CDS Hardware Update

High Reliability Ultra-Fast Shutter (HRUF)
D2200426-v1
Update 11/22/23

Dean Schaetzl for the CDS group

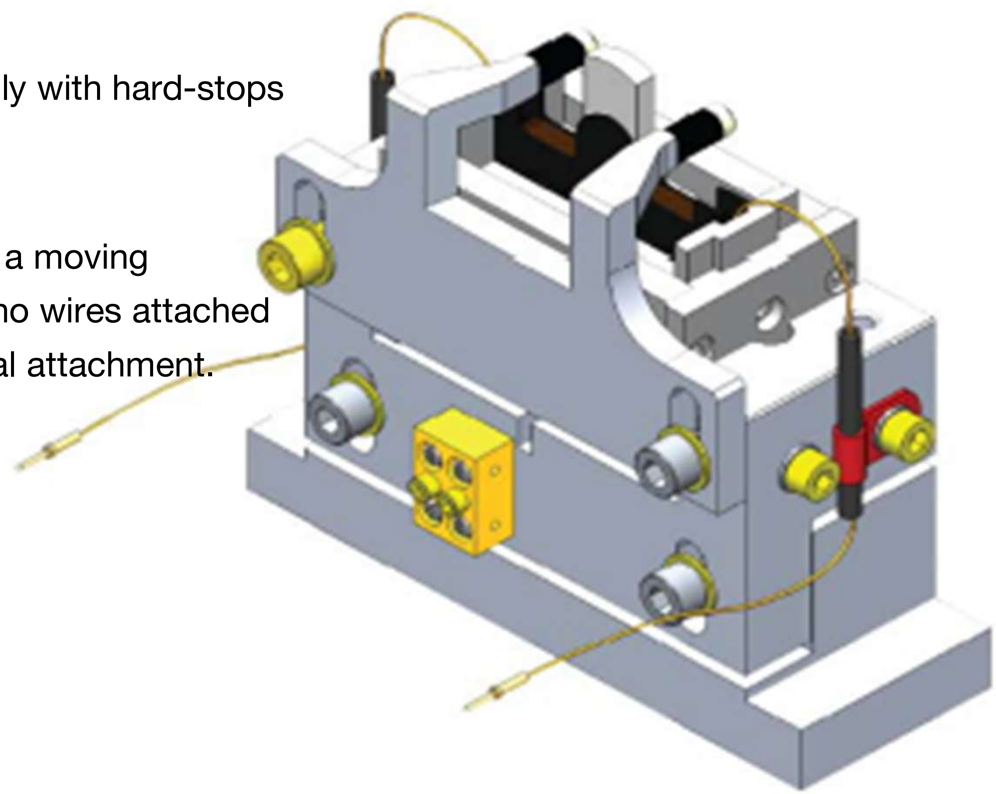
LIGO-G23xxxxx-v1

Fast Shutter Upgrade
High Reliability Ultra Fast (HRUF)

Responsible: D. Schaetzl
Updated: September 25, 2023

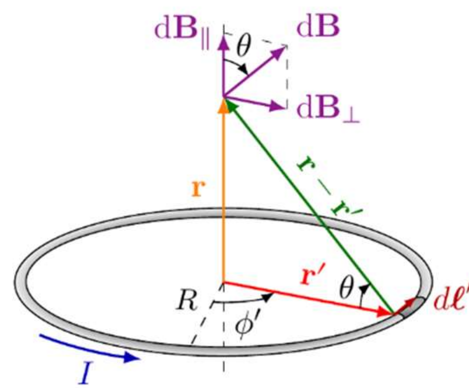
ECR: E1900177 DCC: E1900180

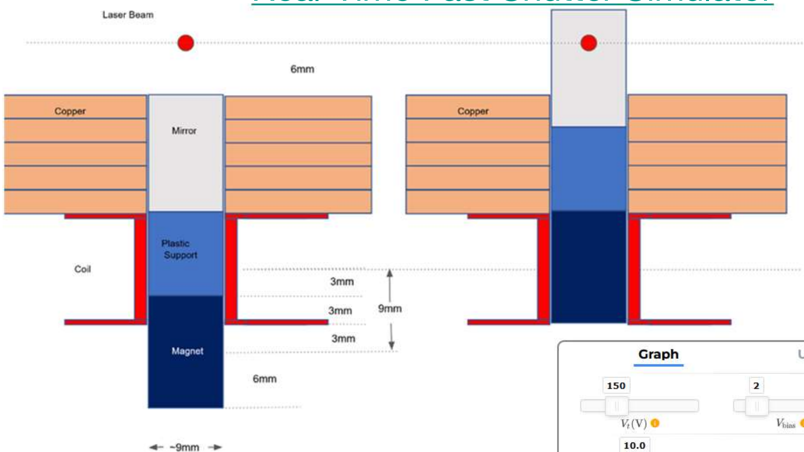
- Why do we have a Fast Shutter?
  - *Optical energy stored in the LIGO arms during normal interferometer (IFO) operation is dumped into the antisymmetric (AS) port upon loss of lock. The stored energy can be of order 50J, which appears at the AS port as an optical transient lasting a few tens of milliseconds. In order to protect sensitive photodetectors in the AS port beampath from damage, a shutter is required to quickly block the laser beam upon a lock-loss event*
- Current Fast Shutter design (D1003318)
  - Wires are attached to the moving parts
    - Work Hardening
  - Arresting of the shutter is done mechanically with hard-stops
    - Stress
    - Debris
    - Physical Shock (Stopping)
- New electro-magnetic ultra-fast shutter design of a moving payload consisting of magnets and a mirror with no wires attached
    - A non-moving coil requiring electrical attachment.
    - Self Arresting



Fast Shutter Upgrade
High Reliability Ultra Fast (HRUF)

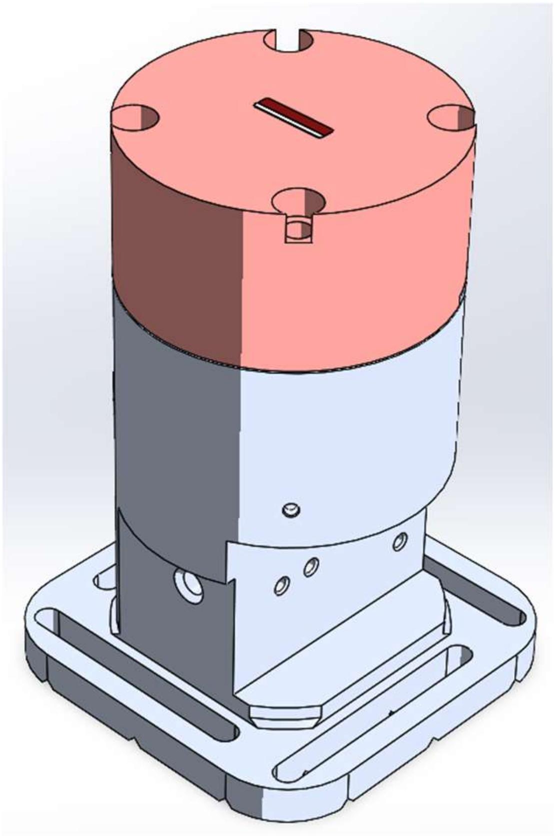
- How do we make it better?
  - We first want to build a mathematical model of the system to understand the parameters we can tune to optimize the behavior. (modeling by *Serkay Ölmez*)
- Real-Time Fast Shutter Simulator

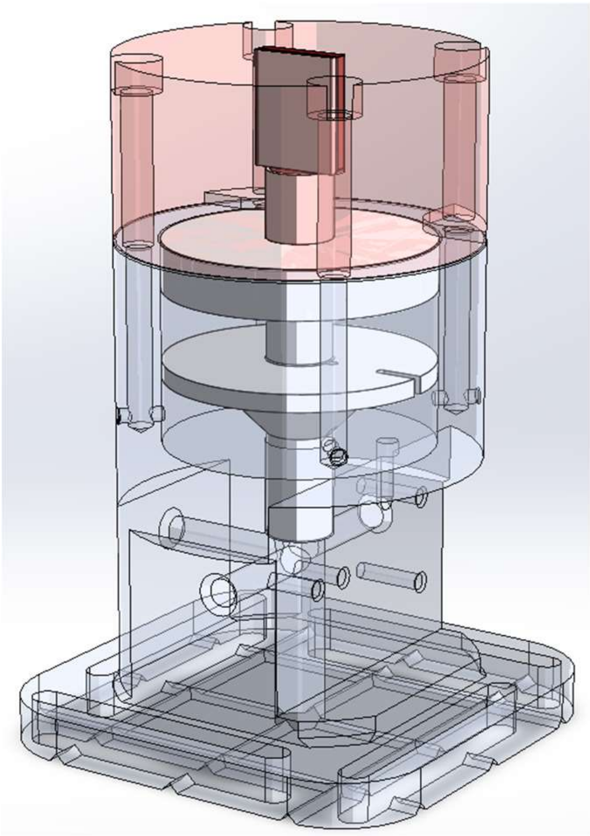




Fast Shutter Upgrade High Reliability Ultra Fast (HRUF)

