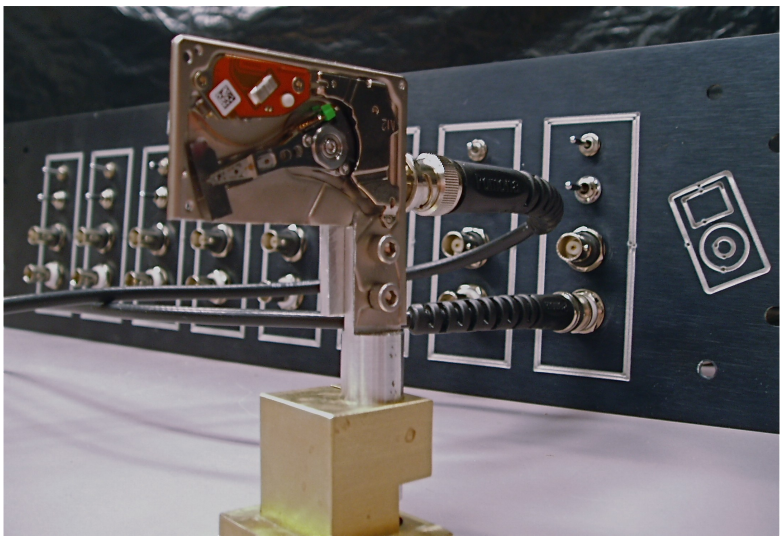
Ultrafast Mechanical Shutters for Laser Cooling Applications: The iShutter System



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Applied Science 479
Engineering Physics
University of British Columbia
January 14th, 2008

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January 14, 2008

Dear Dr. Madison and Dr. Jones:

Enclosed is a copy of Paul and Davey's recommendation report entitled, “Ultrafast Mechanical Shutters for Laser Cooling Applications: The iShutter System.”

The main objective of this project was to build, test, and characterize ten mechanical shutters. Over the course of the project the desired outcome was modified to encompass twenty mechanical shutters. To date the circuits for all twenty units have been completed, two circuit panels that each carry eight circuits have been cut, and three mechanical shutters have been fabricated, tested, and characterized.

The purpose of this report is to clearly document the progress of the project over its lifetime, to provide complete details needed to finish the twenty shutters and to fabricate more, and to present the characteristics of the three shutters that have been completed.

We hope that the results of this project will have a positive impact on your operations, and look forward to working with you to complete all of the twenty shutters in the coming months.

Sincerely,

Paul Lebel

Davey Mitchell

Executive Summary

A set of Ultrafast Mechanical Shutters for beam optics experiments has been developed and characterized. These shutters are constructed from modified hard drives, and are based on an existing design published by the atom optics group at the University of Melbourne. This design exploits the coil and actuator arm of a conventional hard disk drive to swing a shutter flag into the path of a laser beam, thereby occluding it. This actuation is powered by a customized pulse of electrical current delivered to the coil.

The authors have made several notable improvements on the design. Instead of using conventional 3.5 inch hard drives, the shutters were fabricated from miniature iPod hard drives. Two eight-channel "iShutter" control boxes have been built, allowing the driver circuits to be mounted in a convenient centralized location, some distance away from the shutters. As a result, each unit consumes minimal space on an optical table, allowing the devices to be used more liberally as needed. Finally, the iShutter system has been characterized extensively at three different supply voltages, displaying high levels of performance and reliability.

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1. Introduction

In laser cooling experiments, it is often necessary to actively enable or disable certain optical fields from interacting with the ultracold sample. An experimental sequence to trap and study cold atoms might use up to four or five different frequencies (or more for multiple trapped species). These need to be applied at precise times throughout the experiment and from various angles, totaling up to as many as 18-20 individual beams entering the vacuum cell. There is certainly no need to control every one of these beams, but at the very minimum each frequency (up to six beams) requires the capability of shuttering.

The need for a shuttering device follows from the fact that a laser cannot be simply switched on or off, as these lasers are highly sensitive and frequency-stabilized, and rapidly extinguishing the laser diode current would drive the system outside of its closed-loop equilibrium state. Even under identical external conditions, the non-equilibrium thermal condition produced by the sudden switch-off will prevent subsequent re-powering attempts from bringing the laser to its previous state. Hence, it is necessary to enable or disable the laser's propagation by external means.

1.1. Shutter Applications

The mechanical shutter enables/disables the propagation of any laser through a complex network of optics used for polarization, beam shaping, frequency shifting, and geometric positioning. Figure 1 shows an example optical setup used to amplify, shift, and polarize four different optical frequencies in a dual species experiment. Amongst the complexity, mechanical shutters can be seen as the small, rectangular, yellow boxes positioned at some point between each laser and its final destination in the vacuum chamber.

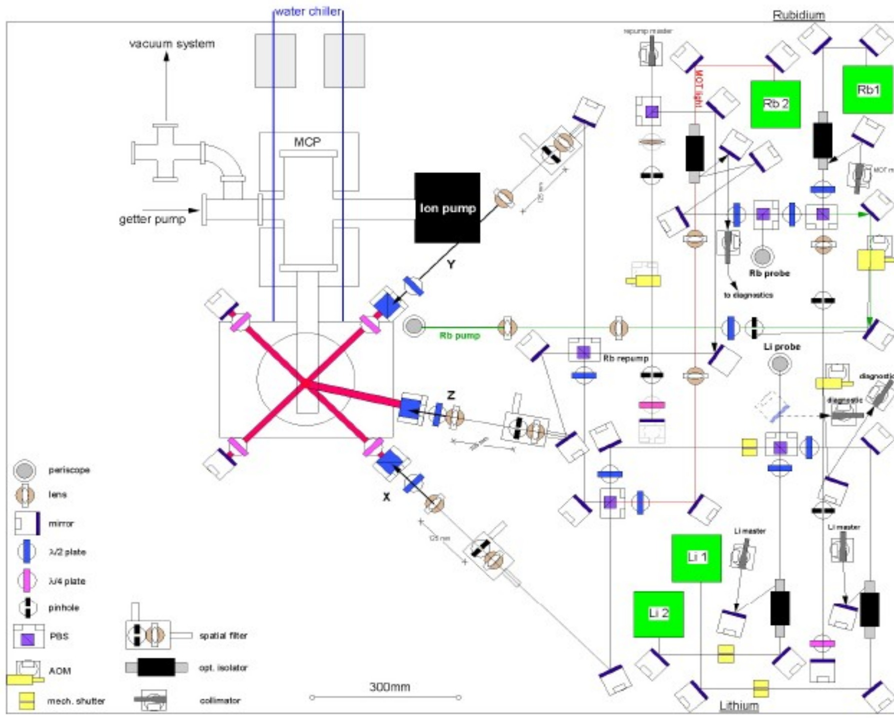


Figure 1[Schuster 2007]: The Photo-Association experiment in the Laboratory of Ultrastable Femtosecond Optics. Mechanical shutters can be seen as yellow boxes.

1.1.1. Transfer to a Magnetic Trap

A common example of a process requiring shuttering is the transfer of cold atoms from a Magneto-Optical Trap (MOT) into a purely magnetic trap. A MOT is a powerful trapping and cooling technique, used as the first step towards cooling atoms to degeneracy. MOTs use a combination of radiation pressure and magnetic potential to confine and cool atoms directly from background vapour pressure in the cell. Any atoms with low enough kinetic energy are collected in the center of the MOT potential, and remain held there against gravity and collisions with other particles that may be present. After equilibrium is reached (ie. the number of atoms in the trap has reached a maximum), the atoms can be transferred into a purely magnetic trap for further cooling by non-optical methods. In this case, the MOT lasers are turned off while a strong magnetic field is simultaneously switched on. These two events must be very well coordinated if a high transfer efficiency is desired, which can be easily accomplished with an automated control system and a good optical shutter.

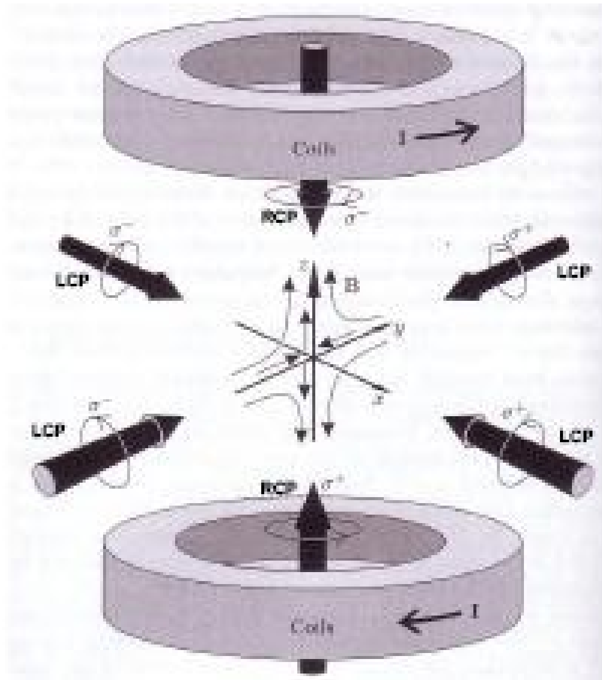


Figure 2[Schuster 2007]: An illustration of basic MOT trapping theory. The six inward-pointing arrows represent circularly polarized laser beams to be extinguished on command when transferring atoms into a purely magnetic trap.

1.1.2. High Speed Imaging

The atoms themselves are isolated inside a vacuum chamber, the means of interacting with them are limited, and the most commonly performed measurement is imaging. To acquire high resolution temporal imaging data, one either needs a camera with an exceedingly high frame rate, or a pulsed light source with a lower frame rate. The first option requires a specialized and highly sensitive camera, whereas the second may be achieved by pulsing an imaging beam at the precise moment that the data is required. In this case, the camera is exposing for a period of time much longer than is required, but light is only captured during the laser pulse which 'illuminates' the sample. It remains to be seen if mechanical shutters will provide the speed that is required for this application.

