



LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Ultra-fast Optical Shutter Design

Peter Fritschel, Rich Abbott

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California Institute of Technology
Massachusetts Institute of Technology
LIGO Hanford Observatory
LIGO Livingston Observatory

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1 Introduction

The Fast Shutter is designed to protect the photodiodes at the anti-symmetric (AS) port of the LIGO interferometer from being damaged by the optical pulse that occurs upon loss-of-lock. At full power operation, this pulse can contain 45 J of energy, in a pulse width of 5 msec, FWHM. The Fast Shutter is an electro-magnetically actuated mechanical beam block/reflector. It is located in HAM6, mounted between the second and third output beam steering mirrors (OM2 and OM3). The shutter protects all AS port photodiodes except for the diode (ASC_AS_C) used as the trigger for the shutter; this diode is protected simply by sufficiently attenuating the beam it receives. The shutter, when closed, reflects the optical pulse into a special beam dump (which is also thus part of the Fast Shutter system). The Fast Shutter is also known as the TOASTR: Turbo Optical Anti-Symmetric Transient Rejector. A collector point for all the documentation associated with the Fast Shutter system is available at [LIGO-E1400177](#).

2 Shutter requirements

The TOASTR is required to protect the photodiodes at the anti-symmetric port from damage. Experimental studies of damage to InGaAs diodes from optical pulses are reported in [LIGO-T1100208](#). From this work we conclude: for diode exposure to thousands of identical optical pulses, the maximum safe single-pulse energy, for a beam diameter of 1 mm, is 50 mJ.

Shutter speed. Simulations of the lock loss transient (time domain) are reported in [LIGO-G1000489](#) and [LIGO-T1000294](#). The conclusions reached there, consistent with the preceding damage limit, are that the shutter needs to be:

- 90% closed within 1 msec of being triggered
- 99.9% closed within 2 msec of being triggered

Shutter aperture. In the ‘open’ state, during low-noise operation of the interferometer, the shutter must be sufficiently clear of the beam to avoid any noise from beam clipping. From previous experience, to avoid beam clipping noise any aperture should be 10 or more times the beam size ($1/e^2$ intensity). Thus in the ‘open’ state, the shutter’s reflector must be at least 10 beam radii away from the beam center.

Shutter lifetime. The shutter should have a minimum lifetime of 10,000 cycles. This corresponds to being used (triggered) 5 times a day for 5 ½ years (in reality we might expect a higher rate of triggering in the first year or two, and a lower rate later on, during science runs).

3 Linear motor basics

The TOASTR is made using a linear electro-magnetic motor, energized with a high current pulse to drive the movable coil upwards into the beam path. Here we describe the basic physics of the concept using Figure 1.

