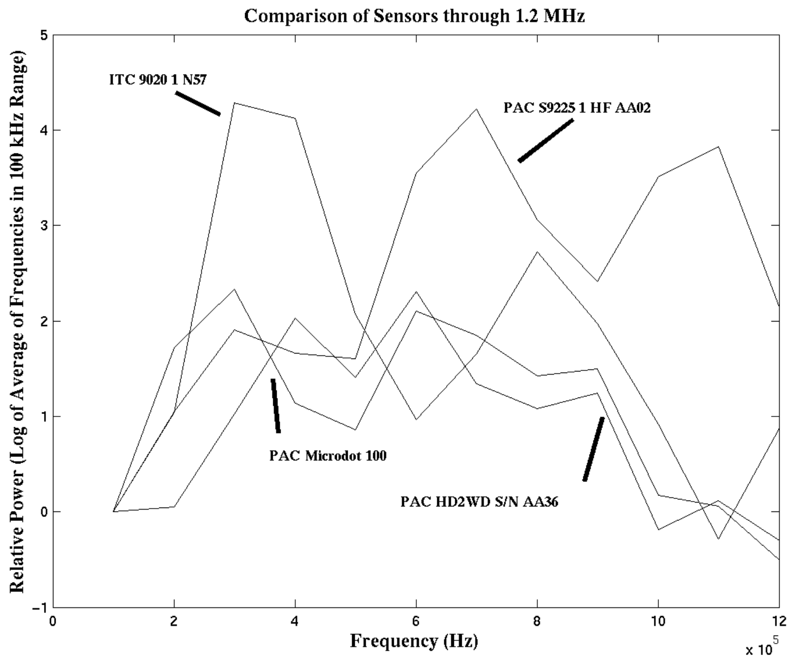

Figure 15. Note that within this range the difference between the sensors is not as clear cut as the differences between methods.

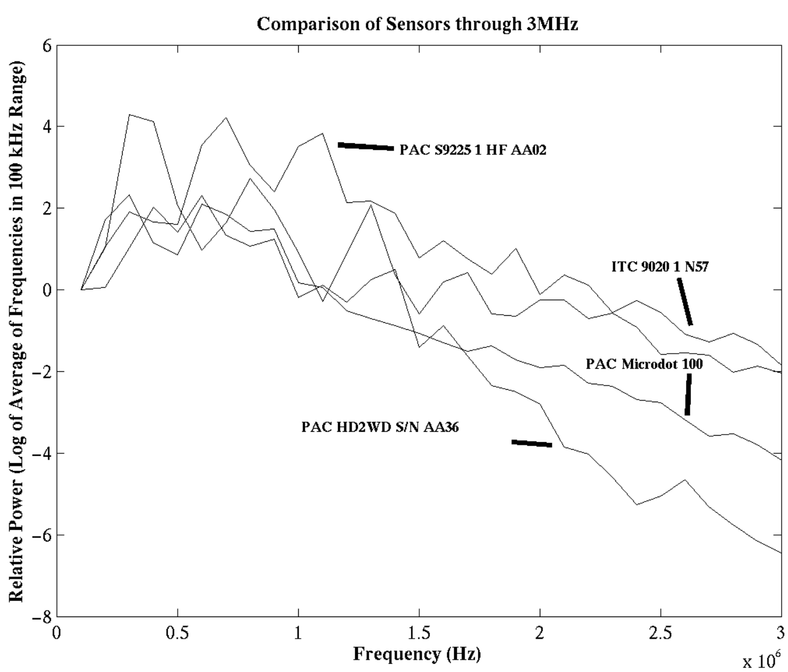

Figure 16. Note that the ITC 9020 1 N37 is equal or better to the PAC S9225 1 HF AA82 at higher frequencies in addition to being more consistent.