1.2. Review of Current Technology

Many different shuttering technologies exist, each with its own advantages and disadvantages:

Shuttering Technology	Advantages	Disadvantages
Mechanical Shutter (commercial) [Newport][Edmund]	Fast, reliable, 100% Extinction/Transmission,	Very expensive for high performance, substantial power supply
Acousto-Optical Modulator (AOM)	Ultrafast (<1 microsecond), highly tunable	RF driver required, optical power loss, not 100% extinction, expensive, careful alignment required
Electro-Optical Modulator (EOM)	Ultrafast (<1 microsecond), highly tunable	HV power supply required, careful alignment required, expensive
Polarization-based shutters	Moderate speed (50ms), low power requirement, no careful alignment required, compact	Very expensive, moderate speed.
Ultrafast Hard Drive Shutter	Ultrafast (~100 microseconds), 100% Extinction/Transmission, inexpensive, low power, no careful alignment required	Relatively large footprint on optical table, potential inconsistency between salvaged hard drives

Table 1: Shutter Technology Comparison

Though all of the above methods work, they vary greatly both in expense and ease of implementation.

- Acousto-Optical modulators use a pressure wave diffraction grating to shift laser frequencies, producing several different orders of diffracted beams. These different order beams are spatially separated, allowing one to select a certain beam based on its angle emerging from the device. For example, shuttering is achieved by using the 1st order diffracted beam, and when the acoustic wave is not present no diffraction will occur and no light emerges at that angle. Since the process happens at radio frequencies, the beam steering, or shuttering, occurs very quickly.

- Although a different phenomenon, electro-optical shutters have similar performance characteristics as acousto-optical shutters, and will not be discussed further.
- Polarization-based shutters use Faraday rotators and/or liquid crystal technology to rotate a polarization between two linear filters. Considering their performance level, the cost of these devices is too great to justify against other competing options, such as our hard disk shutters.
- High performance commercially-made mechanical shutters are readily available, though at considerable cost. A product search returned several mechanical shutters, with sophisticated drivers, of average price on the order of $850 USD. These shutters are designed for general purpose, and use converging blades to accomplish shuttering. The performance benchmark is roughly 1-3ms in pulse duration.

In the case of beam optics, one can obtain a very fast shutter time by focusing the beam down as small as possible, so that the shutter can cross the entire beam in a very short time. For example, the authors in [Scholten, 2007] achieved a 0.7µs rise time across a 0.7µm beam, with a 10mm/ms shutter flag velocity; greatly enhancing the effective shuttering speed.

2. Discussion

The objectives of the Ultrafast Mechanical Shutter project were to enhance and customize a proven design to meet the needs of the sponsor, providing them with a high quality product, far exceeding the value per dollar of its commercially-made counterparts. The sponsors are to receive as a project deliverable a number of working units for use in their optics experiments, tested and calibrated. The proven design on which this is based has been developed at the University of Melbourne in Australia and described at http://optics.ph.unimelb.edu.au/atomopt/shutter/shutter.html.

The current work has implemented a number of notable improvements on the previously published design. Our group has miniaturized the shutter design by constructing them from tiny iPod hard drives, consuming far less precious space on the optical table than the original 3.5" large format hard drives used by U of Melbourne. In addition to smaller mechanical components, the authors have modularized the power supply and driver circuits, combining them into one control box which can be located some distance away from the experiment. In effect, this further reduces the footprint of the shutter by removing the circuit from the back of the device.

In addition to reducing the footprint of the shutters, this change reduces clutter on the optical table by centralizing the control system in close proximity to the other control electronics of the experiment. Each shutter is controlled and powered through a single BNC cable emerging from the front panel of the control box.

Figure 3: iShutter Control Panel. Acknowledgments to Bernhard Zender as our waterjet cutter operator.

After some initial attempts at improving the shutter speed, it was concluded that the maximum speed was a function of the pre-fabricated voice coil structure and the chosen power supply voltage. Data will be presented in the results section displaying the shuttering speed (rise and fall times) as a function of power supply voltage.

2.1. Theory

The following section outlines some basic theory of hard drive operation, leading to the selection of the device as exceptionally well-suited to modification as an optical shutter. The manufacturing technique is described, along with a testing and calibration protocol to ensure the devices are functioning up to the standards required by the sponsors.

In essence, one takes a hard disk and extracts its moving components for use as shutter, replacing the control electronics with a customized electrical signal. To understand why the hard disk is so well suited for this application, the basic operation of a drive shall first be described, a visual of which is depicted in Figure 4.

To read and write data, a hard disk drive uses a rotating plate made of aluminum or glass, coated with a thin layer of magnetic material. Digital information is encoded on this thin magnetic domain, by modifying its direction of alignment in tiny sections on the disk. For fast data access, the plate is spun at very high speeds, commonly up to 7200 RPM. The tiny domains on the rotating plate are accessed by a single read head located on the end of an actuator arm, which rotates about a pivot point located near the edge of the disk. In this way, the read head can access any location on the disk: radial position is set by the rotation of the actuator arm and angular position constantly cycled due to the plate's rotary motion.

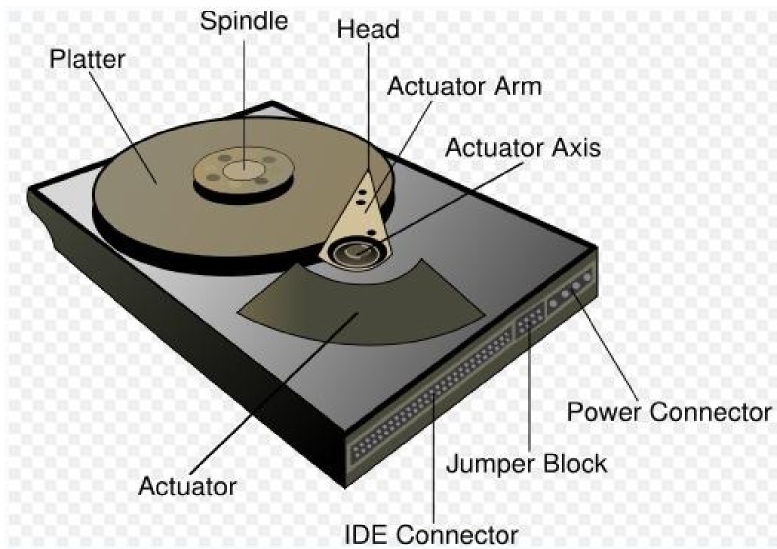


Figure 4: [wikipedia] A cartoon depicting the operation of a large format hard drive. The component of interest is the precise actuator arm/voice coil combination used to rapidly address magnetic domains to within 100nm[Scholten, 2007].

Under normal operation, these arms are rapidly positioned to an accuracy of 100nm [Scholten, 2007] via their voice coil actuators. The rotation is produced by the magnetic force between the current-carrying voice coil and the rare earth permanent magnets, situated above and below the arm's opposite end. The permanent magnets are housed by a support structure, labeled *actuator*. This actuator structure, voice coil, and actuator arm are kept intact; together they form the electromechanical assembly which converts a well-timed pulse of current into ultrafast beam blocking motion.

This assembly is extracted from the drive by first removing the disc platter(s) and any superfluous control electronics. Once only the actuator and chassis remain, a band saw was used to remove the portions of the chassis that are not useful as a shutter mount. In general, only a small L-shaped portion of the chassis was used for this purpose. The extracted assembly of an iPod hard drive is shown in Figure 6, along with its driver circuit in Figure 8.

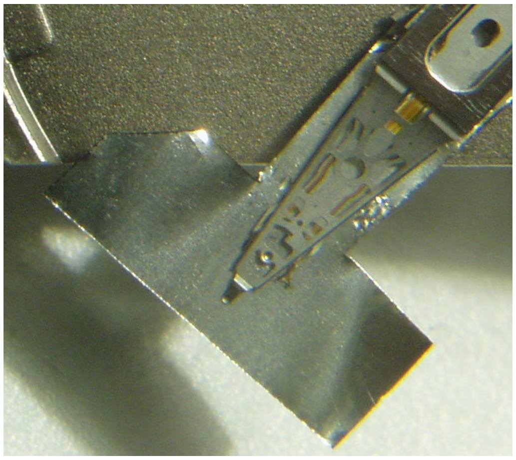


Figure 5: A close up view of a shutter flag made from 25 micron steel foil.

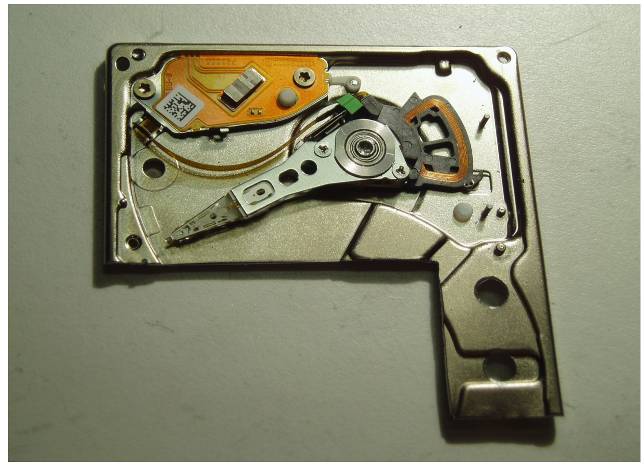


Figure 6: Extracted iPod hard drive assembly with actuator magnet removed

Although most of the term was spent working with large format drives, the subject of this report is our end product: the iShutter system. It is fortunate that the construction of an iPod hard drive is very similar to that of the large format drive. In fact, the only observed differences are related to its size:

- They are constructed of molded steel instead of machined aluminum (presumably to maintain rigidity at such a thickness), and are assembled with tiny torque screws.
- The magnet is only one-sided, presumably to save space, whereas other drives make use of a magnet pair that sandwiches the voice coil.
- The electronics are connected with ribbon cables, which are also used to drive current to the voice coil actuator via a pinout array mounted on the back of the drive. This pinout array allowed us to solder directly to solid pins without having to strip insulation from the microscopic magnet wire itself.
- Despite its reduced size, the throw of the actuator arm (full range of motion) is nearly equal to that of the 3.5 inch drives.

2.2 Design and Specifications

Here the mechanical and electrical details of the iShutters will be presented, along with performance specifications. Although the iShutter is a relatively simple device, the device is explained in terms of the design decisions made by the authors, which have led to what they consider an extremely robust, reliable, and user-friendly system.