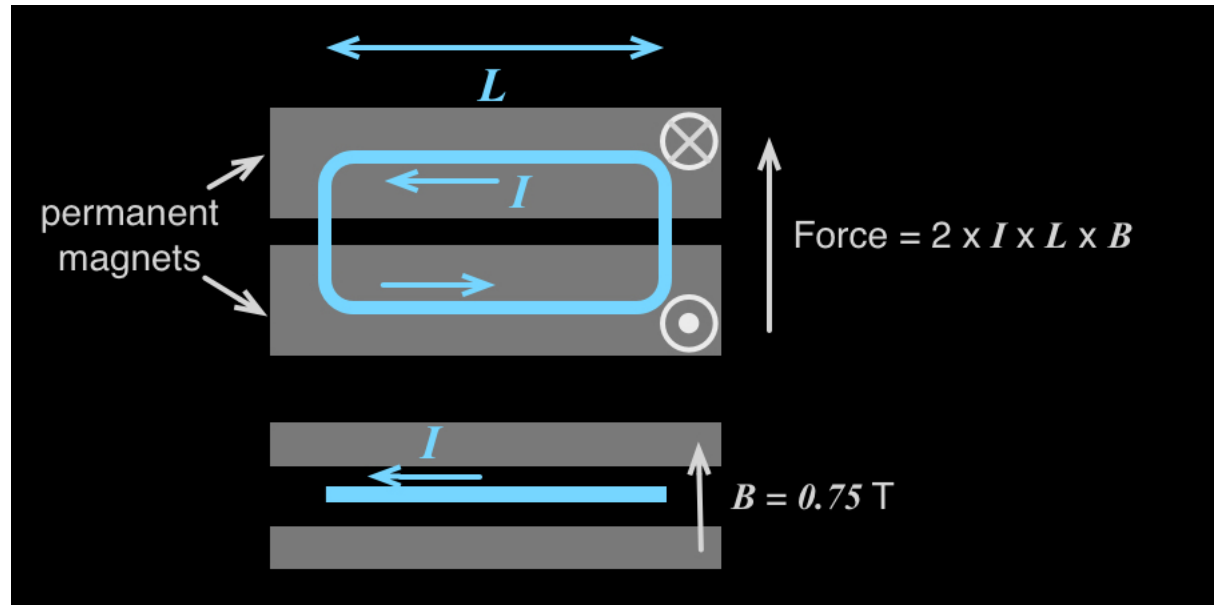


Figure 1. Conceptual sketch of the linear motor design for the fast shutter. The multi-turn coil is represented by the thick blue line. At the top is a side view of the motor, with a top view shown at the bottom. There are 4 rectangular permanent magnets, arranged as shown. The coil would be wrapped on a bobbin (not shown), and free to move up and down in the gap between the two sets of magnets (i.e., along the direction indicated by the white arrow labeled ‘Force’). The position of the coil as shown is before any current is applied (i.e., shutter open).

Before the shutter is triggered (in the **open** state), the movable coil straddles the upper and lower pairs of magnets. At the instant the current pulse is first applied, both horizontal sections of the coil thus experience a force in the same direction; the polarity of the pulse is such that this force is upwards. As long as the coil straddles the upper and lower magnets, the force is:

$$F(t) = 2 \cdot I(t) \cdot L \cdot B,$$

where L is the coil length, and $I(t)$ is the total current through the coil cross section (i.e., current times number of turns).

Under the simplified assumption that the force is constant over the travel, the coil has a constant acceleration, a ; the acceleration required to travel 6 mm (the nominal distance from shutter to beam) in 1 msec is $a \geq 1.2 \times 10^4 \text{ m/sec}^2$. For a total coil assembly mass of 20 gm, a force of 240 N is required. Assuming $L = 5 \text{ cm}$, $B = 0.75 \text{ T}$, and 400 turns on the coil, a current of 8 amps is required. This will turn out to be a bit of an underestimate due to dynamical effects explained later, but this gives the order of magnitude of the parameters.

A novel aspect to the magnetic design is the use of opposing magnetic polarizations between the upper and lower permanent magnets. The effect of this opposing field is to provide a decelerating force that arrests the coil - without mechanical contact - at a predetermined point in its upward travel. This feature obviates the need for a dedicated mechanical stop thus eliminating mechanical damage and reducing the peak acceleration experienced during the arresting phase of operation. A mechanical arresting feature is included to stop the coil in the event of a catastrophic malfunction, but no contact is made to the mechanical stop during normal operation.

4 Linear motor design

The linear motor assembly is shown in Figure 2.