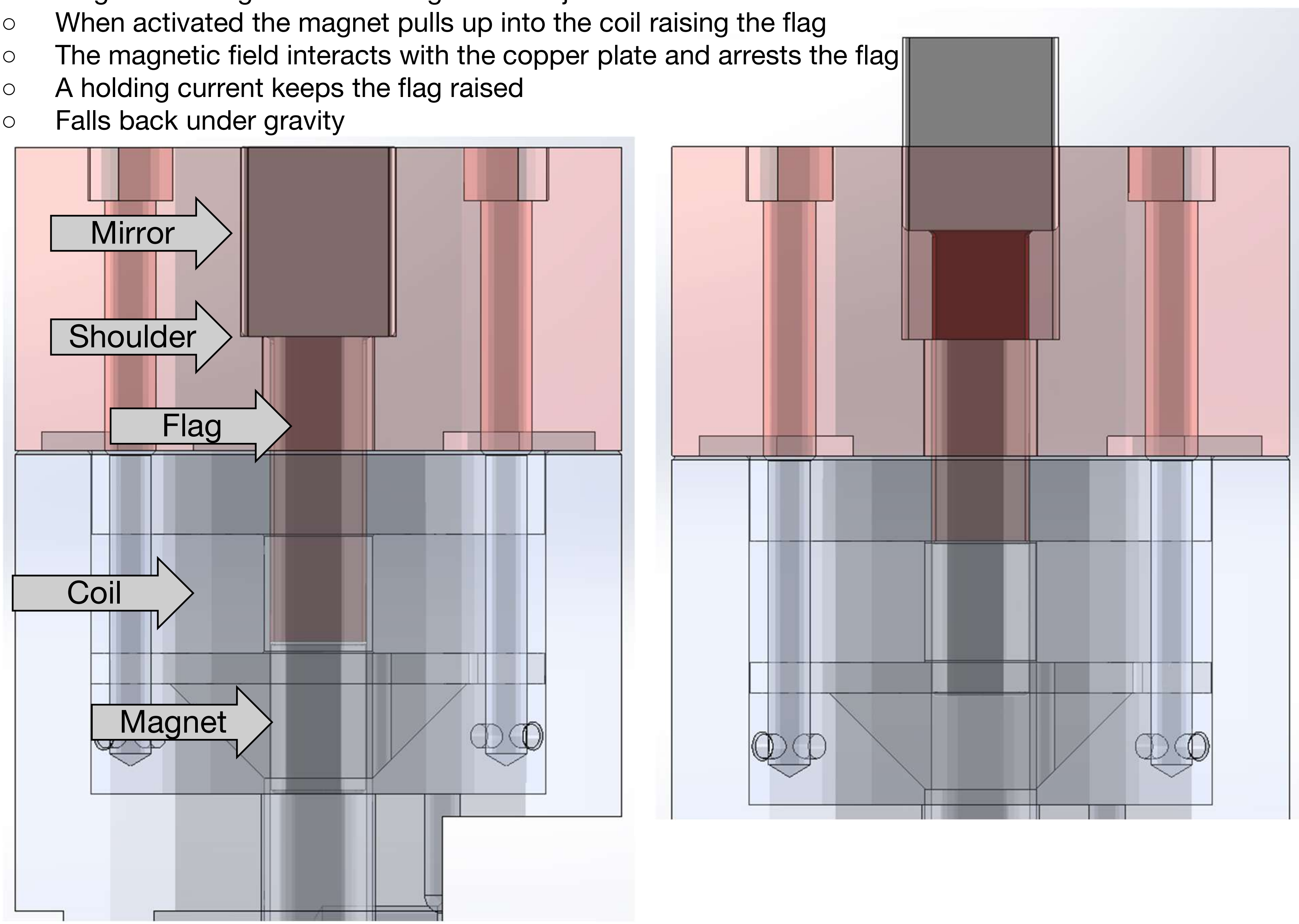
- A prototype was constructed and studied to create a moving shutter without the need for wires attached to the payload
- High-Reliability Ultra-Fast Mechanical Shutter (HRUF) Assy D2200426





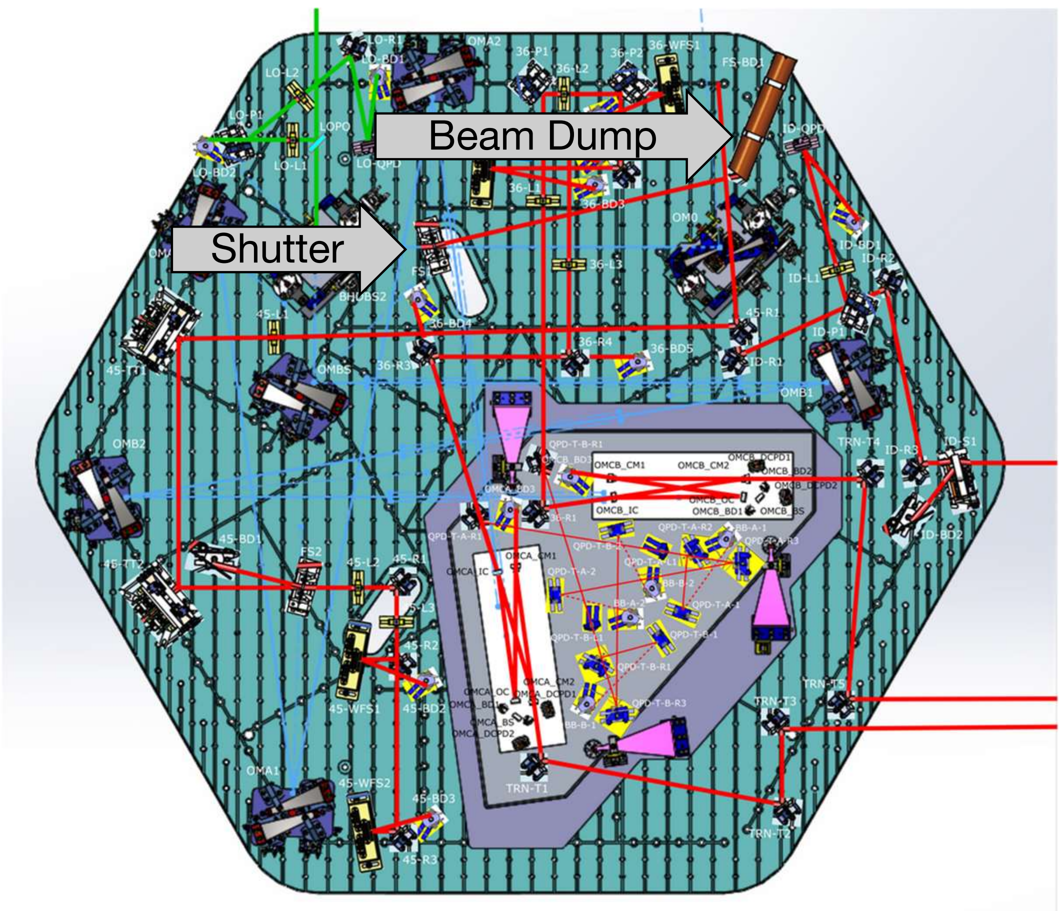
Fast Shutter Upgrade
High Reliability Ultra Fast (HRUF)

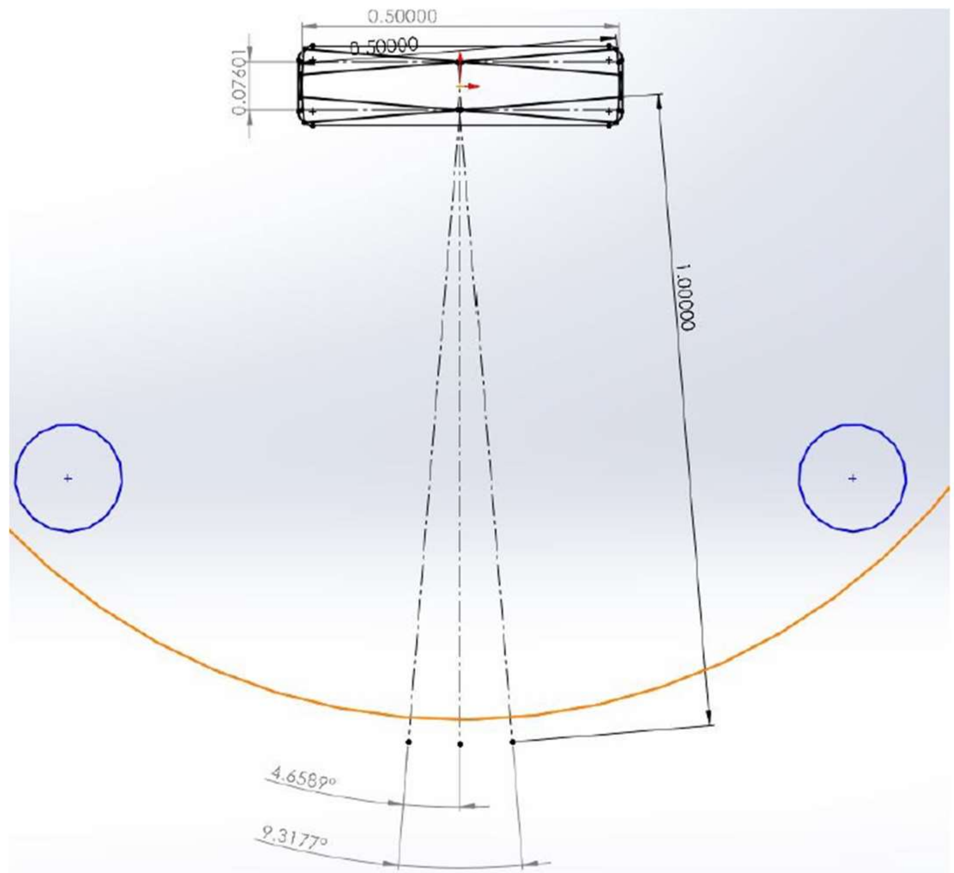
- How Does it Work?
  - Magnet and flag rest on the flag shoulder just inside the coil
  - When activated the magnet pulls up into the coil raising the flag
  - The magnetic field interacts with the copper plate and arrests the flag
  - A holding current keeps the flag raised
  - Falls back under gravity



Fast Shutter Upgrade
High Reliability Ultra Fast (HRUF)

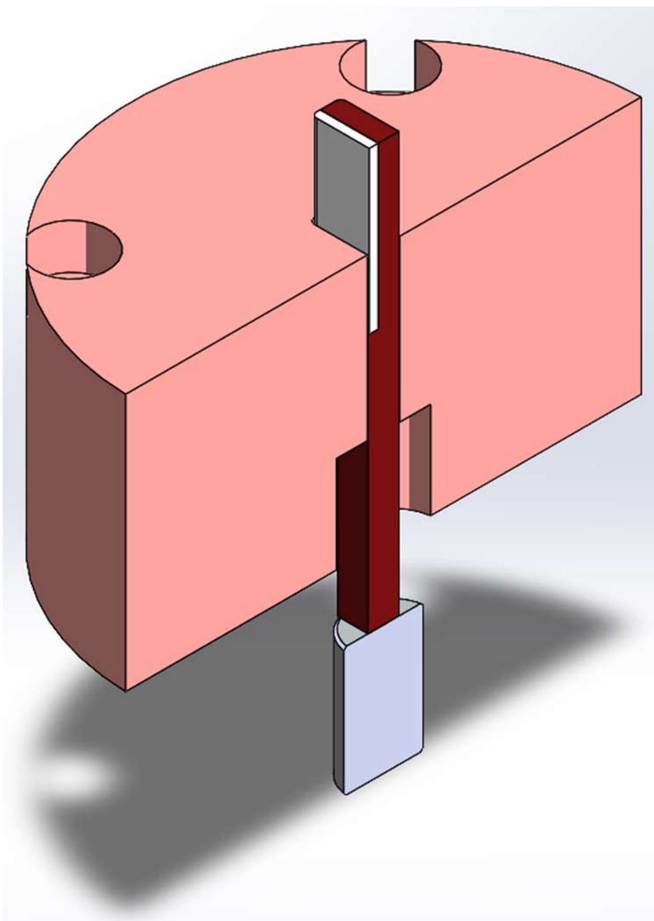
- What have the issues been?
  - The throw to the beam-dump is relatively long so any rotation of the FS mirror on deployment could swing and “paint” the chamber
  - Tolerances must be kept very tight while still allowing free movement of the flag