2.2.1 Mechanical Design Decisions

Referring to section 2.1, the drive must be 'gutted' for its moving mechanical parts. There are several ways in which one could cut apart a hard drive; the one chosen attempts to minimize the leftover structure while still retaining enough support to rigidly mount the actuator arm/bearing/voice coil combination onto a half-inch optical post. Ensuring a mechanically stable mount is critically important to the design of the shutter—if the device tends to wobble to and fro, there can be no guarantee of performance repeatability. Again referring to Figure 6, the hard disk is intentionally cut at a height such that the shutter flag will pass just below the remaining edge. This makes rough alignment easy, while minimizing chassis size.

The shutter flag is a 25 micron steel sheet, and is glued onto the actuator arm to increase the surface area available for beam blocking. The optimal size of the sheet is the minimum size it can be to completely block a 5mm beam, while still giving the arm time to slow down before it strikes the end of its range of motion. If that flag were too small, it would be very difficult achieve fast extinction of the beam while also slowing it down before it either completely passes the beam or bounces from the end of its range of motion. If the flag were too large, it would either be difficult to move rapidly or become damaged after some time. Finally, performance repeatability also relies on the flag because the laser must be aligned to the same location on the flag to ensure consistent latency time. Please see Appendix A for exact dimensions of the flag and other mechanical parts.

The entire shutter is mounted on a half inch post, for compatibility with all the mounting hardware in the

QDG lab. A custom post with a flat section and two mounting holes has been designed to hold together both the shutter and the mount for its BNC cable through with the driving current is delivered. This post contains two clear holes for 6-32TPI sized imperial threaded fasteners to compress all three components.

2.2.2 Electrical Design Decisions

The voice coil is driven by a custom circuit, very similar to that published by Scholten et al., shown in Figure 8. The circuit utilizes the LMD18200 DC motor controller chip for current switching. As wired in our driver, the chip receives a TTL signal to its direction pin, simply toggling the direction of current flow through the coil. The circuit also has the ability to receive a Pulse Width Modulation (PWM) signal, which rapidly drives the internal MOSFET gates on and off to switch current through the voice coil. Our group originally made plans to use this feature for active damping of the actuator arm, however it was soon discovered that it was not a worthy pursuit, for reasons explained below.

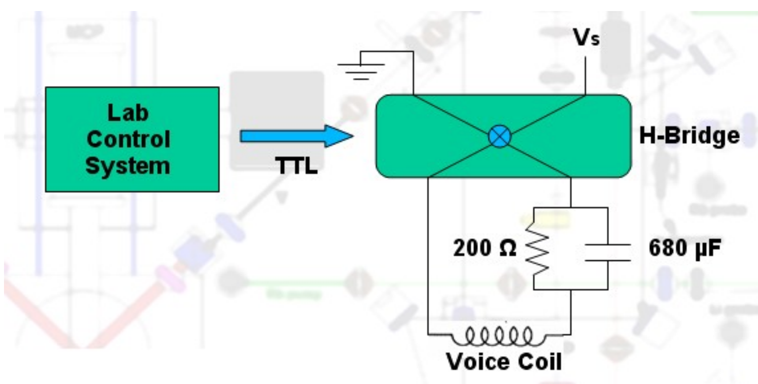


Figure 7: Functional Schematic of the Driver Circuit

Figure 7 Shows a functional schematic of the driver circuit. The salient feature of this circuit is the RC combination in series with the voice coil. Its purpose is to store a large amount of charge, to be released the instant a rapid switch in shutter position is desired. When the driving pulse is begun, a huge current is delivered to the coil, accelerating it to speed. This current, however, rapidly decays to a small steady-state value, which is the holding current keeping the arm at one side or the other. This small, steady current contributes to the low average power consumption.

Due to the exponentially decaying nature of the available current in a short pulse, once the actuator arm is initially accelerated, its motion cannot be fully reversed without applying a much longer pulse in the opposite direction. In fact, once the arm is fully accelerated, it is not even possible to prevent it from striking the other end of its range. It is for this reason that the authors did not pursue any active damping; as the maximum possible strength of reverse braking was already being applied, and any attempt to fine-tune the pulse would still result in the application of full strength braking. In this case, the length of the braking pulse was manually tuned to be as long as possible without actually un-blocking (or re-blocking) the beam for a second time. For more details please refer to section 2.4.

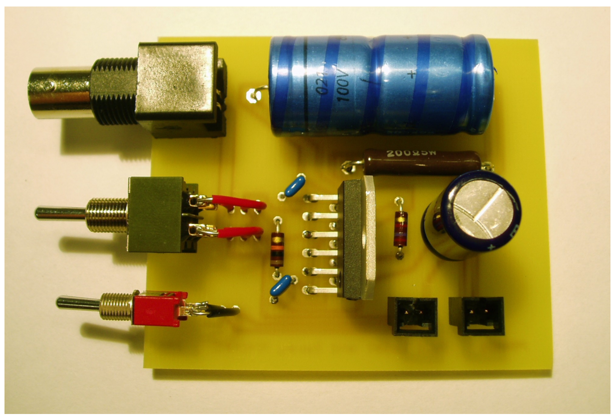


Figure 8: An iShutter driver circuit, ready to be Panel-Mounted

2.3 Methods and Testing Protocol

The shutter testing protocol is designed to test all parameters relevant to the sponsors' application. Dr. Madison and Dr. Jones have indicated that the most important parameters are low variation in latency time, shutter flag damping, and reduction of physical size. This section describes the rationale and method for each performance test.

The apparatus used to test the mechanical shutters is completely contained inside a 90 cm by 45 cm area on an optics table in Dr. Madison's Lab, and is shown in Figure 9. It consists of a 14 mW laser beam that is first passed through two mirrors which allow height and lateral adjustment of the beam. The beam then travels past the mechanical shutter to a neutral density filter to give a beam of 0.2 mW. Finally, the beam passes through a lens which focuses the beam onto a photo-diode detector. At one physical stop of the shutter arm's throw the laser is completely unblocked, with its full power passing through to the diode. At the other physical stop of the shutter arm's throw the laser is completely blocked, allowing no power from the laser to pass through to the diode.

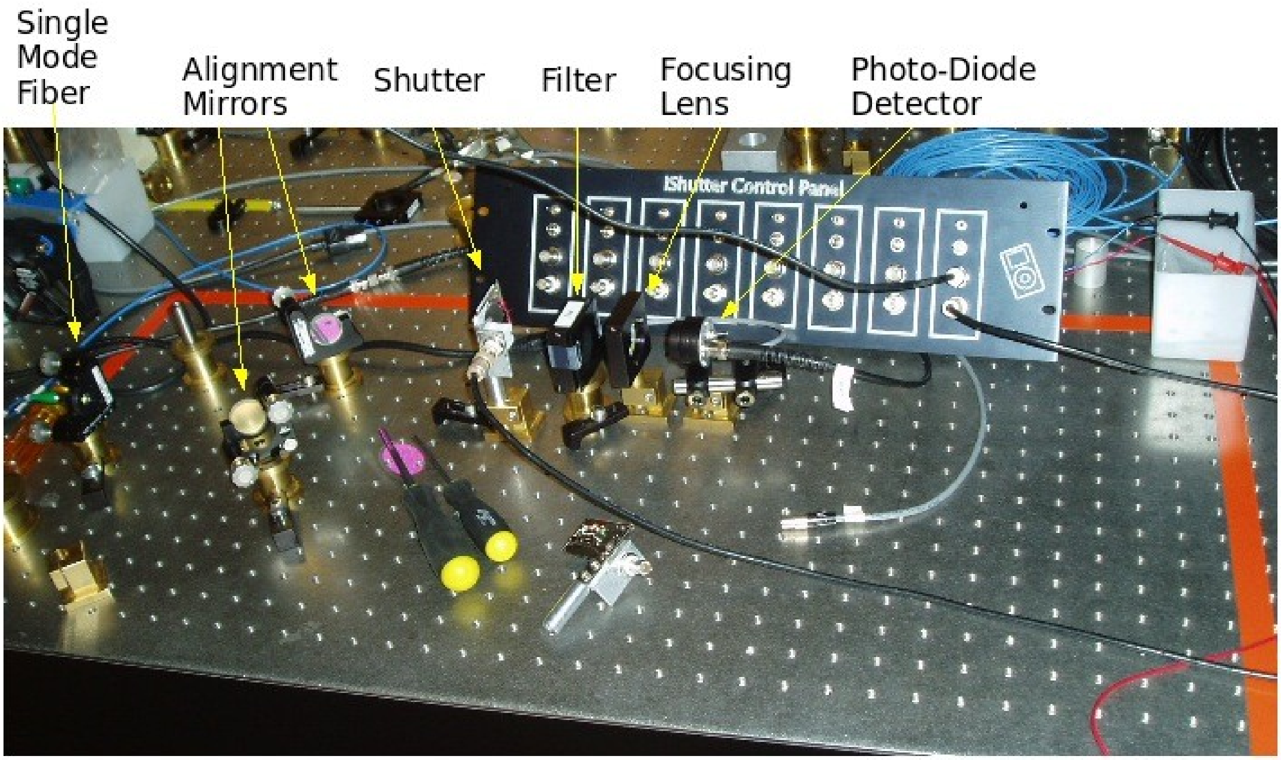


Figure 9: Testing Setup, 90cm x 45cm

The purpose of the tests is to characterize the shutter's ability to block and unblock the laser. The desired characteristics of shutters for laser cooling applications include:

- Rapid enabling and disabling of laser propagation
- Reproducible rise and fall times
- Reproducible latency times
- Shutter arm damping

First each test is described, and then its rationale is discussed.

Test Description: Rapid enabling/disabling of laser propagation refers to how quickly the mechanical shutter can cause the power that the laser is transmitting to the diode to rise/fall from 10% to 90% of full power.

Rationale: The reason that this characteristic is required to be as fast as possible is that optical experiments which require the laser beam to be enabled or disabled ideally want that to occur in zero time.

Method: The Tektronics oscilloscope in the lab was programmed to measure the rise and fall time of the laser using the output of the photo-diode. This data was then exported to a comma separated values (csv) file using LabView and subsequently analyzed in MATLAB.

Test Description: Reproducible rise and fall times refers to the stability of the time it takes for the shutter to enable and disable the laser.

Rationale: The desire for this characteristic to have very low variability stems simply from the need of an experimenter to know exactly how long it is going to take to enable or disable the laser. Also, if multiple experiments are being run, this value needs to be as close to a constant as possible between the experiments so that an extraneous variable is not introduced into the system.