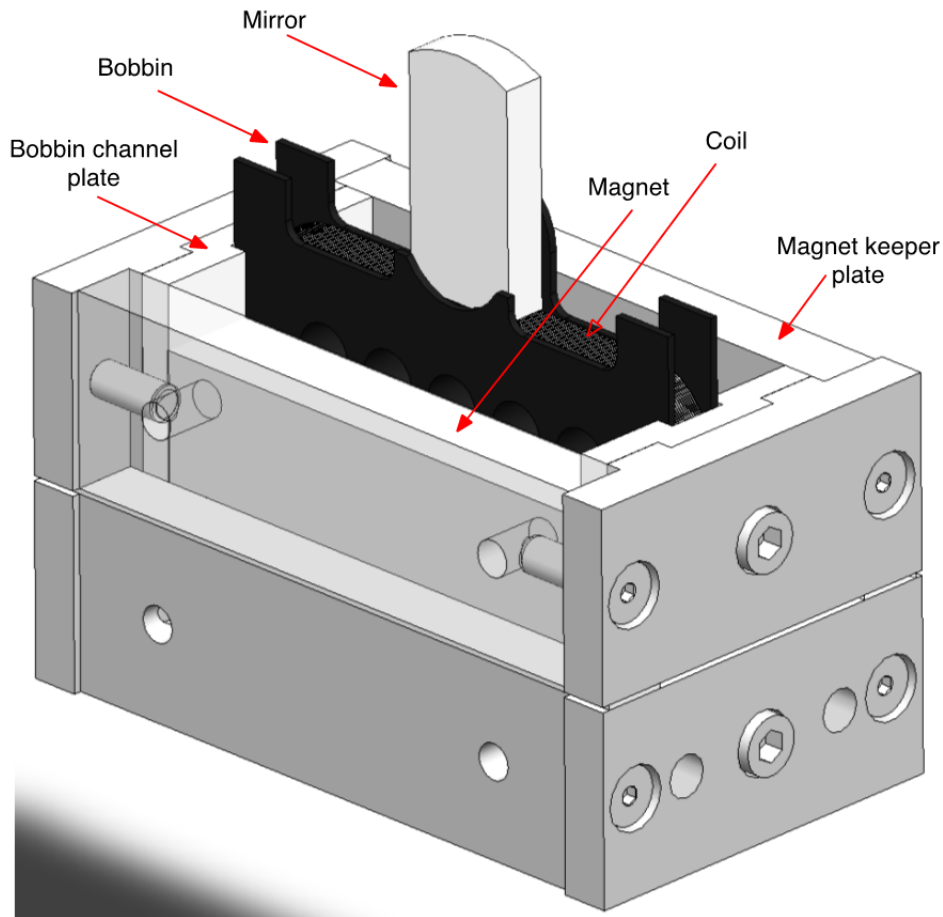


Figure 2. Linear motor assembly for the TOASTR (D1102130). The mirror is an ion-beam sputtered high-reflector (fused silica substrate); the bobbin and bobbin channel plates are of PEEK; magnets are NdFeB; magnet keeper plates are nickel-plated 1018 cold roll steel.

5 Coil assembly design

The coil assembly is shown in Figure 3, and its mass parameters are listed in Table 1.

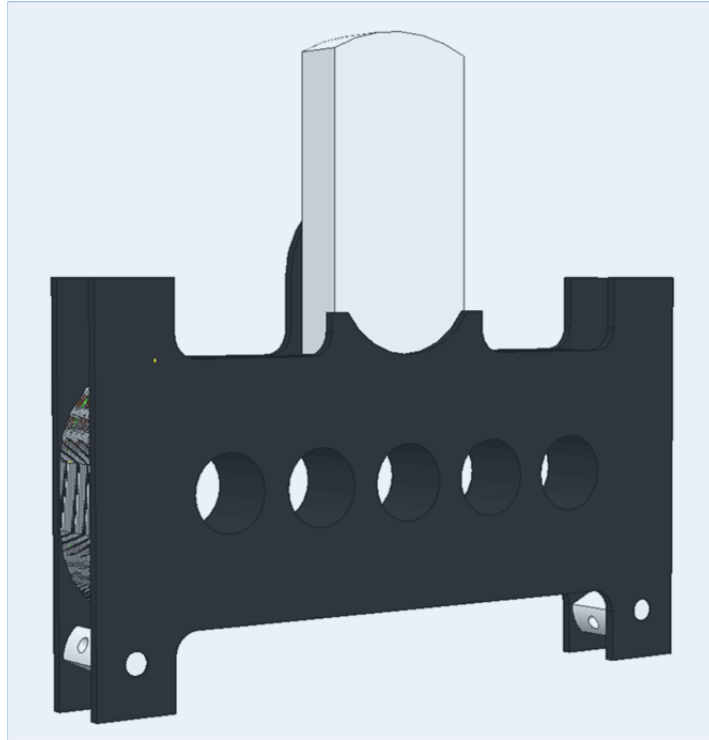


Figure 3. TOASTR coil assembly. The coil form (bobbin) is made of PEEK, and is drilled out in the center to reduce mass. The ends of the bobbin are made wider to provide more stability for travel within the channel plates (not shown). The mirror is made from a 1” diameter off-the-shelf mirror, ground down in thickness for fit, and in width to reduce mass; it is bonded to a tab on the bobbin using EP30-2 epoxy. The coil is wound by Polytech Coil Winding, using 32 awg, polyimide-insulated copper wire. The coil is potted during the winding process, using Epoxy Pax EP 1730-1. The coils have approximately 300 turns.

PEEK bobbin	3.18 gm
Mirror, D1300969	2.58 gm
Copper: 32 awg, 23 ohms	12.25 gm
xx	xx
Total mass, measured	

Table 1. Masses of the fast shutter coil assembly elements.