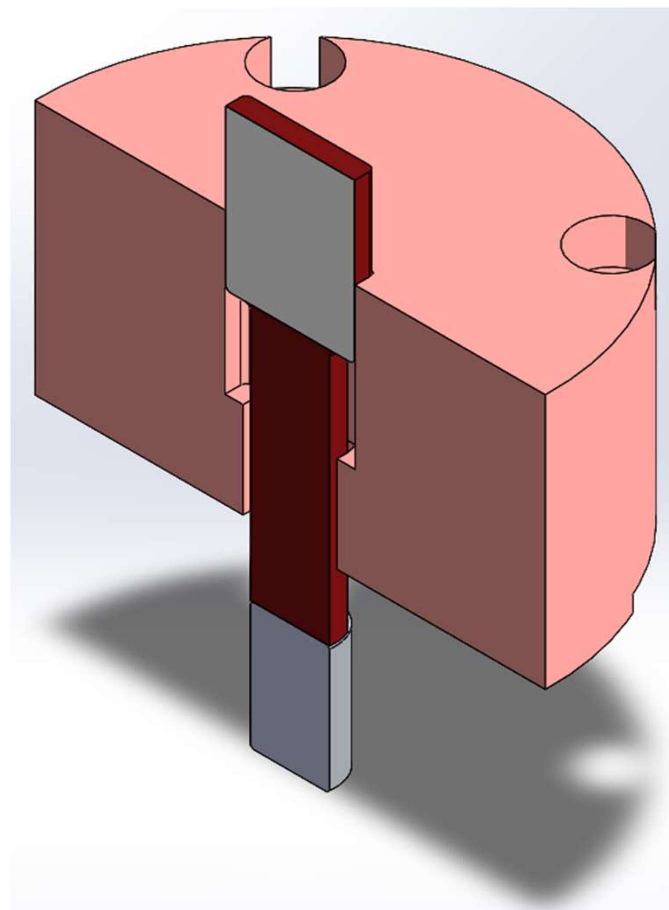




Fast Shutter Upgrade
High Reliability Ultra Fast (HRUF)

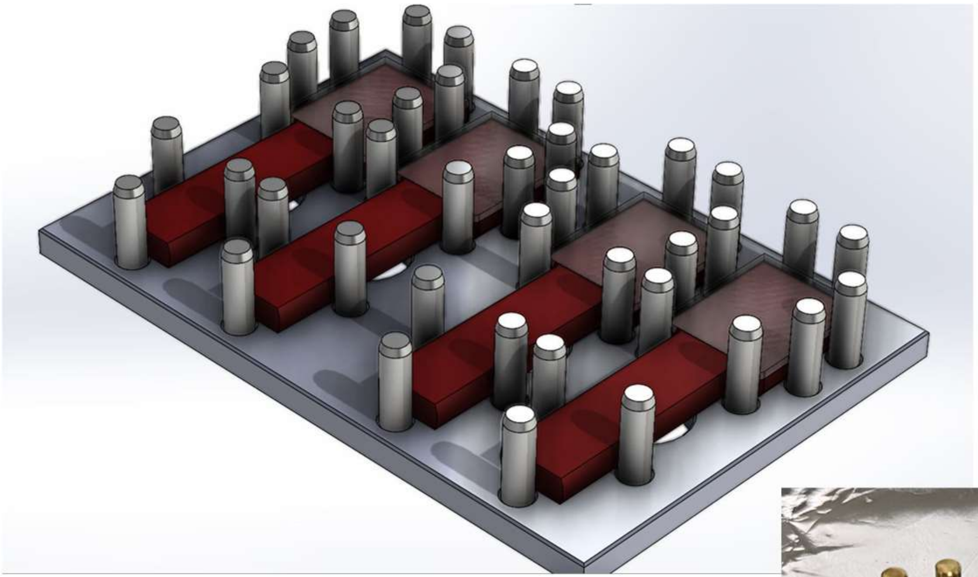
- What have the issues been?
  - How do you assemble it?
  - What order?
    - Magnet-to-Flag
    - Mirror-to-Flag
  - The magnet doesn't fit through the copper plate (square peg in a round hole)
  - The mirror cannot be attached when the flag is in the copper

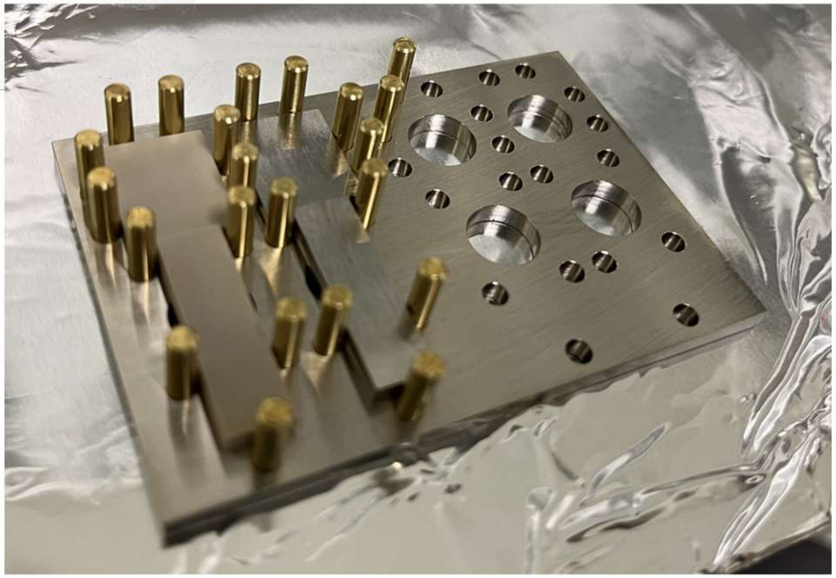




Fast Shutter Upgrade
High Reliability Ultra Fast (HRUF)

- What have the issues been?
  - The mirror cannot be attached when the flag is in the copper
- Mirror-to-Flag Fixture D2300217
  - Holds the flags still and positions the mirrors correctly for glue-up





Fast Shutter Upgrade
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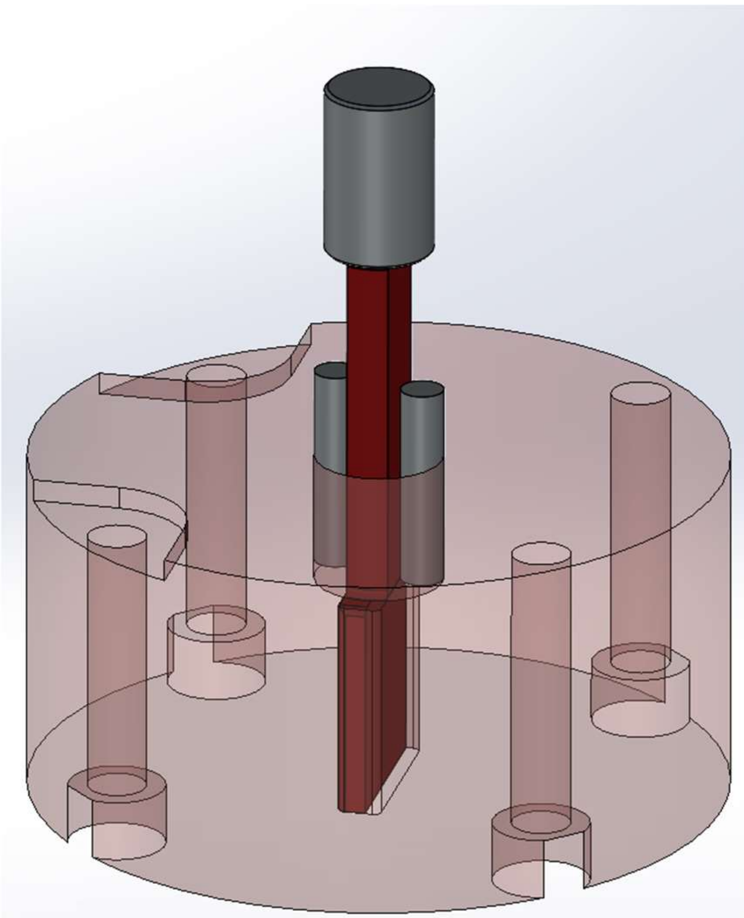
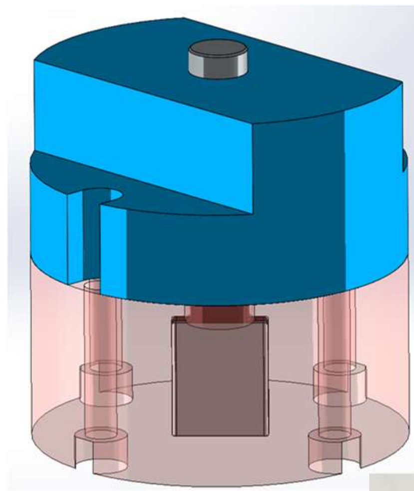
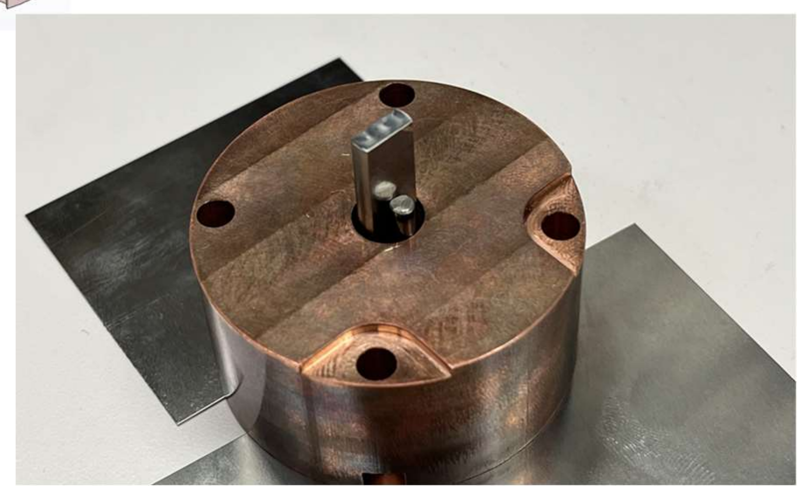
- First Attempt
  - We first attempted to glue a magnet-to-flag
    - The EP-30 Epoxy used was past expiration and did not properly cure
    - Precision pins were used to hold the flag relative to the copper and fixture but were still too magnetic and twisted during assembly