Method: The data collected from the oscilloscope while measuring rise and fall times is analyzed in MATLAB for repeatability.

Test Description: Reproducible latency times refer to the stability in the time between when the leading/falling edge of the TTL signal instructing the shutter to enable/disable the laser is sent to the shutter, and when the shutter has cut/exposed the beam to 50% of full power.

Rationale: This is crucial knowledge for experiments that require the laser to be enabled or disabled at a certain time.

Method: The Tektronics oscilloscope in the lab was programmed to measure the rise and fall time of the laser using the output of the photo-diode. This data was then exported to a comma separated values (csv) file using LabView and subsequently analyzed in MATLAB.

Test Description: Shutter arm damping refers to the technique of reverse-driving the shutter arm immediately after it has completely enabled or disabled the beam in order to slow it down before hitting the arm's physical stops. This will reduce the audible noise emanating from the shutter, the vibrations transmitted into the optical table, and the physical wear and tear on the shutter.

Rationale: This is an important factor because if the shutter arm is moving too quickly when it hits its physical stop, the shutter can produce a loud clicking noise, can transmit vibrations into the optical table which can potential affect other components attached to the same table, and can physically damage itself.

Method: This was the most involved testing procedure, and required generating a custom arbitrary waveform. This was done using the DS345 Stanford Systems Arbitrary Waveform Generator. For purposes of simplifying the explanation, consider that the beam is propagating and that we want to disable it. The main idea behind this method is that the shutter should initially be driven forward by the TTL to disable the beam's propagation. As soon as the beam was completely blocked the shutter should then be driven in reverse by the TTL until the audible noise of the shutter arm slamming into its physical stop was minimized. Once this was accomplished the shutter should finally be driven forward again to hold it at its physical stop. A picture of this waveform and the resulting photo-diode response of the beam is shown in Figure 10.

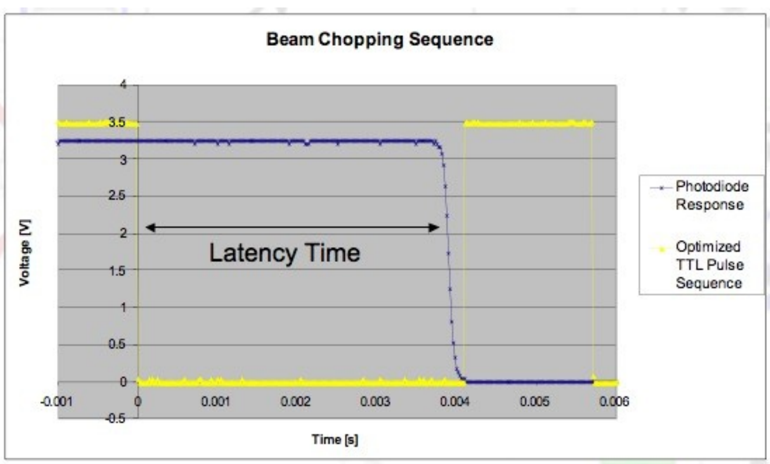


Figure 10: Arbitrary waveform (yellow) and resulting photo-diode response (blue)

Note: No measurements of mechanical vibrations were conducted on the shutters as they will not be mounted on the master laser table, and thus minimal vibrations will have no large effect on any experiment mounted on the table. However, this would be a beneficial test to conduct were the shutters ever to be used in an environment that required minimal vibrations. A good place to start would be to test the unit mounted directly onto the table, and then to test the same unit mounted on the table, but with an intervening sorbothane buffer.

2.4. Results

2.4.1 Results Introduction

Tests were done throughout this project as it progressed through several stages from large format hard drives with simple drive circuits to iPod hard drives with more sophisticated drive circuits. For both brevity and relevance, only the tests that were done on the final products being transferred to the project sponsors will be included in this report.

Because repeatability is important between the different mechanical shutters, this section includes results from three randomly selected shutters out of the twelve iPods that were received. As described in the *Methods and Testing Protocol* section, the tests that were conducted include rise and fall time speeds, rise and fall time reproducibility, latency time reproducibility, and shutter arm damping effectiveness.

All of these tests were conducted with the shutter operating at 0.5Hz. This frequency was quick enough to allow a large number (on the order of 70) data points to be collected in a relatively short two minute test period, and slow enough to ensure that the shutter became completely stationary between shutter arm movements

These tests were conducted on a non-focussed beam about 0.3mm wide. The width of the beam was calculated by cutting it with a razor mounted on a micrometer and taking the distance between when the photo-diode was collecting 90% of the beam's max power, and when it was collecting 10%. The beam profile is shown in Figure 11. This data indicates that the beam's cross section is not an ideal Gaussian, and has some skew. However, as this profile is constant across the tests, the data given by each of the three shutters is directly comparable.

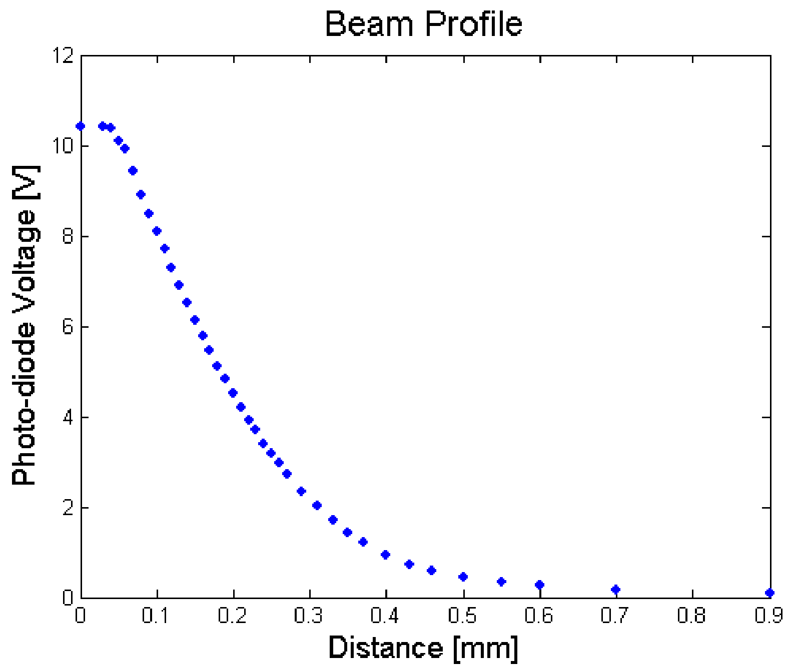


Figure 11: Beam Profile

Tests were conducted at three voltages. Testing was done at 12V for two reasons. The first is that a possible power supply for the shutters will be a computer power supply, and these operate at 12V. The second is that the drive circuits stop operating at about 9.9V, which means 12V is about as low as the circuits can be driven, and will produce results at one end of the performance spectrum.

Testing was done at 30V because this constitutes the other end of the performance spectrum from 12V. This is because the circuit is equipped with a 200Ω, 5W power resistor, which using $P=V^2/R$ indicates that the maximum voltage which can be used is 31.6V.

The third set of tests were done at 16V because this was the voltage the authors had been using for all of our previous testing throughout the project, and thus allowed us to compare the performance of the iPod hard drives with the large format hard drives. For the sake of brevity and relevance, the data associated with the large format hard drives is not included in this report.

2.4.2 Data

Although the data is more easily compared in the graphs that follow, Table 2 summarizes all of the means and standard deviations that were calculated for each test.

Fall Time						
	12V		16V		30V	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Shutter 1	1.54E-004	4.42E-006	1.32E-004	2.59E-006	8.66E-005	3.56E-006
Shutter 2	1.73E-004	5.04E-006	1.45E-004	3.76E-006	9.32E-005	3.13E-006
Shutter 3	1.70E-004	5.11E-006	1.45E-004	3.36E-006	9.26E-005	3.31E-006
Average	1.66E-004	4.86E-006	1.41E-004	3.23E-006	9.08E-005	3.34E-006
Rise Time						
	12V		16V		30V	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Shutter 1	1.68E-004	4.18E-006	1.34E-004	2.86E-006	9.47E-005	3.27E-006
Shutter 2	1.76E-004	4.97E-006	1.48E-004	4.88E-006	1.08E-004	3.97E-006
Shutter 3	1.69E-004	4.30E-006	1.41E-004	3.68E-006	1.01E-004	4.02E-006
Average	1.71E-004	4.48E-006	1.41E-004	3.81E-006	1.01E-004	3.75E-006
Fall Latency Time						
	12V		16V		30V	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Shutter 1	3.88E-003	1.39E-006	3.33E-003	1.75E-006	2.42E-003	1.44E-006
Shutter 2	3.94E-003	5.97E-006	3.37E-003	2.14E-006	2.40E-003	6.48E-006
Shutter 3	3.83E-003	1.76E-006	3.21E-003	7.09E-006	2.33E-003	9.89E-007
Average	3.89E-003	3.04E-006	3.31E-003	3.66E-006	2.38E-003	2.97E-006
Rise Latency Time						
	12V		16V		30V	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Shutter 1	4.05E-003	4.16E-006	3.38E-003	2.16E-006	2.43E-003	2.41E-006
Shutter 2	4.40E-003	2.29E-006	3.68E-003	1.37E-006	2.68E-003	3.11E-005
Shutter 3	4.37E-003	2.29E-006	3.69E-003	1.81E-006	2.70E-003	2.93E-006
Average	4.27E-003	2.91E-006	3.58E-003	1.78E-006	2.61E-003	1.21E-005