6 Laser pulse dumping

For a beam radius of 0.5 mm, the lock-loss pulse energy density can be as high as 5000 J/cm². This is well into the regime of laser drilling (melting and vaporization) of materials¹. For alumina ceramic (a high melting point material), Wagner gives a ‘machining threshold’ of about 750 J/cm². Therefore, we decided against the approach of absorbing the laser pulse with some material on the shutter. Instead, our solution is to reflect the pulse with a mirror, and direct it into a dump that is capable of absorbing the pulse energy.

We believe that a high-reflectivity dielectric mirror made using ion-beam sputtering (IBS) will be able to handle the pulse energy, though we’re not aware of any testing in our pulse length regime. IBS coatings are typically sold as having damage thresholds of >40 J/cm² at 1064nm (Precision Photonics or REO, e.g.), but this is for much shorter pulses, 20 nsec. Damage threshold scales as (pulse duration)^{1/2}, but still for short pulses (< 100 nsec). For our 10 msec pulse, we should also look at the CW damage threshold, which is tested to be >17.6 MW/cm² by Precision Photonics, compared to the peak intensity in the lock-loss pulse of about 2 MW/cm². So an IBS coated HR mirror should be able to handle the pulse with no damage.

The reflected laser pulse will be directed to a beam dump: a copper tube, gold-coated to increase the reflectivity and avoid oxidation of the copper; see Figure 4. The local heating of the dump is analyzed as follows. The peak power of the pulse is 8.5 kW (from T1000294). For a beam radius of 0.6 mm, incident at 45 deg, the maximum intensity is: $I_m = 2P_{max}/\sqrt{2}\pi\omega^2 = 1.1 \times 10^{10}$ W/m². The surface temperature of an absorbing material, for a temporally Gaussian laser pulse, is given by Bechtel² as:

$$\Delta T(t) = \frac{I_m(1-R)}{(\kappa\rho c)^{1/2}} \frac{\tau^{1/2}}{2^{1/4}} \eta(t/\tau)$$

where κ, ρ, c and R are the thermal conductivity, density, heat capacity, and reflectivity of the material, respectively; τ is the Gaussian pulse half-width; and η contains the temporal evolution of the temperature, and has a maximum value of 1.5. From T1000294, $\tau = 3$ msec. Using the material properties of copper, the max temperature rise is: $\Delta T = (1-R) \cdot 18,000$ °C. With a gold coating, $R > 98\%$, and $\Delta T < 360$ °C, safely below the melting point of both gold and copper.

¹ R.E. Wagner, *Laser drilling mechanics*, J. Appl. Phys., **45**, 4631 (1974).

² J.H. Bechtel, *Heating of solid targets with laser pulses*, J. Appl. Phys. **45**, 1585 (1975).

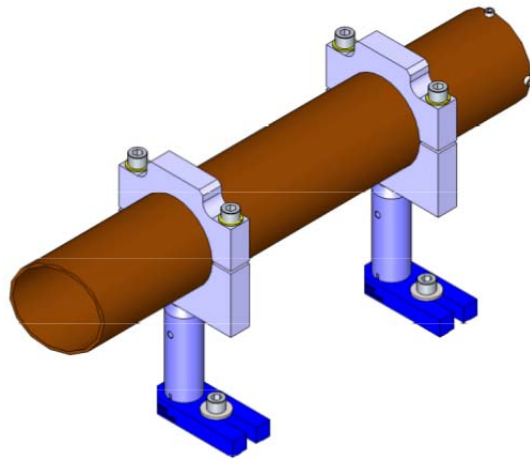


Figure 4. Beam dump for the TOASTR reflected pulse; D1300548. The gold-plated copper tube is 12" long and 2" diameter.

7 Fast Shutter Assembly

The full TOASTR assembly is shown below in Figure 5. For simplicity, we decide not to include any type of sensor in the TOASTR. The interferometer (PSL) laser beam and the trigger detector in HAM6 can be used to diagnose the position and functioning of the shutter (discussed below).