Fast Shutter Upgrade
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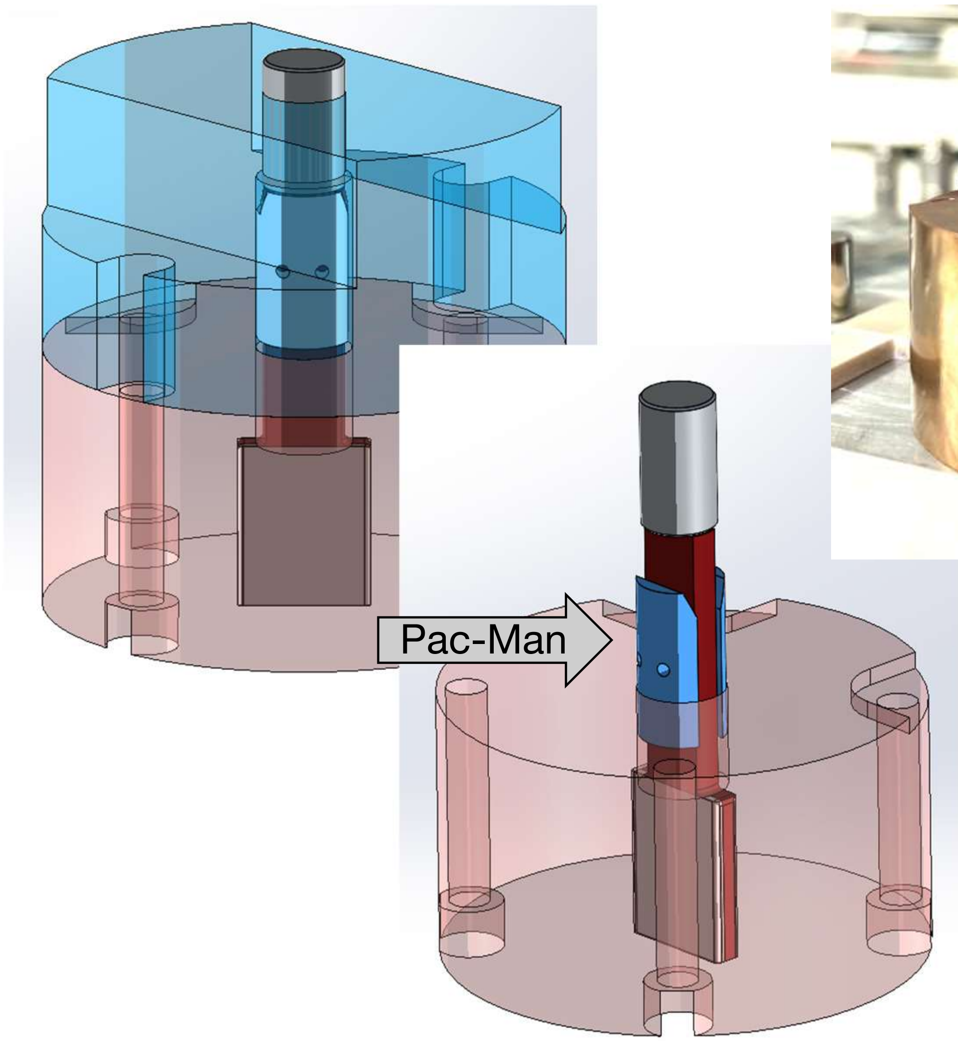
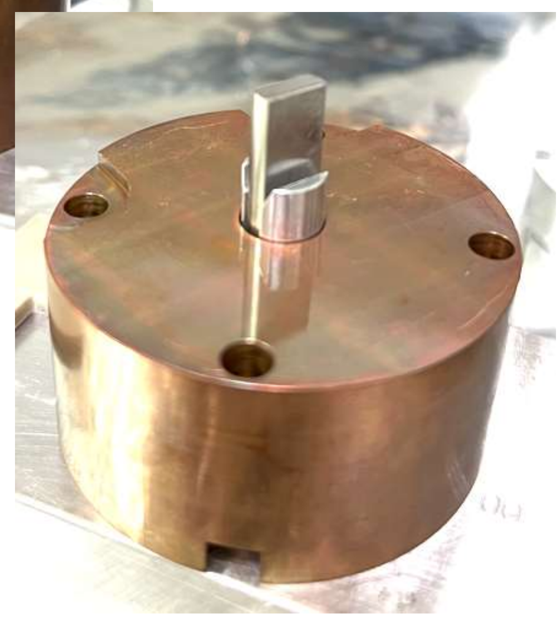
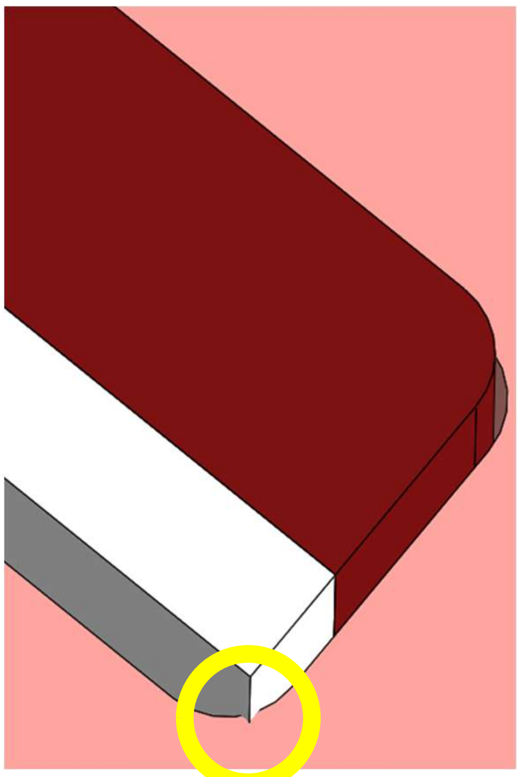
- Magnet-to-Flag Fixture D2300218
  - The “Pac-Man” was developed to hold the flag and copper relative to the fixture
  - Must be short enough to be removed when the magnet is glued, but long enough to bridge the transition of the pieces

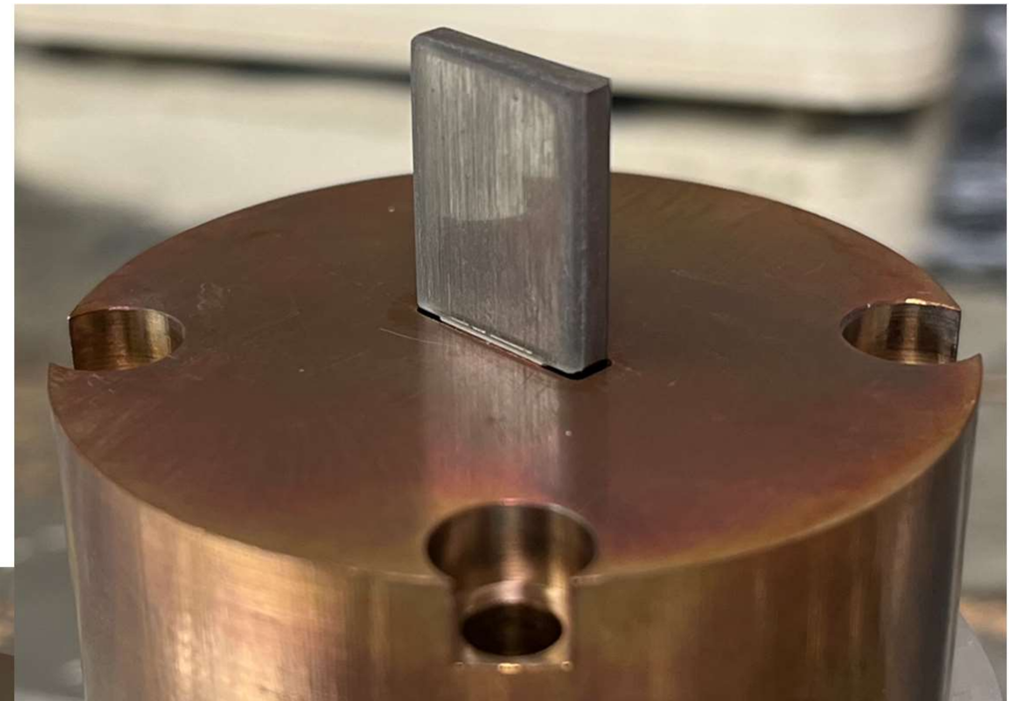




Fast Shutter Upgrade
High Reliability Ultra Fast (HRUF)

- Gluing the Mirror-to-Flag
  - Gluing successful
- Mirror Edges not beveled
  - Tolerance revenge!
  - Manual shaping of test optics
- The depth of the mirror on the flag with the epoxy is tight and does not always fall smoothly
- v2 = 0.005” taken out the flag thickness at the mirror





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- Initial test firing
    - Does not fall back down
    - Does not seem to break

Slow-Mo(ish)

Real-Time

Fast Shutter Upgrade
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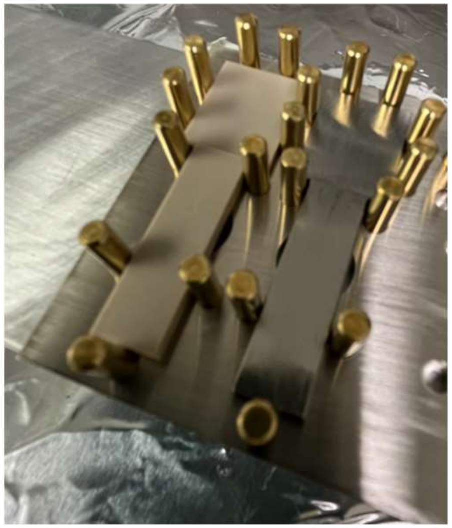
- Timeline
  - All of the physical parts are in-hand or in production as of 9/13
  - Magnets and mirrors need to be epoxied together
  - Testing once the assembly is complete
  - Expenditures for 4 complete assemblies
    - Main Bodies S615433 $4809.11
    - Flag-to-Mirror Jig S612944 $1132.27
    - Magnet-to-Flag Jig S607572 $523.69
    - Copper Plates S587290 $1821.33
    - Bobbins S586150 $1296.54
    - Flags (Ti & PEEK) S603440 $2443.14
    - Terminal Cover S616093 $1885.25
    - Ti Flags, Pac-Man S621897 $3569.90
- 10/25/23
  - First epoxy test failed. Expired epoxy?
  - Parts sent to C&B for a proper Class B clean
  - 10/23 Parts back from C&B
  - 10/24 Test optic glued to flag
    - One PEEK and one Titanium
  - 10/27 Glue successful
    - Flag thickness possible issue
      - Flag redesigned
  - 11/7 New flags, M-to-F jigs arrived
    - Class B clean
  - 11/20 Glue –up failed
  - 11/22 Magnet-to-Flag glue-up curing