Table 2: Shutter Rise/Fall and Latency Data

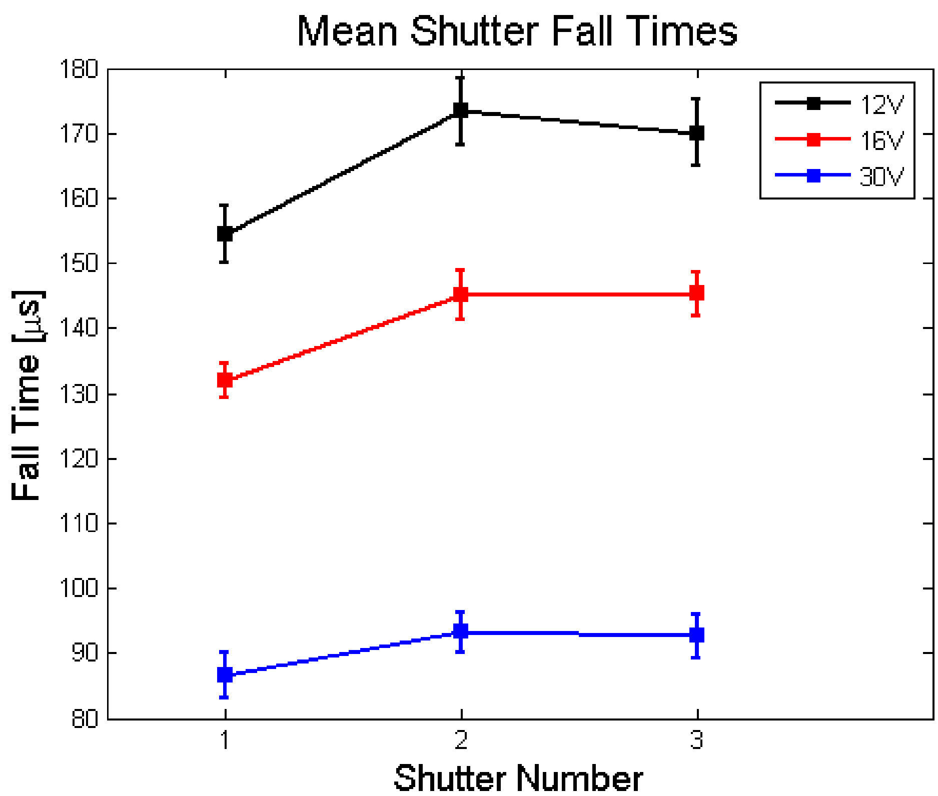


Figure 12: Mean Shutter Fall Times

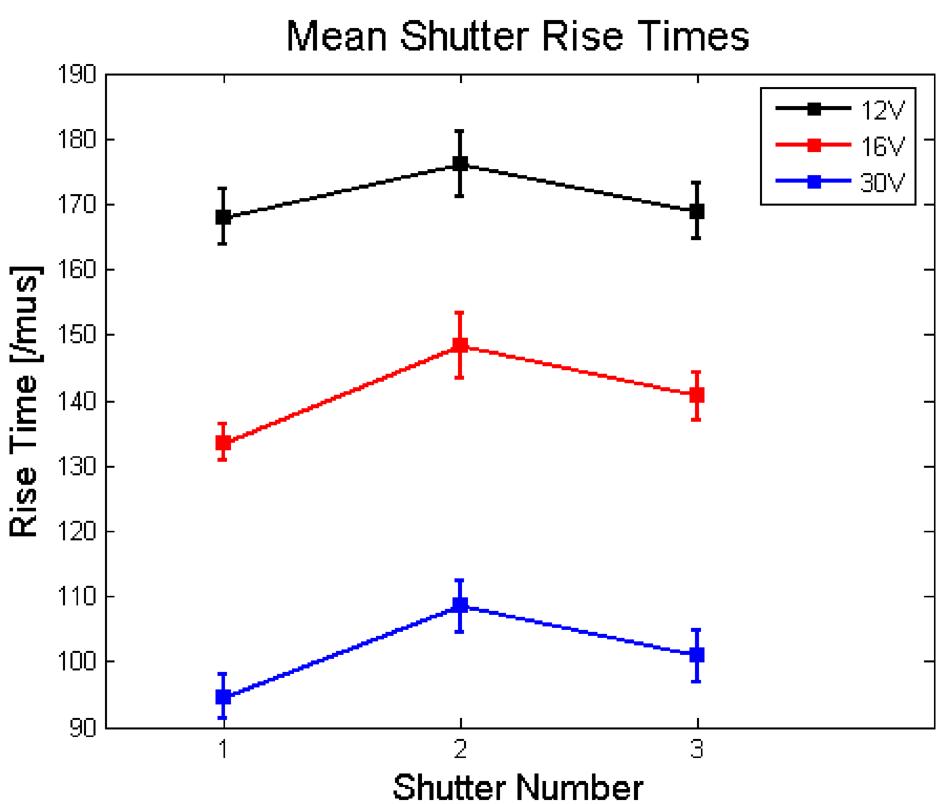


Figure 13: Mean Shutter Rise Times

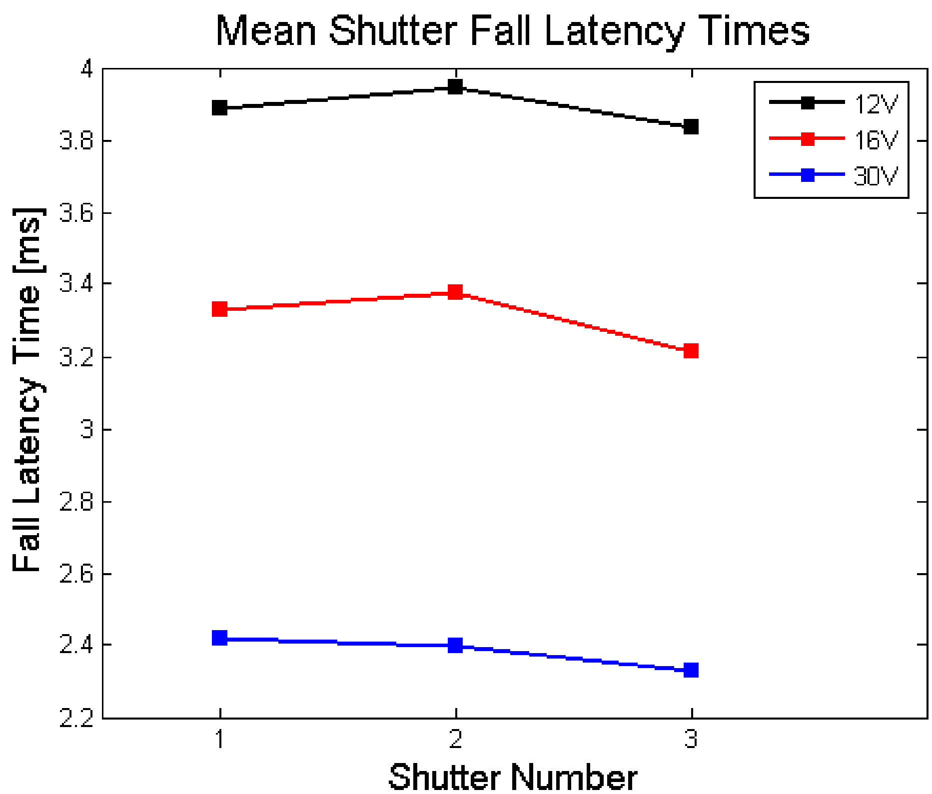


Figure 14: Mean Shutter Fall Latency Times

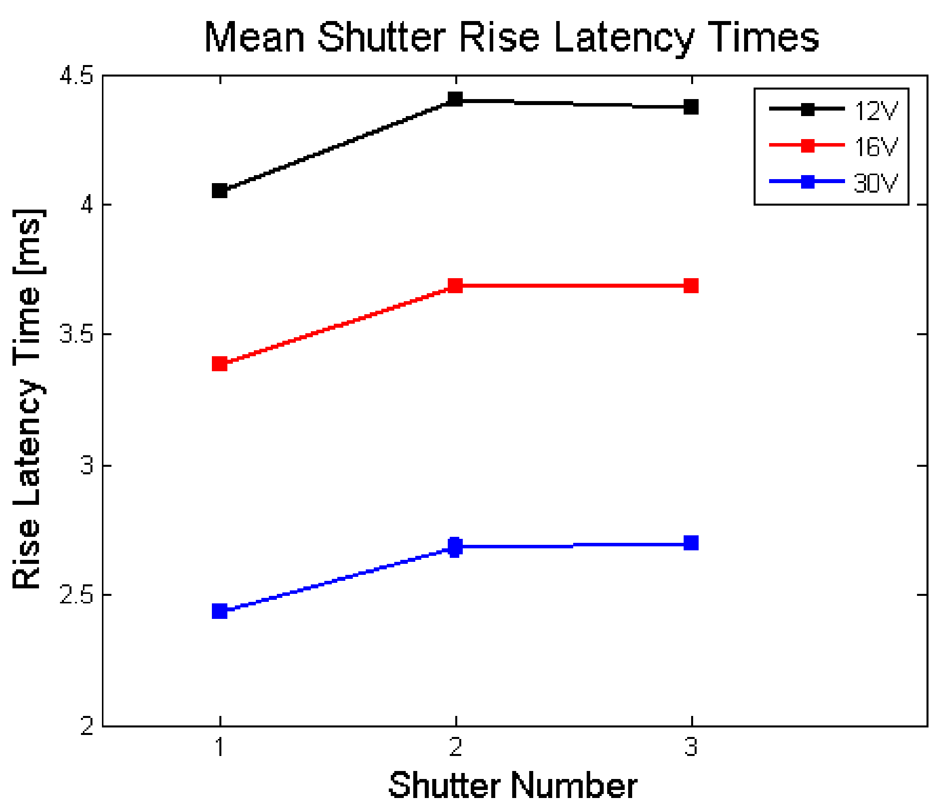


Figure 15: Mean Shutter Rise Latency Times

The following conclusions can be drawn by looking at the fall and rise time data in Figures 12 and 13:

- As the voltage increases the fall and rise times decrease.
- Although 16V is only 22% of the way between 12V and 30V, the average fall time for all of the shutters is 33% of the way between 12V and 30V, while the average rise time is 43% of the way. This seems to indicate that the rate of improvement in fall and rise times decreases as the voltage increases.
- Between the whole range of shutter voltages, from 12V to 30V, the average fall time decreases by a factor of 1.83 and the average rise time by a factor of 1.69, indicating that a gain in performance of almost a factor of 2 can be achieved.
- The average standard deviations for both 16V and 30V and for both fall and rise times, are almost equivalent, whereas those for 12V are about 35% higher. This seems to indicate that initially, increasing the voltage improves the repeatability of the fall and rise times, but that after about 16V these improvements no longer occur.
- The three units have comparable standard deviations for a given voltage, but have slightly different means. This seems to indicate that while the standard deviation can be reliably believed to be within a certain bound between all of the units, each unit needs to be tested individually for its mean if the mean differences exhibited here are deemed too large to be taken as equal and equivalent to their average.