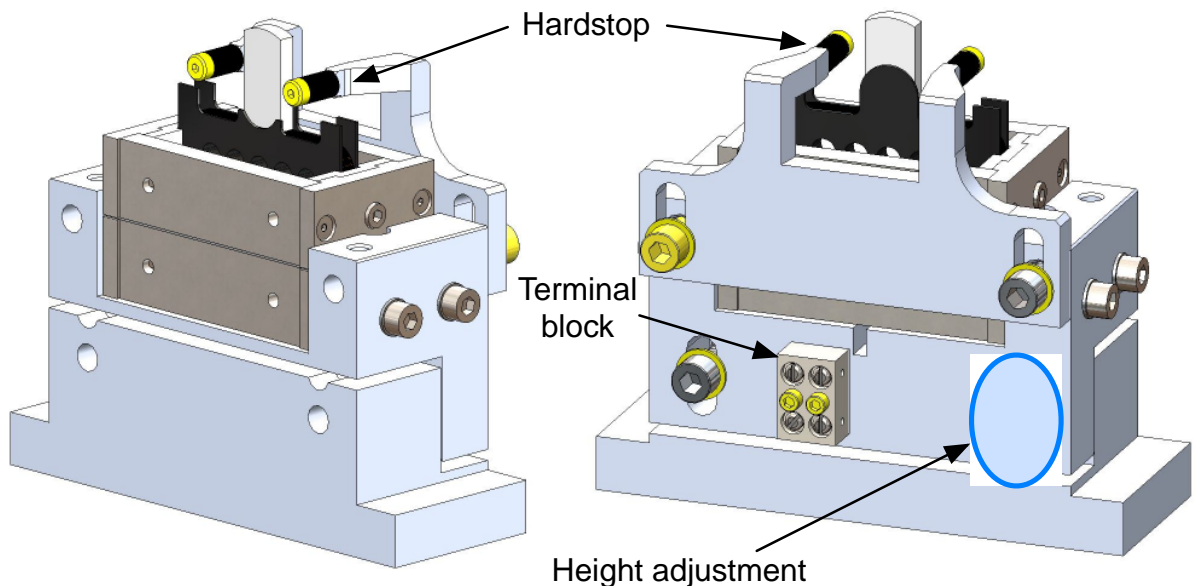


Figure 5. TOASTR assembly (D1003318); left: Front view; right: back view. The coil assembly is shown in the 'up/closed' position. The coil wires (not shown) are connected to the PEEK terminal block; the other side of the terminal block is fed with the drive cable (not shown) coming from the chamber feedthrough. The height of the linear motor assembly is adjustable as shown. The adjustable hard-stop is provided as a

backup mechanism (the black cylinders are Viton tubing); in normal operation, the coil assembly does not contact the hard stop.

8 Performance

8.1 Data taken with the shutter operating at atmospheric pressure

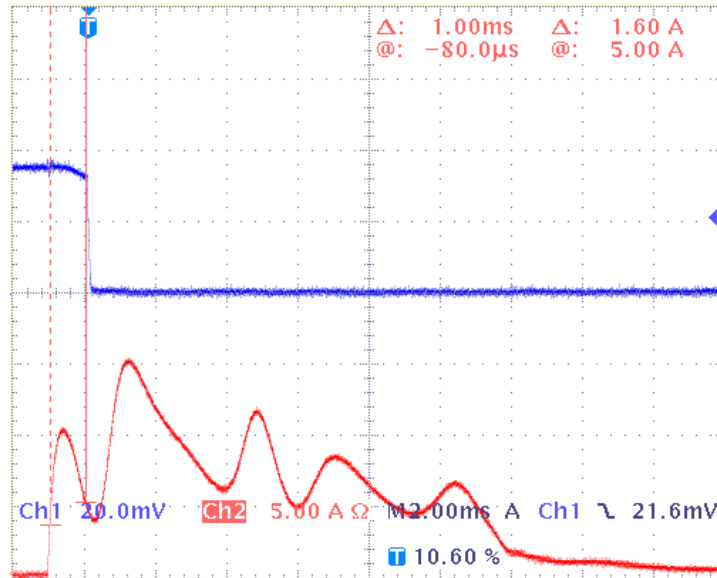


Figure 6 shows optical gate in blue (low being the blocked state) and motor current in red. The motor current essentially maps out the acceleration of the motor windings (bobbin) within the permanent magnetic field. The first peak corresponds to an upwards acceleration transient, the second peak corresponds to a negative acceleration (slowing down) in the opposite polarity magnetic field.

