Investigation into the Breakdown Voltage of a Wire
LIGO

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1 Abstract

An experiment was conducted to determine the actual breakdown voltage (BDV) of the given wire, used at LIGO. The manufacturer lists the BDV as 11kV. Given the physical dimensions of the wire, predictions for the lowest and highest breakdown voltages were calculated. Weight was added to the wire to increase the chance of encountering a BDV. However, because the wire physically broke when 12.525 kg was applied to it, the wire could not be tested further and thus the BDV of the wire could not be determined. Additional data showed that after a BDV is encountered when a clamp is applying a force to the wire, there is lasting damage to its dielectric and the wire will breakdown almost immediately upon testing. This data substantiates claims that the wire should be discarded after a breakdown as its ability to resist arcing decreases. The data also provided insight into further research that can be conducted. Richard Abbott supervised and provided insight for the experiment.

2 Introduction

The wire, BAE Wire & Insulation HEAVY ALLEX (HML) MW16C 240C (Figure 3), is used at LIGO. The manufacturer lists the BDV as 11kV. It is important that the BDV matches that given by the manufacturer to mitigate the chances of issues in the field.

The goal is to design a reasonable way to test the wire that mimics the setup used at LIGO. A rough sketch is given in Figure 1. The idea of the setup is to wrap the wire around a curved surface or object, and then hang varying weights off of it. A metal sheet was used in the first experimental setup to investigate the effects of hanging the wire off a sharp edge. A thin metal rod was used in the second experimental setup to investigate the effects of winding the wire around a curved surface.

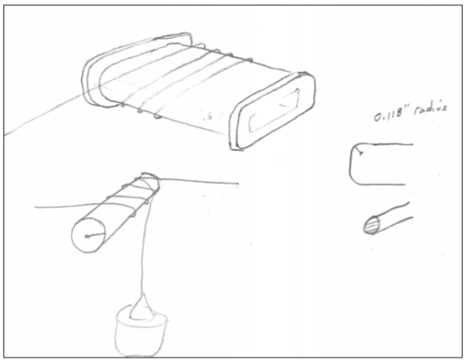

Figure 1: Rough sketch of setup. The idea was to reasonably replicate how the wire would be used at LIGO.

The BDV of the wire was tested using the Vitrek V74 Hipot Safety Test, given in Figure 2. A hipot test, also known as a dielectric withstand test, determines the breakdown voltage limit of wire insulation. Thus, testing the wire with the Hipot Tester will tell us at what voltage the wire breaks down (i.e. when its insulation fails). The Vitrek HIPOT tester has a maximum output voltage of 5000VDC. As such, the predicted 11kV breakdown threshold cannot be explored using this piece of test equipment. An additional research goal will be to design a way to make some relatively measurable reduction in the thickness of the wire insulation that might offer insight into coil winding damage. Therefore, the wire will need to be modified by decreasing its insulation thickness to observe sparking. Then, results can be applied to the actual diameter of the wire to calculate its BDV.

Due to limited time in the laboratory, this experiment primarily investigated the general effects that applying the maximum voltage, 5000VDC, had on the wire. In the first experimental setup, repeated testing was conducted on the wire hanging off a sharp edge with a non-negligible force applied to it to simply encounter a BDV and observe its lasting effects on the wire. In the second experimental setup, the wire was wound and experienced insignificant local dielectric damage. In the latter experimental setup, the following factors were changed to increase the chance of encountering a BDV: 1) the number of turns of the wire on the metal rod and 2) the weight hanging off of the wire.

Figure 2: Hipot Tester used, Vitrek V74 Hipot Safety Tester. Notably, the maximum voltage able to be applied is 5000V.

Figure 3: Wire used. The properties of the wire are listed below.

	Minimum	Nominal	Maximum
Wire	31.7	32	32.3
Insulation + Wire	34.1	34.6	35.1

Table 1: The properties of the wire used at LIGO are the following: 20 AWG, Heavy insulation, Polyimide. All dimensions given are measured in mil.

3 Hypothesis

The following calculations predict the best and worst cases for the BDV of the wire. For reference, the BDV in air is $(3 \cdot 10^6)\ \frac{V}{m}$ and 11 kV is the BDV the manufacturer lists for the wire. Based on the nominal values given in Table 1, the insulation thickness is: (34.6 - 32)/ 2 mil = 1.3 mil = $(1.3 \cdot 10^{-3})$ in.