The following conclusions can be drawn by looking at the fall and rise latency time data in Figures 14 and 15:

- Compared to the mean lengths of both the fall and rise latency times, which are on the order of milliseconds, the standard deviation, or jitter, is negligible as it is on the order of microseconds.
- Although it cannot be seen on the graphs, Table 2 indicates that there can be a fair degree of variability between the units' latency times, with slightly more variability in the fall latency time than the rise latency time. If this variability is deemed too large, then each unit will need to be tested individually for its standard deviation.
- The three units have slightly different means. If the mean differences exhibited here are deemed

too large to be taken as equal and equivalent to their average, each unit needs to be tested individually for its mean.

- The rise latency time for shutter 2 at 30V exhibited a standard deviation that was an order of magnitude higher than the standard deviations for all of the other latency time measurements. Figure 16 is a graph of the data taken for this case, and shows a result that was also seen in other measurements of latency times, but not to such a great extent. One explanation for this phenomenon is that as the shutter heats up it latency jitter decays toward zero, but is initially quite large. This may indicate that the shutters may need a 'warm-up' period if a sequence of measurements with a very accurate latency time are required.

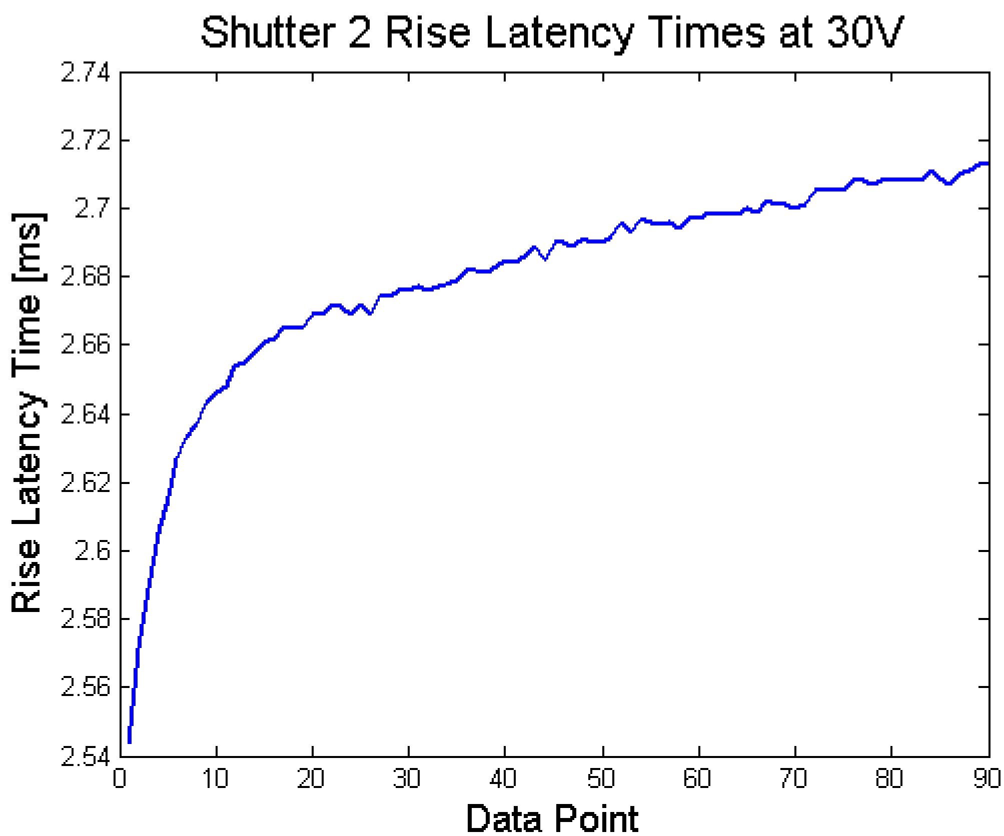


Figure 16: Shutter 2 Rise Latency Times at 30V

3. Milestones and Scheduling

It is the authors' opinion that given this report and access to a machine shop, a competent student or hobbyist could construct a shuttering system consisting of a control panel, eight driver circuits, and eight shutters with a total of about 40 hours labor. The breakdown for this estimate is as follows:

Task	**Time (hrs)**
Machine 8 Mounting Posts	8
Machine 8 Mounting Brackets	2
Disassemble 8 iPods	1
Cut and Drill 8 iPods	2
Populate 8 circuits	8
Wire connections	3
Machine Front Panel	5
Cut and Glue shutter flags	1
Assembly and testing	5
Misc/Contingency	5
TOTAL	**40**

The following milestones represent significant events in the life of this project, and summarize our progress throughout the term. Due to the tremendous waiting period to receive the iPod shipment, these milestones are not necessarily consistent with those written in the project proposal, which are also shown below as a reference.

De Facto Milestones	Date
Ordered iPod hard drives	September 21st
Two tested and characterized large format prototype units	October 28th
Two optimized large format prototype units (arbitrary waveforms developed)	November 8th
Decision not to fabricate more units until iPods arrive	November 22nd
iPod Hard Drives arrived	December 1st
First iShutter constructed	December 1st
Decision to remove circuit from shutter and make centralized control panel	December 7th
Full system ready for testing, with three iShutters	January 10th

Table 3: Project Milestones

Proposed Milestones	Date	Percent
Two tested and characterized prototype units	October 16, 2007	30%
Two optimized prototype units	October 28, 2007	20%
Two fabricated and tested production units	November 4, 2007	20%
Production units completed	November 18, 2007	30%

Table 4: Proposed Milestones

4. Technical Resources and Budget

The shutters have required very little resources outside what the QDG lab and the laboratory of Femtosecond Optics have to offer. All labor has been performed in-house, within the two labs themselves and the student machine shop. Disassembly and modifications of the hard drives occurred in the machine shop, whereas all the electrical and testing working occurred in the QDG lab.

Although two prototype driver circuits were etched using the photo-lithography station in the QDG lab, the twenty circuits for the deliverable product were sent to the PCB service "www.barebonespcb.com" for manufacturing. This company manufactured great quality inexpensive circuits; in much less time than if the authors had etched twenty copies themselves.

The following is a list of resources used within the QDG lab throughout manufacturing and testing:

- Oscilloscope (Tektronics TDS3054)
- Dielectric Mirrors
- Plano-convex lens
- Razor blade and translation stage for beam profiling
- High speed photodiode
- BNC cables
- Arbitrary waveform generator (Stanford Research System DS345)
- Optical table
- Single mode, clean spatial profile laser beam at 780 nm
- Linear DC power supply, used between 12-30 V for testing
- Soldering iron, solder, wire leads, pliers, cutters, strippers, Digital Multimeter
- Data acquisition software written in LABVIEW
- Blue Chip Coffee and cookies

5. Conclusions

The initial attractiveness of the Ultrafast Mechanical Shutter project resided in the innovation of uniquely modifying a commercial device to be used for a completely different purpose than its design originally intended. That it has been shown to out-perform custom designed products in a well-studied market is truly incredible, and perhaps speaks of further uses and/or improvements of hard disk drives for other applications. The open-ended aspect of the project has been explored by transforming the single shutter concept into a comprehensive optical shuttering system, along with other improvements in performance.

The project authors have taken away valuable experience in engineering and project management, and generated a deliverable that has value for the project sponsors. Considerable enjoyment and satisfaction has been derived from the work and completion of the iShutter system, and in that sense the success of the project is twofold.

The authors have demonstrated the iShutter system's performance to well exceed that of most commercial solutions within a factor of ten in cost:

- At 16V supply voltage, the iShutter shows a mean rise/fall time of 141 us
- At all voltages, the average jitter in latency time is less than 8 us
- Total unit cost is $55
- Highly expandable to include more units

These characteristics speak for themselves in terms of value to the sponsor, and the overall success of the project.

6. Recommendations

1. The fabrication of the remaining shutters requires the following tasks to be completed:

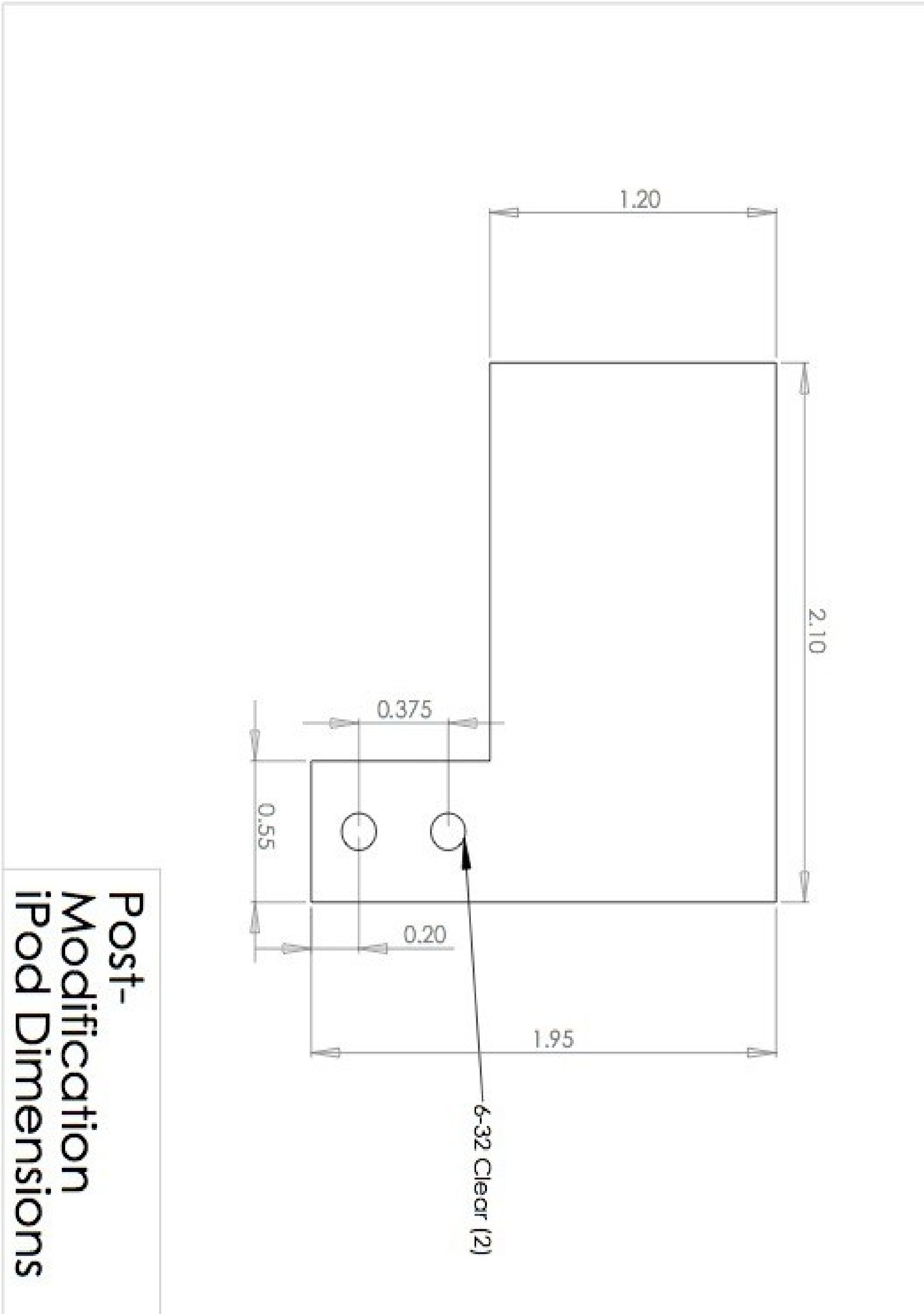
    - Obtain up to six more iPod hard drives
    - Machine the remaining mounting posts and brackets
    - Solder BNC connectors to the iPod pinouts
    - Assemble the shutters
    - Characterize the shutters