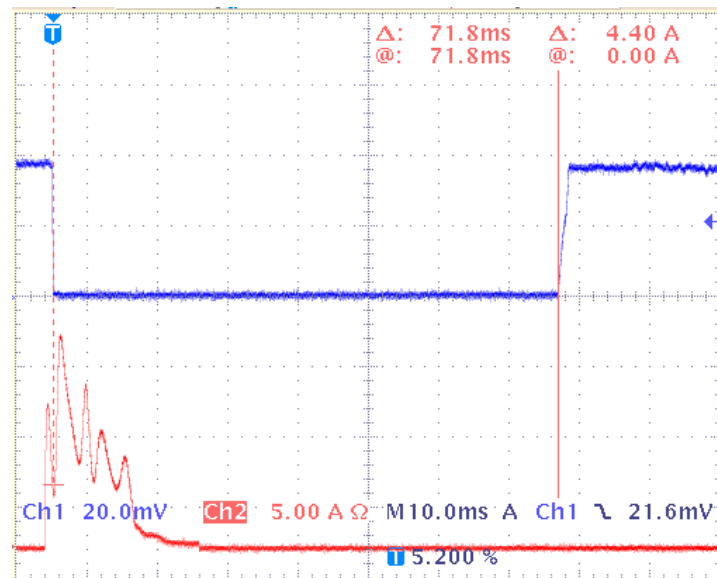


Figure 7 shows that the shutter blocks light (shown in blue with the low state being blocked) indefinitely without mechanically overshooting and permitting light to once again pass.

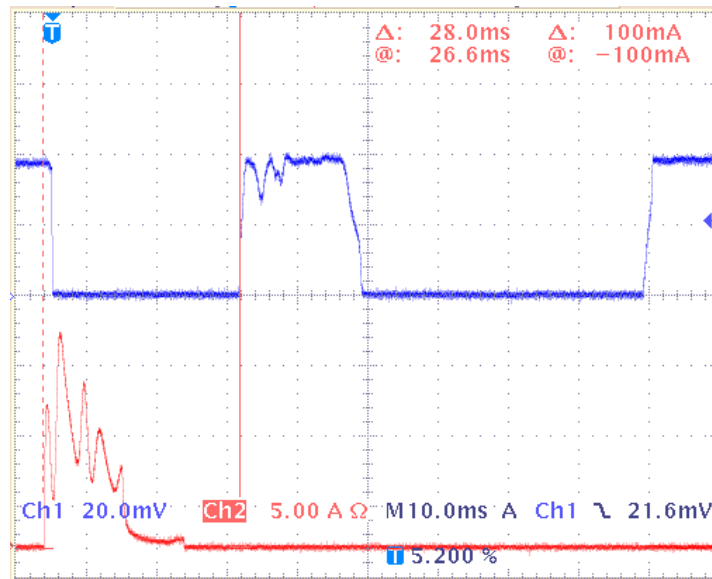


Figure 8. Deliberately shortening the applied pulse shown in red can result in overshoot as the dynamic response of the shutter is changed. Light can be seen once again passing the shutter (blue trace).

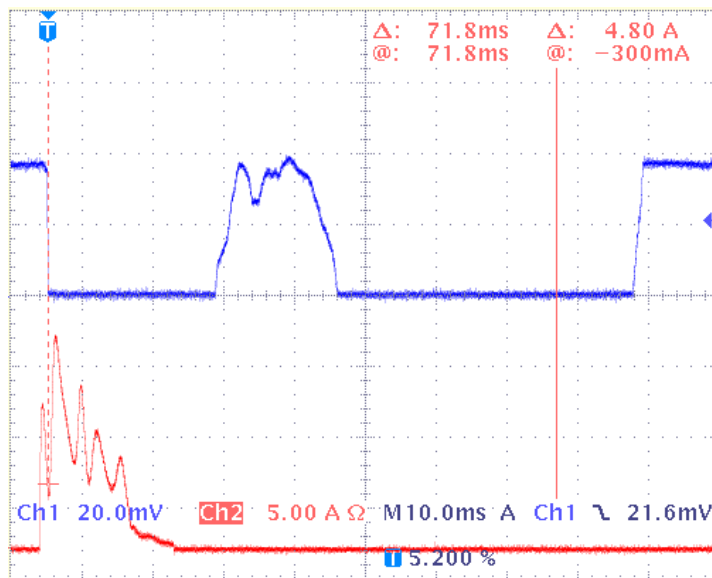


Figure 9, another illustration of the variability of the dynamics by pulse width tailoring as in the previous figure.