The following equation will be used to calculate the highest and lowest BDVs. Here, X represents the value of subtracting the wire diameter from the total wire thickness (i.e. wire + insulation). Furthermore, the polyimide dielectric strength based on the nomimal values is: nom = $\frac{11kv}{(1.3 \cdot 10^{-3})in}$. The following equation will be used:

$$V_{BDV} = X \cdot \frac{11kV}{(1.3 \cdot 10^{-3})in}$$

1. The "worst" BDV was calculated. This case is for the minimum combined wire diameter and insulation thickness (34.1 mil) and the maximum wire diameter (32.3 mil). As such, 34.1 - 32.3 = 1.8 mil = $(1.8 \cdot 10^{-3})$ in.:

$$V = (1.8 \cdot 10^{-3})in \cdot \frac{11kV}{(1.3 \cdot 10^{-3})in}$$

$$V_{BDV} = 15231\ V$$

$$V_{BDV} = 15.2\ kV$$

2. The "best" BDV was calculated. This case is for the maximum combined wire diameter and insulation thickness (35.1 mil) and the minimum wire diameter (31.7 mil). As such, 35.1 - 31.7 = 3.4 mil = $(3.4 \cdot 10^{-3})$ in.:

$$V = (3.4 \cdot 10^{-3})in \cdot \frac{11kV}{(1.3 \cdot 10^{-3})in}$$

$$V_{BDV} = 28765\ V$$

$$V_{BDV} = 28.8\ kV$$

Therefore, the best and worst cases are higher than what the manufacturer predicts, 11kV, for the BDV. The manufacturer likely claims 11kV to be cautious in the presence of manufacturing variations.

4 Procedure and Results

4.1 Experimental Setup 1

The wire was hung off of a sharp edge at a 90° angle. In the following setup, note that the clamp provides a non-negligible force to the wire over the given area and off the right angle. This procedure was conducted on March 3, 2020.

1. C-clamp was clamped onto a thin metal sheet.
2. Wire was first wound around rod on C-clamp, then hung off the side of the metal sheet.
3. Two hanging weights were tied to the end of the wire hanging off the sheet. Afterward, the weights were measured with a scale as 350 g and 355g, respectively. The final setup is seen in Figure 4.
4. The wire was tested 5 times with the Hipot Tester at 5000VDC. One lead is grounded to the metal plate and the other is hooked up to the wire. The results are given in the next section.

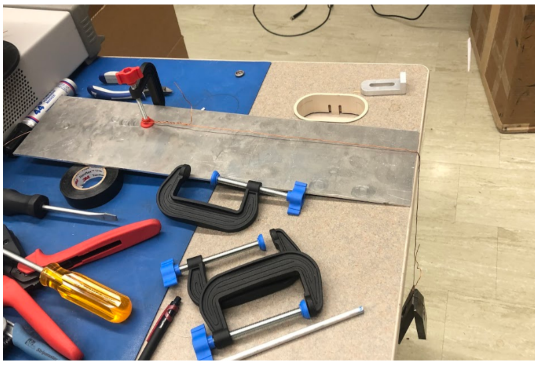

Figure 4: Apparatus Diagram for First Experimental Setup. The wire is wrapped around the C-clamp clamped to a metal sheet. It then hangs off the sharp edge.

4.2 Observational Results 1

The wire was tested 5 times at the maximum voltage, 5000VDC.

On the third test, sparking was encountered. After that, the wire was tested twice more. For the latter tests, the wire shorted and would fail almost immediately at 49V. This implies a permanent change has occurred to the wire.

4.3 Experimental Setup 2

The next objective was to design a setup that is similar to that of the one used at LIGO. The setup design, as seen in the wiring diagram in Figure 5, is similar to the way the wire is wound around a curved surface there. Notably, the wire experiences insignificant local dielectric damage, unlike it did in the latter experimental setup. This procedure was conducted on March 11, 2020.

Note: Testing of the wire in the below procedure indicates a Hipot Test of 5000VDC.

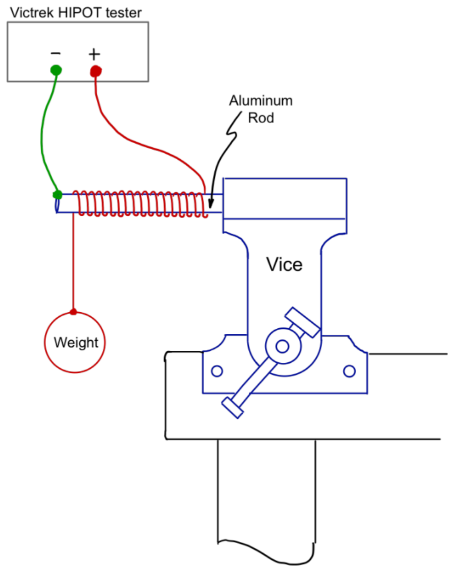

Figure 5: Wiring Diagram for Experimental Setup. Wire is wrapped around a thin rod and clamped in a vice, which provides a negligible force. The tester leads are then hooked up to the wire and the rod, enabling the wire to be tested.