Fast Shutter Upgrade
High Reliability Ultra Fast (HRUF)

- Update April 2024
  - Review of where/what/when
  - Some initial data has been collected
    - Fundamental Speed Limit?
  - Reliability issues continue
  - Evaluation of system parameters
    - Capacitance
    - Magnet start position
    - Applied Voltage
    - Body material
    - Piston effects

Fast Shutter Upgrade
High Reliability Ultra Fast (HRUF)

- ## Some Review/Background
  - Fast Shutter Electro-mechanical Requirements T1300906
    - Most other documents reference ≤ 2mS
      - This is based on modeled rise-times associated with the IFO loss of lock dynamics

Parameter	Value
Maximum time to block beam	≤ 1 mSec
Driver electronics peak output current	20 amperes peak
Driver electronics maximum output voltage	500 volts DC
Total time shutter must remain in blocked state	20 mSec to 40 mSec
Pulser duty factor	1 pulse per minute maximum
Fault detection	Must be able to detect disconnected interface cable from shutter controller or to shutter. Must be able to sense unpowered shutter controller.
Beam blocking modes	Fast blocking mode from rest condition plus a mode where the shutter can be held in the up position indefinitely

Fast Shutter Upgrade
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- Fast Shutter Interface Requirements T1300906
  - Outputs (all are bit level outputs on a single female 25 pin D-sub connector)
    - High current pulse – Delivered via cable to in-vacuum fast shutter.
    - Unique output connector must be used to avoid inadvertent miswiring
    - Ready to fire – (High when ready) Indication that energy storage capacitor is charged
    - Pulse in progress – (Low during pulse) Indication that a pulse is being delivered to the shutter
    - Blanking pulse – (Low during pulse) A separate indication that a trigger event has occurred. This may be used to blank a watchdog such that the shutter doesn't cause HAM6 watchdog trips when it fires.
    - Power supply fault – (Low on fault) Window comparators used to verify all power supply voltages are present
    - Fault condition – (Low on fault) Indicative of an unpowered shutter controller, an unplugged input cable from shutter controller, or an unplugged cable to the shutter.

Fast Shutter Upgrade
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- Fast Shutter Interface Requirements T1300906
  - Inputs
    - Trigger input – BNC. Must receive a low-on-fault TTL level signal transition from shutter controller and respond in edge trigger only manner to prevent recurring pulses if the input trigger cable is disconnected.
    - High voltage power – Via a circularly polarized plastic connector (CPC).
    - Up to 500 VDC supplied from remote power supply.
    - Current requirements will be less than 100mA.
    - Low voltage power – Bipolar 18 volt supplies on standard LIGO 3 pin chassis power connector.
    - Reverse pulse input – BNC connector that allows an external pulse to drive the shutter back into its hole in case it gets stuck in the vacuum system.

Fast Shutter Upgrade
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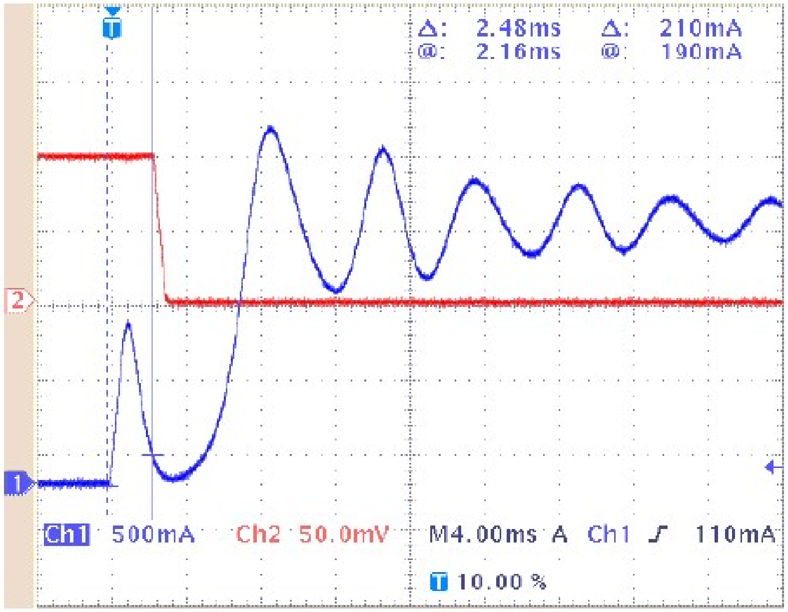
- Old Shutter Testing – How Fast Did It Go?
  - So far unable to locate an actual tested value of the block time of the installed units? Lots of other info and slow-mo movies
    - Fast Shutter - movie files E1600303
    - Rich Abbott - Fall and Rise of the Fast Shutter G1902365
    - Fast Shutter Update G1900843
    - Fast Shutter Simple Simulation T2100004
    - Fast Shutter Requirements E2200061
    - Fast Shutter Design Update G1901417
    - Fast Shutter Prototype Measurements T1300833
      - 2.48mS (start of block)
      - 2.4mm travel vs 6mm currently



Fast Shutter Upgrade
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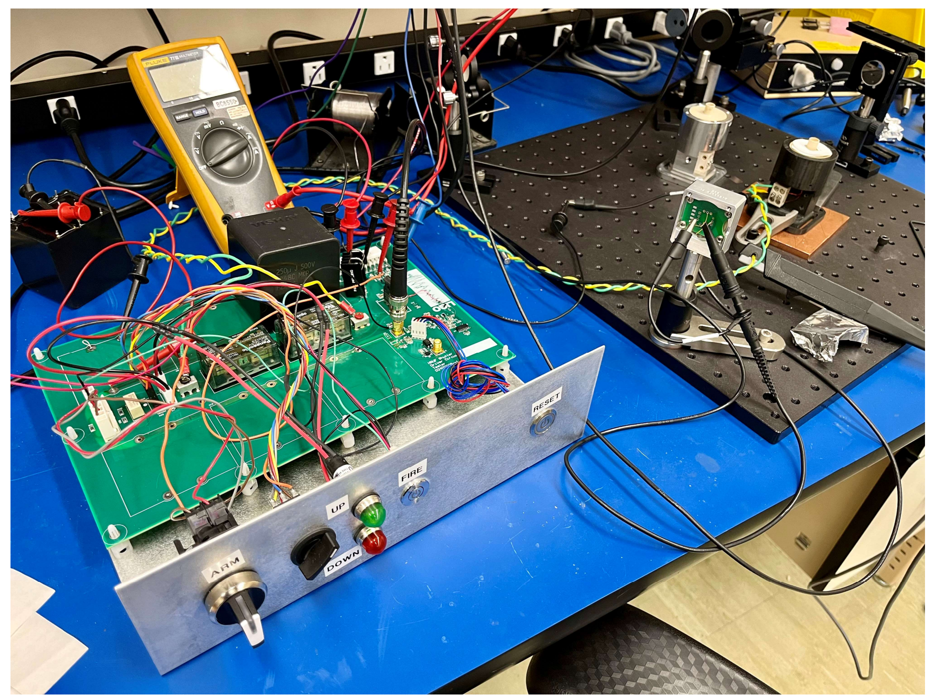
- Fast Shutter Driver Electronics
    - New electronics built and working [D2400008]
    - Some components and parameter changes
        - Gate Rds On
            - Old -> 750m Ω @ 16A, 10V
                - High and low gates
            - New -> 63m Ω @ 22A, 10V
                - Single low side gate
        - Coil
            - Old -> 23 Ω, 14mH
            - New -> 5.65 Ω, 2.35mH
        - Drive Caps ESR (Equivalent Series Resistance)
            - Old -> 2.2m Ω
            - New -> 2m Ω