8.2 Data taken with the shutter operating at ultra-high vacuum ($<10^{-8}$ Torr)

The measured dynamics of the shutter in the absence of air are considerably different than operation at atmospheric pressure. A surprisingly large amount of viscous damping is provided by the suction effect of the shutter bobbin as it rises out of the slot from a resting position. This effect is akin to pulling a boot out of mud and results in a far more oscillatory dynamic response than was anticipated. Mitigation of this effect is obtained by adding resistive damping (20 ohms) to the

pulse driver circuitry. In addition, a carefully chosen pulse width was crafted to shut off the drive at just the right moment leaving the bobbin in a stable position. As considerable current is flowing at the moment in which the current is shut off, a large (several hundred volts) voltage spike is induced. This spike is clamped by use of a diode clamping circuit. The end result is that effective shuttering can be obtained in the absence of the damping effect of air. The final measured shutter speed in this damped configuration was about 1.9 milliseconds to full closure.

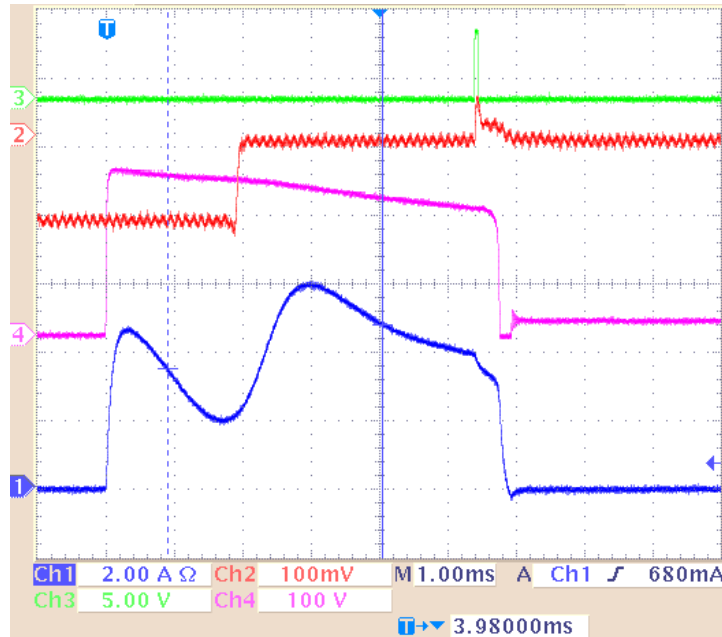


Figure 10 Red trace shows the optical gated signal with the lower state corresponding to the bright condition. The blue trace is the current flowing through the shutter coil. The purple trace shows the applied coil voltage. The green trace is an internal logic signal unrelated to this test. It can be seen that the current pulse is terminated while approximately 4 amperes are flowing through the coil. The negative going inductive kick is effectively clamped, but visible in the purple trace. An anomalous glitch is seen in the optically derived signal (red trace) around the time the pulse is terminated. This anomalous glitch is related to crosstalk in the test setup and is not a real optical feature. Demonstrated shutter time in this test is about 1.9 mSec from the leading edge of the applied blue pulse to the rising edge of the optical gate.

9 Dynamic Tuning

By varying the applied pulse width, operating voltage, source impedance, and total energy storage capacitance internal to the driver electronics, the dynamic behavior of the motor coil can be tailored. The capture transients seen in red in the above figures have an oscillatory nature. The stiffness of the electromechanical spring can be adjusted by changing the applied voltage within the driving pulse. The circuitry that drives the coil has an electrical source impedance that provides some damping to the coil even after termination of the applied pulse. Additional resistive damping can be added to the driver circuit to provide mechanical compensation as needed at the expense of shutter speed. As can be seen by comparison of Figure 7 to Figure 8 and Figure 9, tuning of these

parameters provides a clear region of time (~ 71 msec as shown in Figure 7) during which the shutter effectively remains in the blocked state.

The pulse driver electronics has the ability to provide a low current hold state that can maintain the shutter in the blocked state indefinitely after termination of the fast, high current transient.

10 Signal chain

The TOASTR is a hardware shutter; its signal chain is shown in Figure 11. The detector used for triggering is ASC-AS_C: the quad photodetector (QPD) in HAM6 that receives a sample of the light transmitted by OM1 (first optic in the HAM6 chain). This QPD is connected to a version of the QPD transimpedance amplifier (D1002481) that includes quadrant-sum output channels on the chassis (uses v5 of the amplifier board, D1001974); this sum output is used to generate the trigger signal for the shutter.