The following details the procedure followed.

1. A thin metal rod was clamped in a vice.
2. Wire was wrapped around the rod by hand 6 times. Tape was placed on the wire to keep it from detaching from the rod. It was first tested, with no weights, for a baseline test. One lead is grounded to the metal rod and the other is hooked up to the wire. The wire was tested and a BDV was not encountered.
3. Two hanging weights, 350g and 355g, respectively, were then hung from the wire. This setup is seen in Figures 6. The wire was tested and a BDV was not encountered.
4. A drill was used to increase the number of turns (the length of the turns was measured at 7.6 cm with a standard ruler, roughly 80 turns), giving tight and plentiful turns. This setup is seen in Figure 7.
5. The two hanging weights were again placed on the wire and it was tested. No BDV was encountered.
6. The weight on the wire was gradually increased and then tested. A 1 lb weight stand was used from here on out. The weights used are seen in Figure 8. The results are given in the following section.

(a) Setup view from diagonal above.

(b) Setup Front view

Figure 6: Apparatus Diagram for first test.

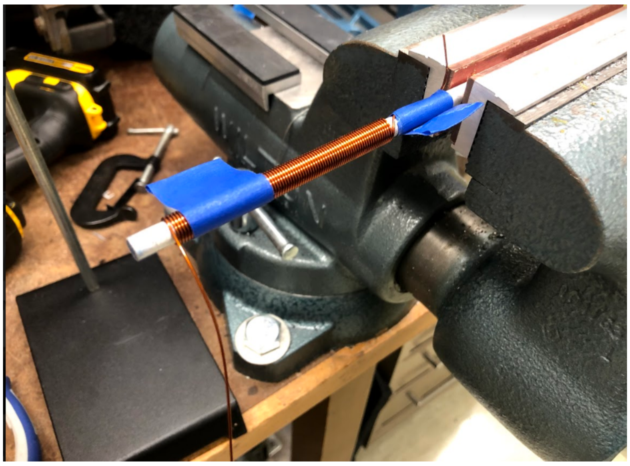

Figure 7: Apparatus Diagram for the second test. Roughly 80 turns are observed.

Figure 8: Weights used in second setup: 1. the 1 lb stand used, 2. is the standard weights, 3 the heavier weights, 10 lbs+.

4.4 Observational Results 2

Table 2 gives the experimental data recorded for the latter experimental setup.

Trial No.	No. of Turns	$\mathbf{m_{added}}$ (**kg**)	BDV Encountered
1	6	0	No
2	6	0.705	No
3	80	0.954	No
4	80	1.454	No
5	80	2.454	No
6	80	3.454	No
7	80	4.454	No
8	80	5.154	No
9	80	6.154	No
10	80	9.525	No
11	80	12.525	Wire Broke Before Testing

Table 2: Observational Results of Second Experimental Setup

Note that a 1b stand (0.454 kg) was used from trials 2-10 to hang the weights on the wire. The weight of the stand is included in the total mass added. Each weight used came labelled with its weight, so they were not weighed (except for the weights in trial two, which, as was previously noted in the first experimental setup's procedure, were weighed on a standard weighing scale).

From the data, it is clear that the wire will physically break between 9.525 kg and 12.525 kg being applied to it.

5 Analysis and Conclusions

Due to limited time in the laboratory, not all of the research goals mentioned in the Introduction were not able to be researched.

The first experimental setup demonstrated that after repeated testing, the wire wears down and will break down almost immediately at 49V. There is lasting damage to the dielectric when the wire arcs since there is a reduction in the BDV encountered in subsequent tests. Thus, the wire is not able to withstand usage over time under these conditions. If the wire breaks down, it should be discarded as it will be permanently damaged. This data should caution those who choose to use the wire as there is irreversible damage to the wire after it breaks down. However, this result must be considered in context, as the wire likely experiences significant local dielectric damage from the clamp used.

The second experimental setup demonstrated that the physical strength of the wire breaks down when 9.525 kg - 12.525 kg is applied to it. In addition, a notable conclusion is that the tension in the wire from winding the coils does not impact the BDV. If premature breakdown is an issue, it may be due to poor surface finish (areas of sharp features) or the cleaning and processing of the wire. While the data did not lead to determining the BDV of the wire when the wire experiences insignificant local dielectric damage, it did provide insight for additional testing of the wire. The predictions calculated for the worst and best BDV's could be investigated in the future, pursuant to the additional research goal given in the introduction: finding a way to minimize the diameter of the wire in a measureable manner such that the BDV of the modified wire would occur at a lower voltage; then, it could be tested by the Vitrek HIPOT tester, which only has a maximum output voltage of 5000VDC.

The experiment conducted provides insight into features of the wire that will aid in future research.