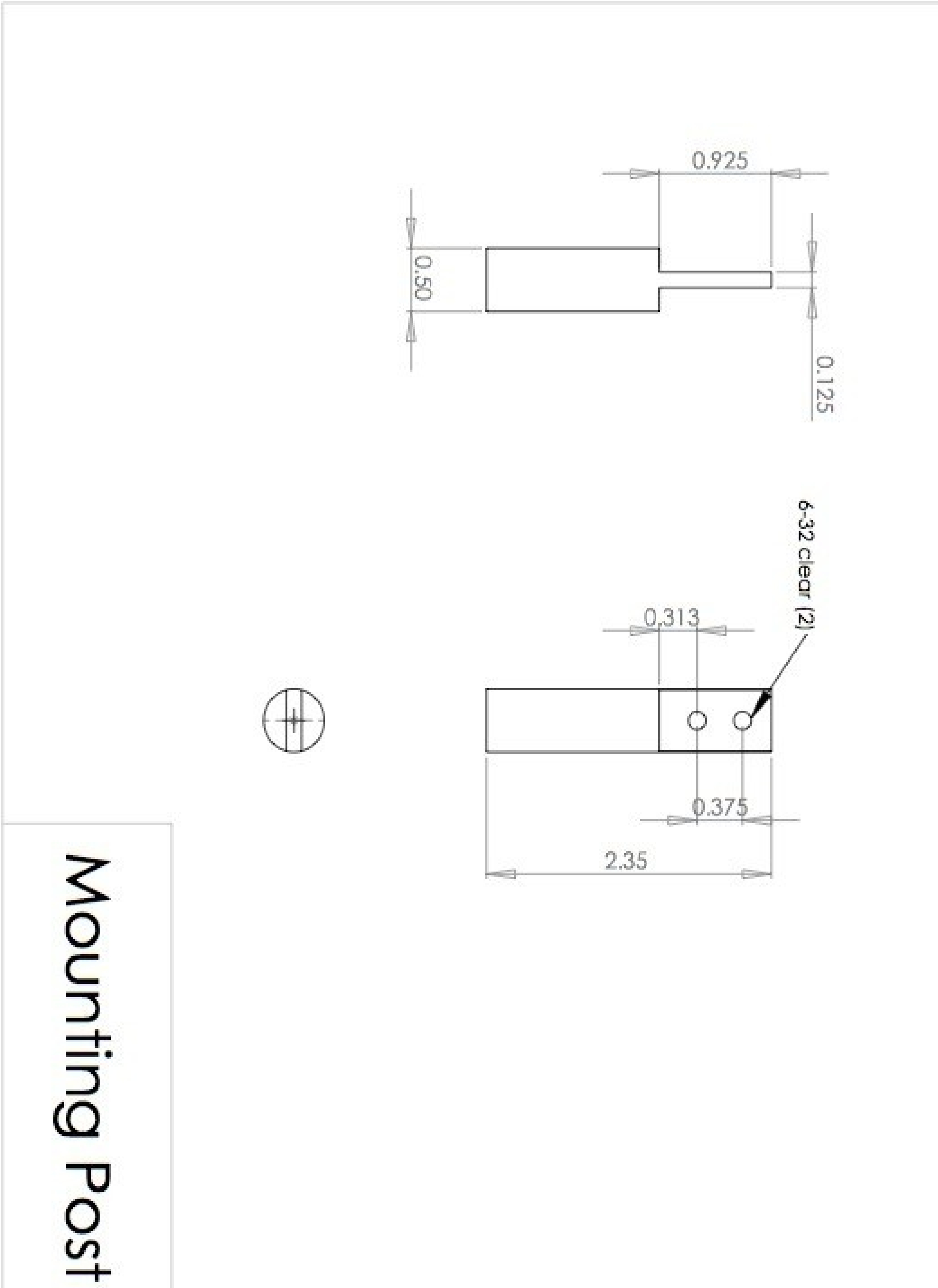
    The authors will more than likely take up this task in the near future, in conjunction with the sponsors, and perhaps the UBC physics machine shop. All required drawings are listed in Appendix A of this document.

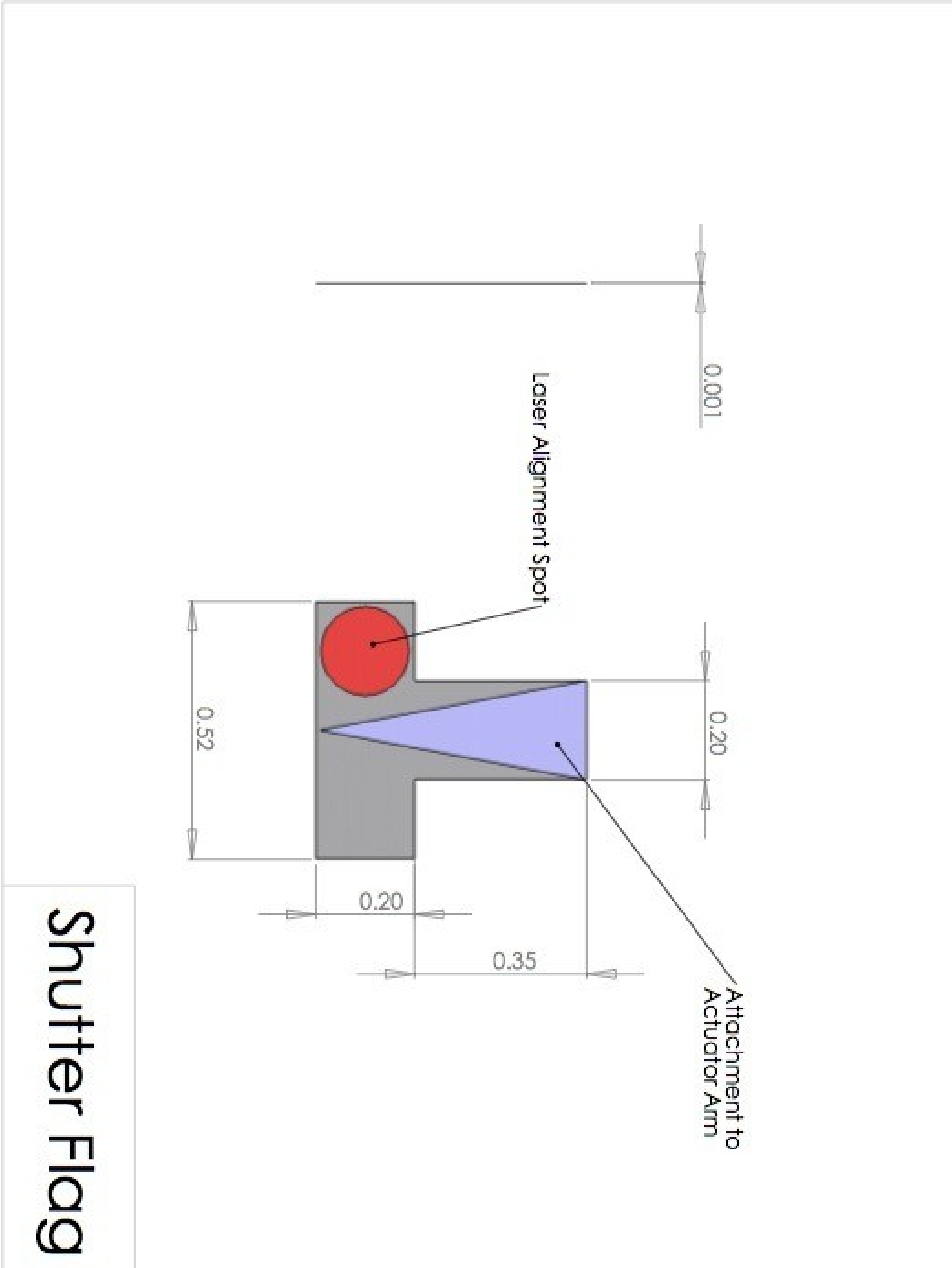
2. Install an appropriate power supply into the two control boxes. This supply would optimally run at 16V, coinciding with the most optimal value tested by the authors. If a voltage other than 16V is desired, the user must calibrate the shutter latency times, as outlined in section 2.4. The supply should either be unregulated, or support a large maximum current (up to 48A)as a contingency for the case where all shutters are in use simultaneously.

3. All tests were conducted on a non-focused laser beam about 0.3mm wide. In order to compare directly with the U of Melbourne's results as well as to demonstrate Ultrafast fall times, it would be necessary to focus the beam down to a width on the order of one micron. Such a test will require two accurate translation stages and two conjugate microscope objectives, in addition to the testing equipment already in use by the authors. This test was not performed primarily due to time constraints.