Fast Shutter Upgrade
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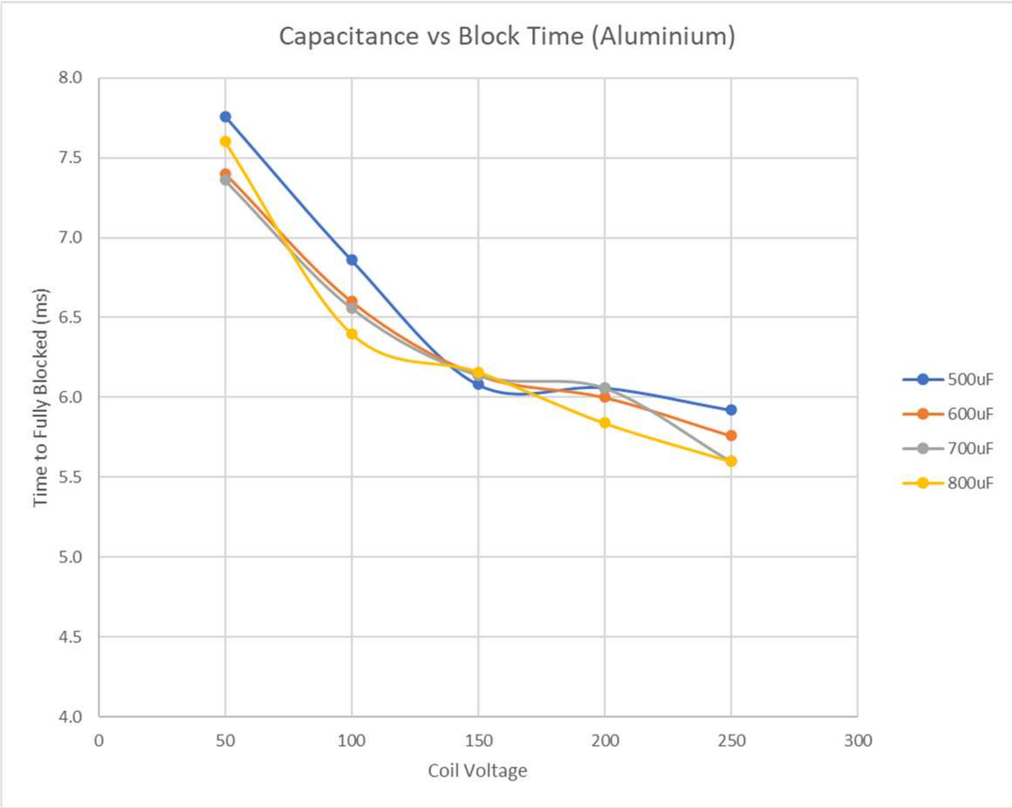
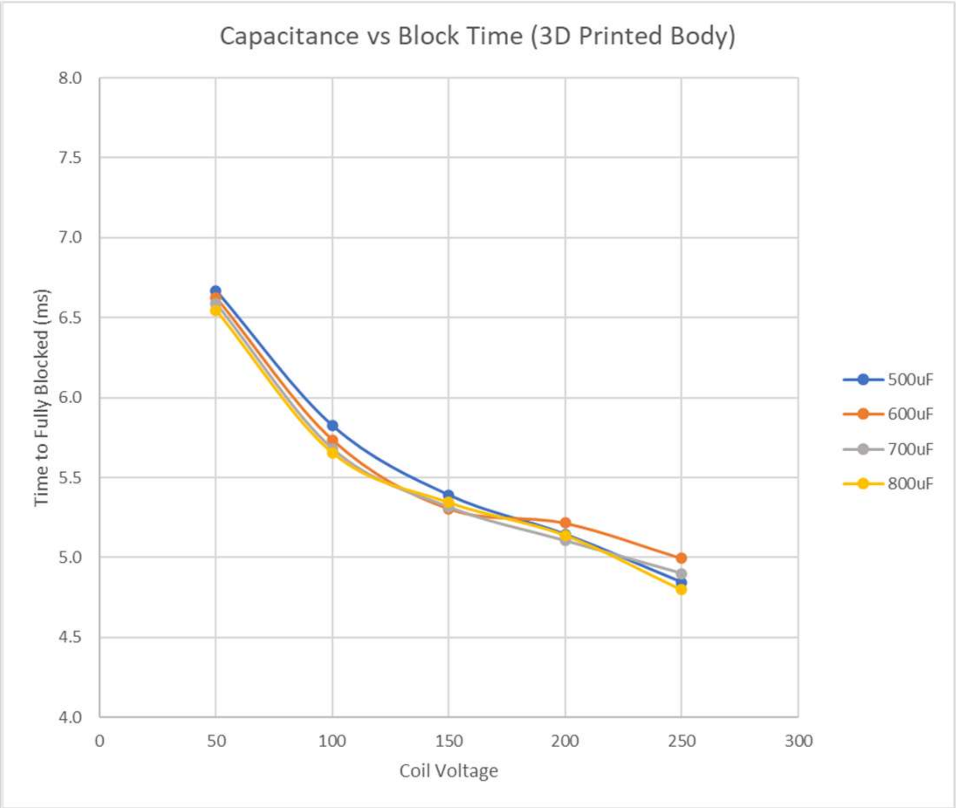
- Initial test data
  - System Capacitance?
  - Aluminum vs PLA?





Fast Shutter Upgrade
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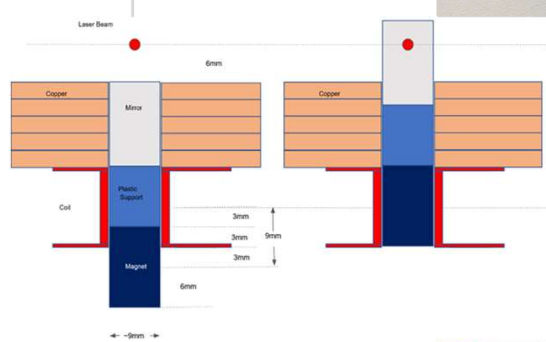
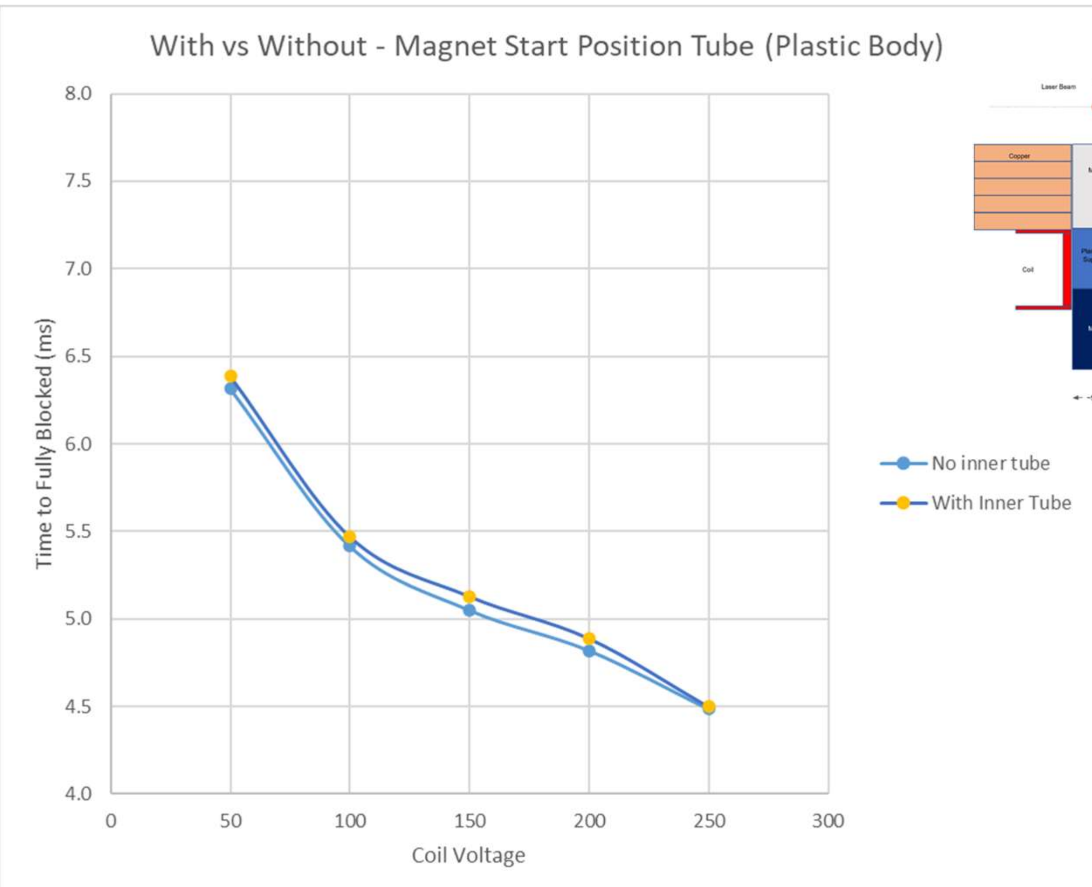
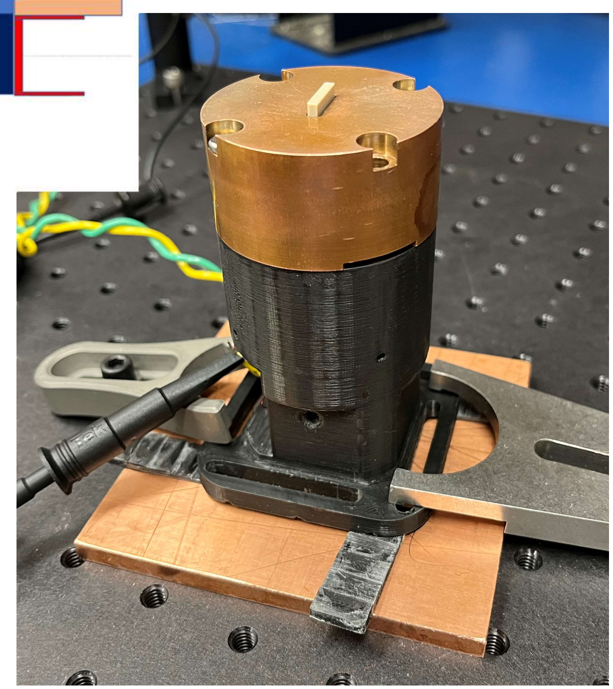
- Magnet start position relative to coil center
  - A small tube was printed to fit inside the bobbin to hold the bottom magnet at the desired start position.
  - Stepped “feet” adjust the base down over the magnet to effectively “raise” the start position of the magnet.
  - Moving the body keeps the beam-to-flag relation the same so the beam doesn’t need to be reset each test.
  - Does the tube create a greater piston effect?
    - A small bit, yes