The QPD amp sum output is sent into a standard aLIGO Shutter Controller: D1102312; see E1200364 for a description and specifications. The Shutter Controller generates a trigger output when the input signal (QPD sum) reaches a threshold; the threshold level is controlled from the EtherCAT system. The trigger output is sent to the Shutter Driver, which generates the current pulse applied to the TOASTR coil. More details of the Shutter Driver can be found in:

Shutter Driver Requirements

[LIGO-T1300906](#)

Shutter Driver Circuit

[LIGO-D1300780](#)

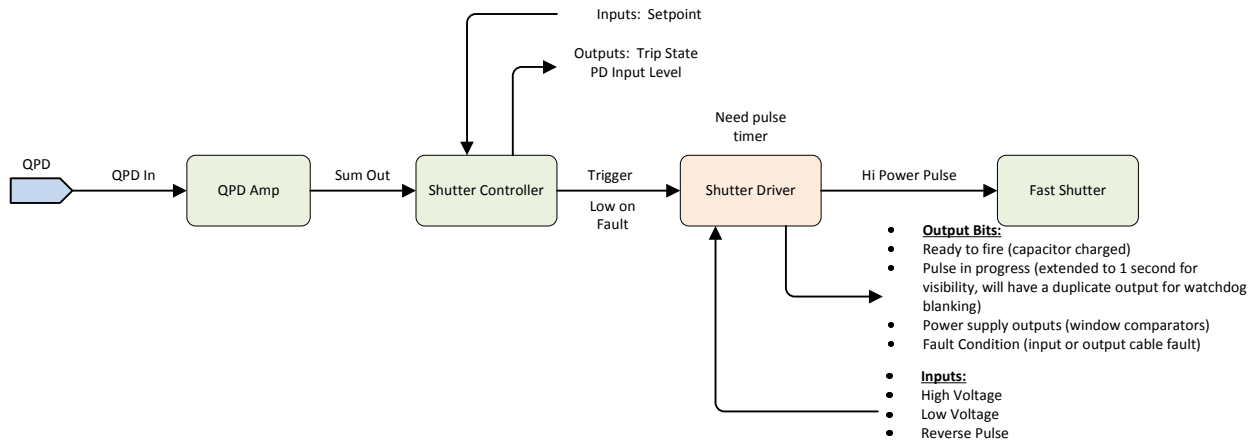
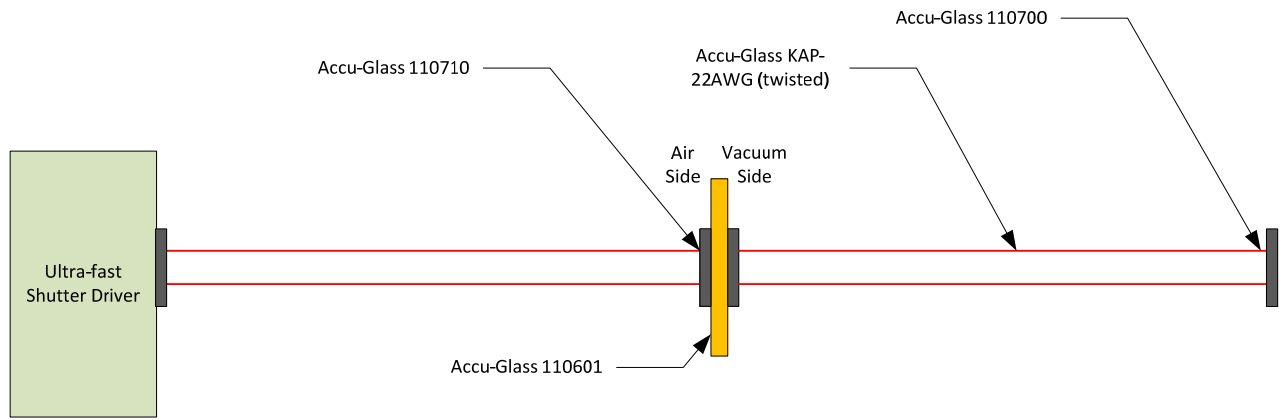


Figure 11. Signal chain for the TOASTR, from E1300819. The Shutter Driver is designed to indicate a fault condition if either its input or output cable is disconnected.

11 Electrical cabling



Accu-Glass 110701



Accu-Glass 110710



Accu-Glass 110601



Accu-Glass 110685



Accu-Glass KAP-22AWG



Accu-Glass 110700