Appendix A – Mechanical Drawings




0.925
0.50
0.125
6-32 clear (2)
0.313
0.375
2.35
Mounting Post


0.001
0.20
Attachment to
Actuator Arm
Laser Alignment Spot
0.35
0.20
0.52
Shutter Flag

Appendix B – Electrical Schematics and Layout

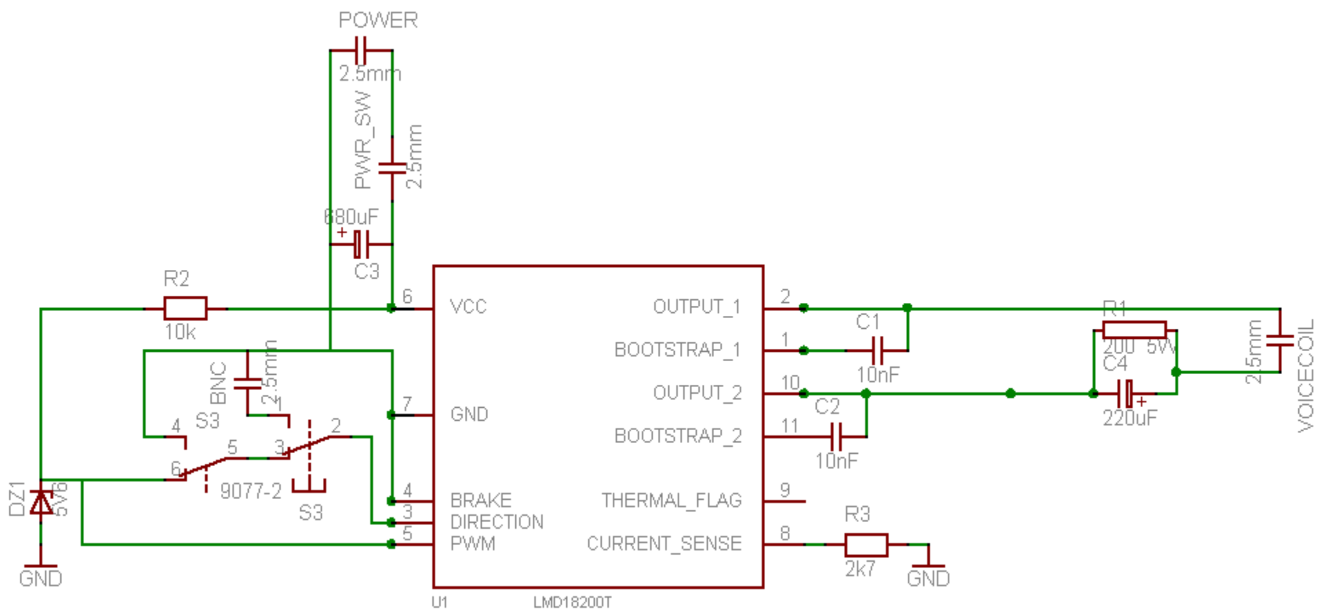


Figure 17: Schematic of the Current Driver Circuit, produce in Eagle Layout Editor

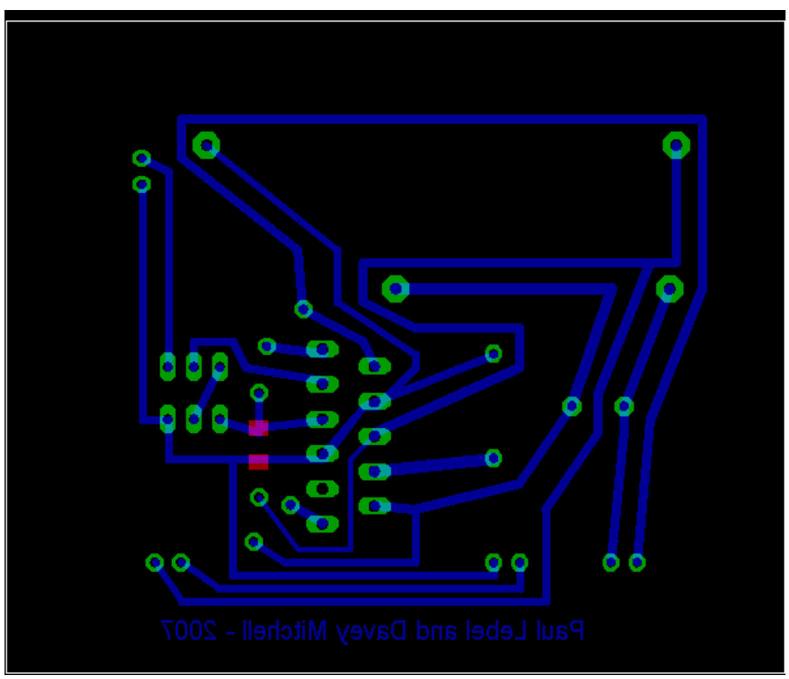


Figure 18: PCB Layout for Production Units, produced in Eagle Layout Editor. To ensure accurate scaling, please inquire the authors for a copy of the technical file.

Appendix C – Optimized Arbitrary Waveforms

A sample optimized arbitrary waveform is shown in Figure 19. The initial rising edge causes charge stored in the circuit's 200μF to dissipate through the shutter's voice coil, causing the shutter arm to actuate. When the shutter flag has completely occluded the laser beam the first falling edge drives the shutter arm in reverse, slowing it down. Finally, once the shutter arm has hit its physical stop, it is again driven forward by the second rising edge, causing it to remain at its physical stop until new information is received. This sequence is then reversed to actuate the shutter arm in the opposite direction.

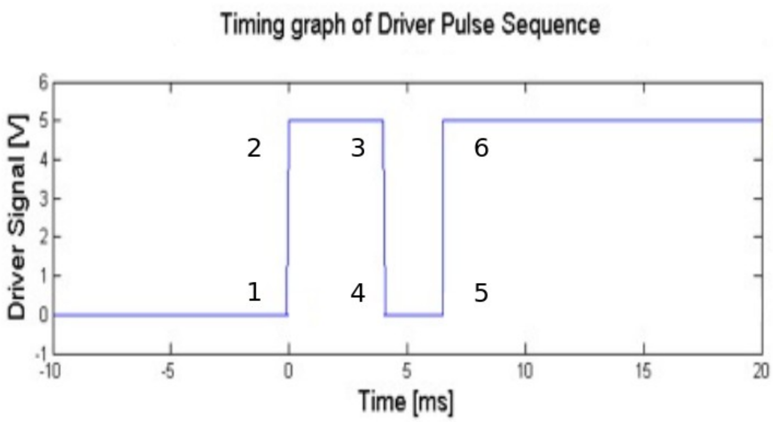


Figure 19: Timing Graph of Optimized Arbitrary Waveform

To generate these waveforms the authors used a SRS DS345 function generator. This generator allows the specification of a series of (x,y), or (time,voltage), pairs, which it then connects with straight lines. Pulse sequences were calibrated for each tested supply voltage. Table 5 displays these sequences in vector format, with each row corresponding to the time and voltage of a vertex in the sequence.

		12V	16V	30V	All Voltages
Drive Direction	**Vector Index**	**x(1µs/div)**	**x(1µs/div)**	**x(1µs/div)**	**y(3.6mV/div)**
	0	0	0	0	0
Up (enable beam propagation)	**1**	8000	8000	8000	0
	2	8001	8001	8001	1400
	3	8045	8038	8025	1400
	4	8046	8039	8026	0
	5	8080	8080	8054	0
	6	8081	8081	8055	1400
Down (disable beam propagation)	**7**	16000	16000	16000	1400
	8	16001	16001	16001	0
	9	16039	16032	16025	0
	10	16040	16033	16026	1400
	11	16080	16080	16054	1400
	12	16081	16081	16055	0

Table 5: Arbitrary Waveform Vector Indexes

Appendix D – Component Cost Analysis

Part Description	Supplier	Part Number	Unit Cost ($US)	Units per Shutter	Total Cost ($US)	Notes
			Note: Prices w/o volume discount			
CONN JACK BNC R/A 50 OHM PCB AU	Digi-Key	A24494-ND	$1.96	1	$1.96	Colour: Black
CONN JACK BNC VERT 50 OHM PCB AU	Digi-Key	A32262-ND	$2.32	2	$4.64	Colour: White
DIODE ZENER 1.3W 5.6V SOD80C	Digi-Key	568-3797-1-ND	$0.17	1	$0.17	
RESISTOR WIREWOUND 200 OHM 5W	Digi-Key	25J200-ND	$1.14	1	$1.14	
CAP ELECT 200UF 50V SU BI-POLAR	Digi-Key	P1285-ND	$1.11	1	$1.11	
CAP 100V 680UF ELECT AXIAL	Digi-Key	4101PHBK-ND	$3.33	1	$3.33	
CAP .01UF 50V CERAMIC MONO 5%	Digi-Key	P4948-ND	$0.72	2	$1.44	
RESISTOR 2.7K OHM .25W CARB COMP	Digi-Key	OD272JE-ND	$0.42	1	$0.42	
RESISTOR 10K OHM .25W CARB COMP	Digi-Key	OD103JE-ND	$0.42	1	$0.42	
CONN HOUSING 2POS .100 W/LATCH	Digi-Key	50-57-9402	$0.44	2	$0.88	
CONN HEADER 2POS .100 VERT GOLD	Digi-Key	WM4800-ND	$1.06	2	$2.12	
IC H BRIDGE 3A 55V TO-220	Digi-Key	LMD18200T-ND	$14.14	1	$14.14	Ordered free samples from National Semiconductor
LOCKWASHER	Digi-Key	A1129-ND	$0.28	3	$0.84	
HEX NUT	Digi-Key	A1128-ND	$0.30	3	$0.90	
SWITCH TOGGLE SP3T .4VA SLDR 5PC	Digi-Key	360-1856-ND	$8.23	1	$8.23	
SWITCH TOGGLE SPST SEAL SLDR LUG	Digi-Key	CKN1549-ND	$6.98	1	$6.98	
CONN SOCKET 20-24AWG 30AU CRIMP	Digi-Key	A25984-ND	$0.40	4	$1.60	
Barebones PCB Circuit Board 3"x2.5"	Advanced Circuits		$5.48	1	$5.48	This was unit price of 20 boards. One board = $45.38
iPod HD	Ebay		$2.00	1	$2.00	
Total					**$57.80**	

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