Fast Shutter Upgrade
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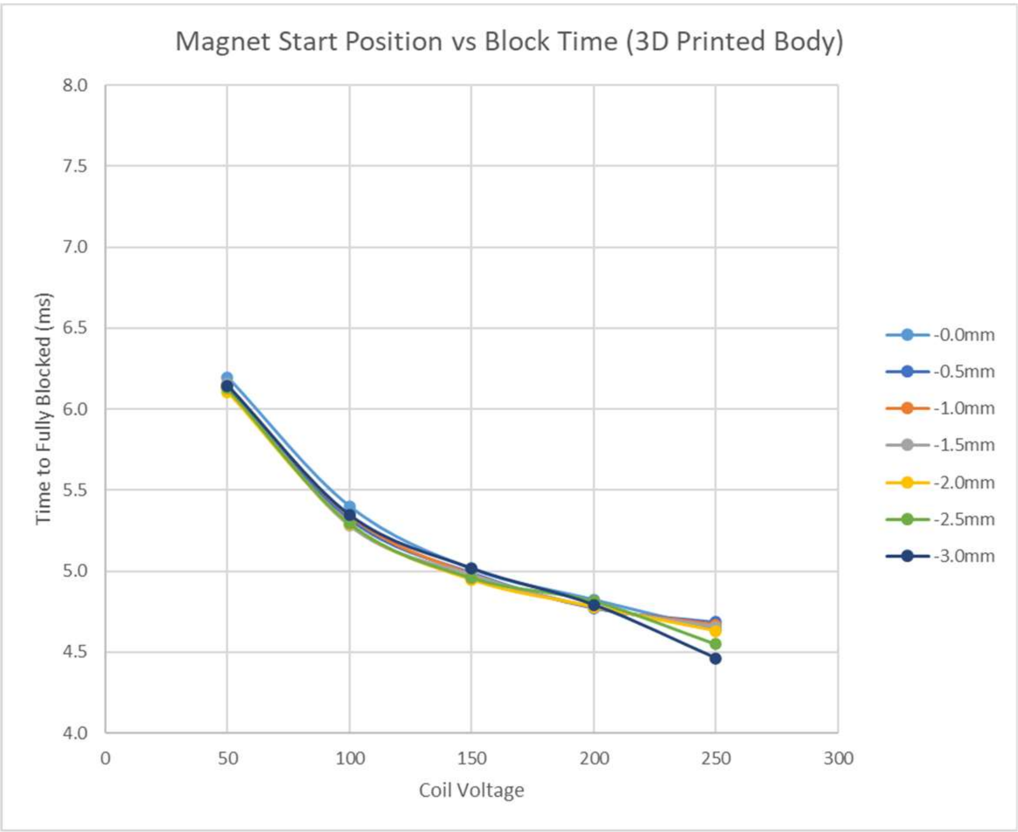
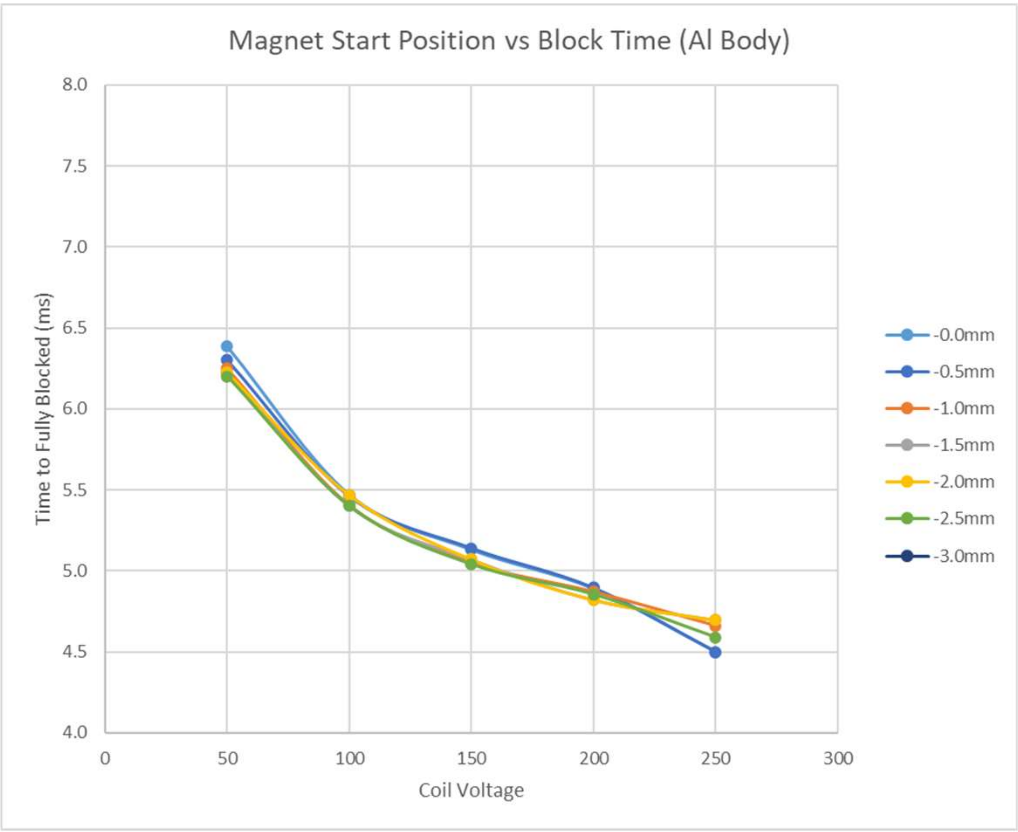
- Magnet Start Position





Fast Shutter Upgrade
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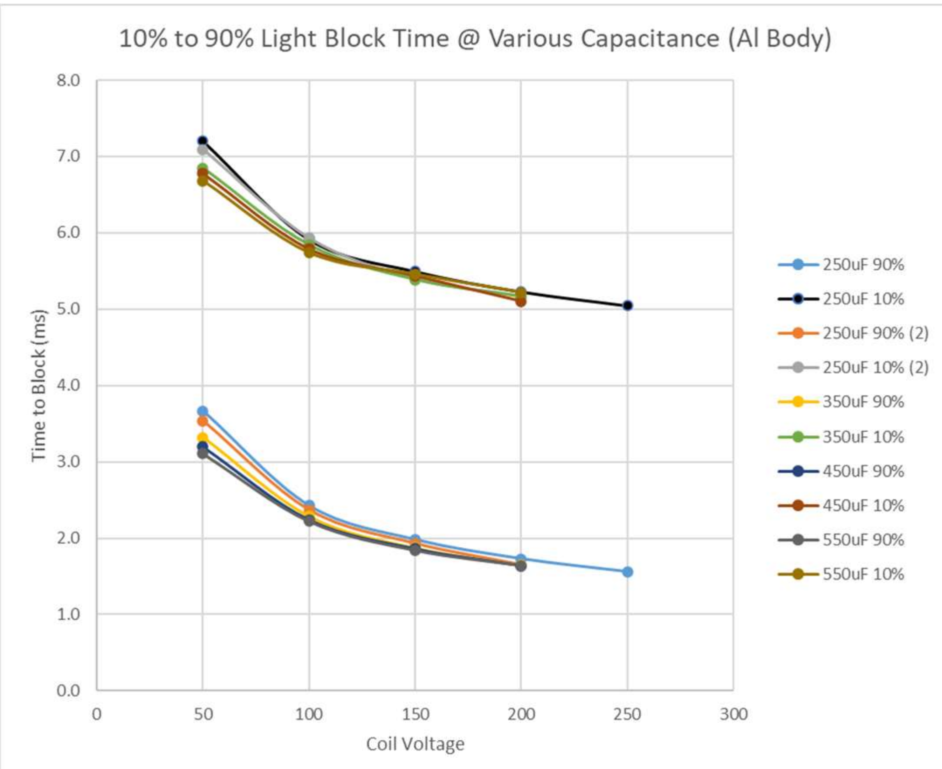
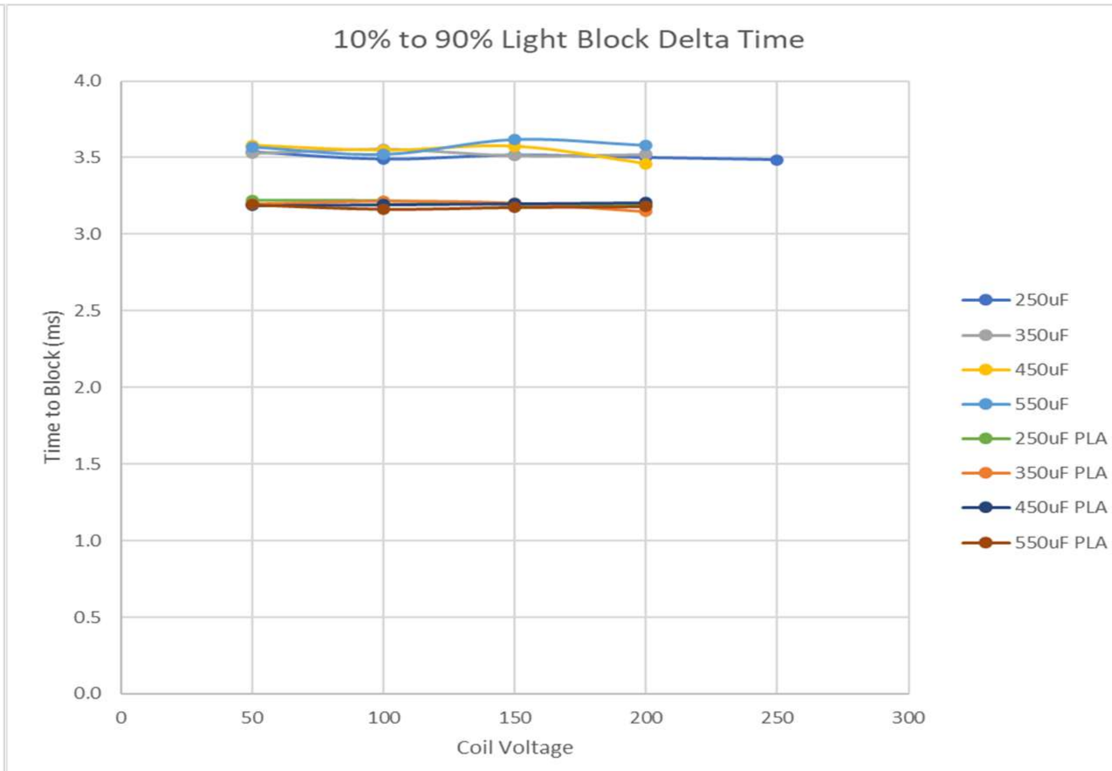
- Started to notice that the delta time to go from 10% to 90% of the beam blocked took the same amount of time no matter the test parameters.
- The Aluminum body has a longer delta time (~3.5mS) than the printed PLA body (~3.2mS)
- Is this a “piston” effect that goes away in-vacuum?





Fast Shutter Upgrade
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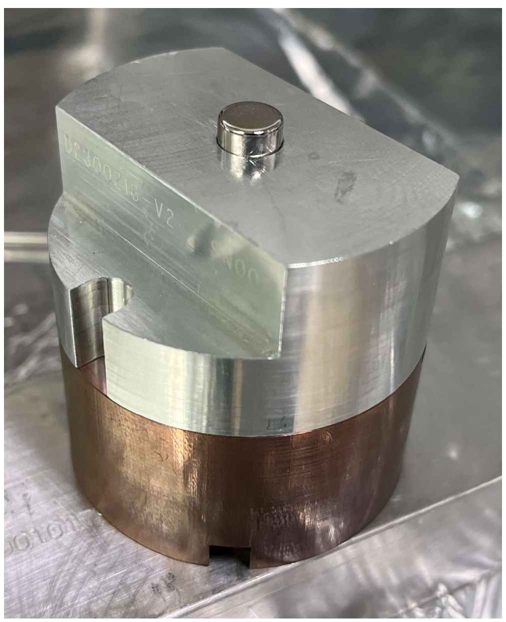
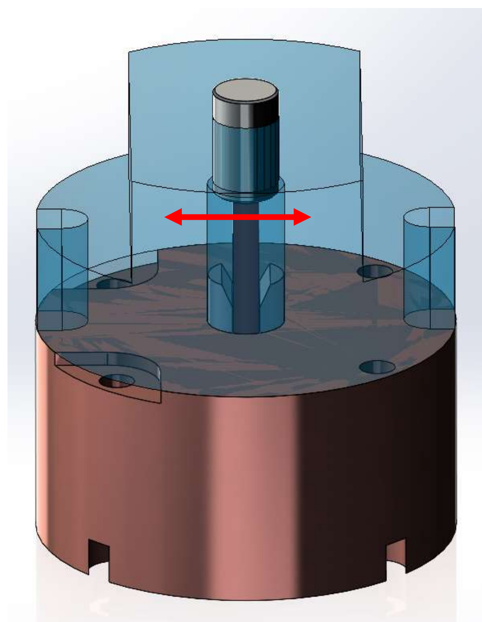
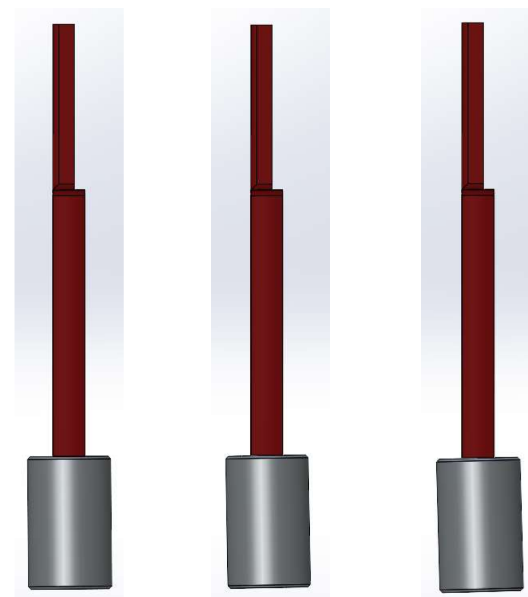
- Reliability of the magnet-to-flag bond has been problematic.
- Getting the magnet aligned on the flag major axis has been hard
  - Had built the Aluminum jig to hold the magnet and align it during the glue up
  - This has not proven to consistently hold the magnet and flag aligned
  - Any slight misalignment causes friction in the bobbin
  - Re-evaluated and using the bobbin with shimming holds everything on the axis in its final configuration
  - Better magnet-to-flag alignment has resulted in more consistent data
  - Bobbins are kept as thin as we can to bring the coil windings as close to the magnet
    - This leads to slight distortion of the bobbin barrel exacerbating the magnet alignment issue







0.5deg 1.0deg 1.5deg

Fast Shutter Upgrade
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- Use itself to restrain itself with 0.002” shimming.
- This has allowed better bobbin alignment without friction against the bobbin barrel

Fast Shutter Upgrade
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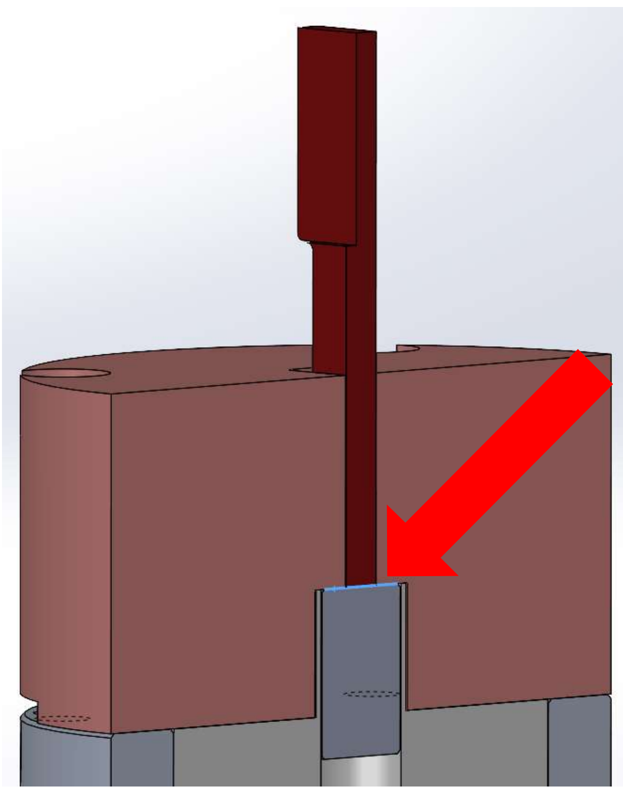
- The magnet-to-flag bond has proven to be unreliable and fails consistently despite alignment improvements.
- Several issues have been explored.
  - Delamination of the magnet chrome plating
    - Flexing of the bond
  - Is the magnet physically contacting the underside of the copper block? (Red arrow)
    - Tested without the flag
    - Machinist Blue die painted on the magnet top
    - Fired @ up to 250 volt
    - Only very slight physical contact indicated by the die



Fast Shutter Upgrade
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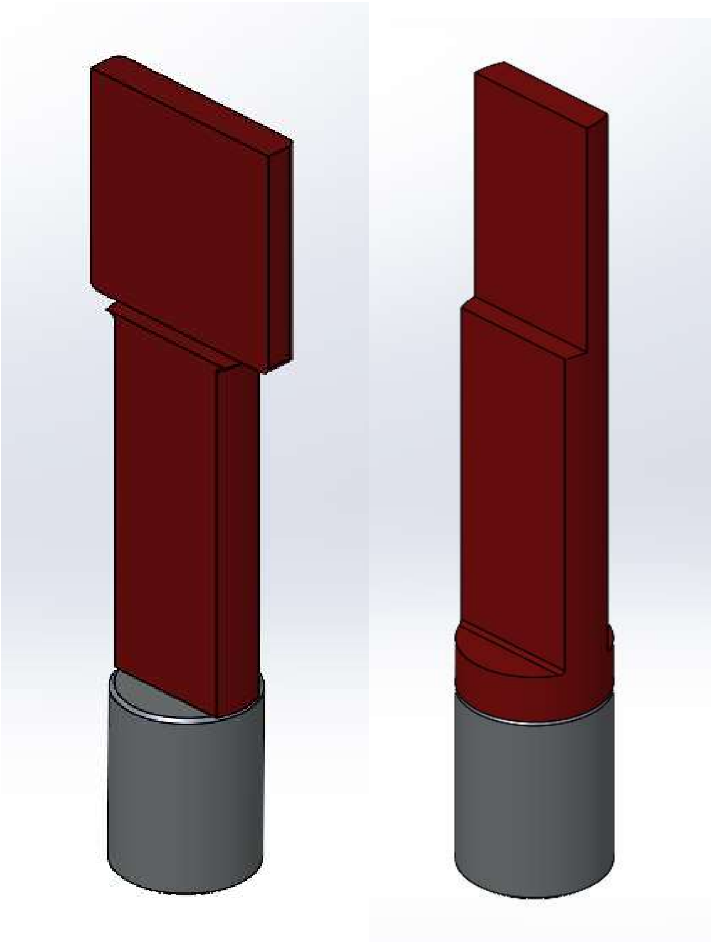
- Fixing the Magnet-to-Flag bond
  - Redesign the Flag for better bond alignment
  - Rounded base increases the glue surface
  - Help to keep the alignment more consistent
  - The round base will not assemble with the copper block with the flag shoulders so they must be removed
  - Removal of the shoulders means there is nothing preventing the flag from falling into the base



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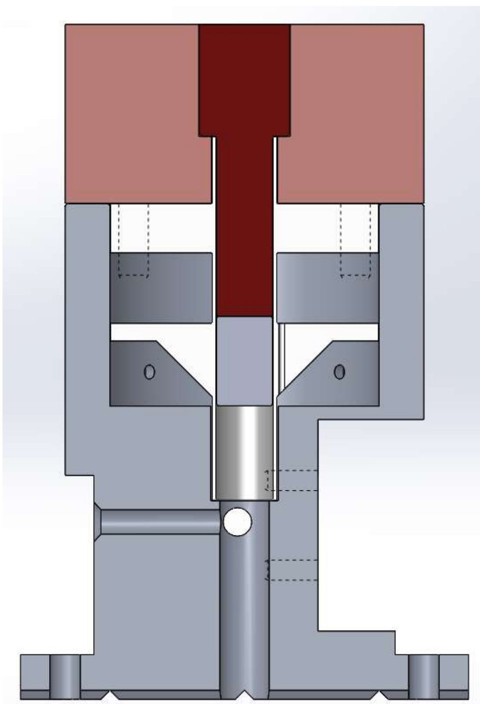
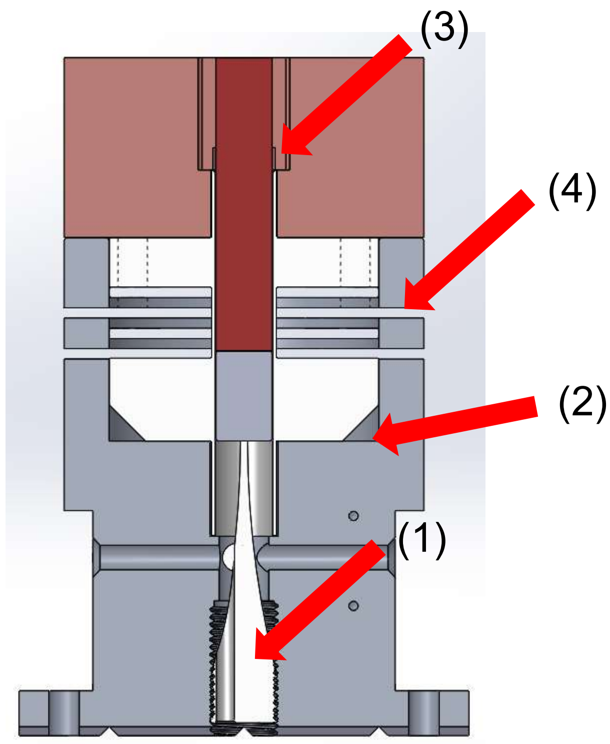
- Adjustable magnet positioner added to the base to replace the flag shoulders (1)
- Bobbin widened to transfer the coil load into the base better (2)
- Bottom hole of the copper plate deepened 0.125” to compensate for the 0.125” tall circular expansion of the flag (3)
- Slots cut into the base to stop counter-eddy currents (4)
  - Can the entire base be PEEK? No eddy currents to worry about





Fast Shutter Upgrade
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- Rework the parts are described
- Test that the flag-to-magnet bond is more reliable
- Test the “piston” effect with restrictors
  - Add vent holes to the copper plate to vent the top side and prevent virtual leaks
- Move the rig into vacuum to test

Fast Shutter Upgrade High Reliability Ultra Fast (HRUF)

- End of April 17, 2024 updates

Fast Shutter Upgrade
High Reliability Ultra Fast (HRUF)

- Follow up questions from April 17, 2024
- Old shutter 18.01g – moving mass (from T1400335)
  - Kinetic Energy = 1997μJ
  - Force = 328mN
- New shutter 6.06g – moving mass
  - Kinetic Energy = 663μJ
  - Force = 110mN
    - Calculations assume 0.467m/S (10-to-90% block time)
- More design specs
  - Shutter speed.
    - Simulations of the lock loss transient (time domain) are reported in LIGOG1000489 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/e2 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).