



The Beauty of Hindsight: Advanced LIGO

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- 1990's: Many table-top and small-scale experiments in
 - » Laser systems
 - » Interferometer topologies
 - » Mirror coating materials science
 - » Extremely low-loss mechanical systems
 - » Many degree-of-freedom servo control systems
- 1999: White paper, based on these 'small science' successes
- Early 2000s: LIGO Scientific Collaboration is born, refines design, shows strong scientific consensus and unity on the path forward
- 2003: Proposal to the NSF from the LIGO Laboratory
- Mid-2000's: Advanced LIGO design refinement, hard choices, 'Projectification'



- 2008: Project Start
- \$205M from the NSF, complemented by \$15M UK, \$15M Germany, \$5M Australia (or so)
- Scope:
 - » (design was separate from the Project, and done before/in parallel)
 - » Remove and dispose of three old interferometers
 - » Build three new interferometers
 - » Install three interferometers
 - Turned into install two, store one
 - » Pay all staff time
 - » Keep to schedule, and don't ask for more money
- 2015: Project End

- What could possibly go wrong?

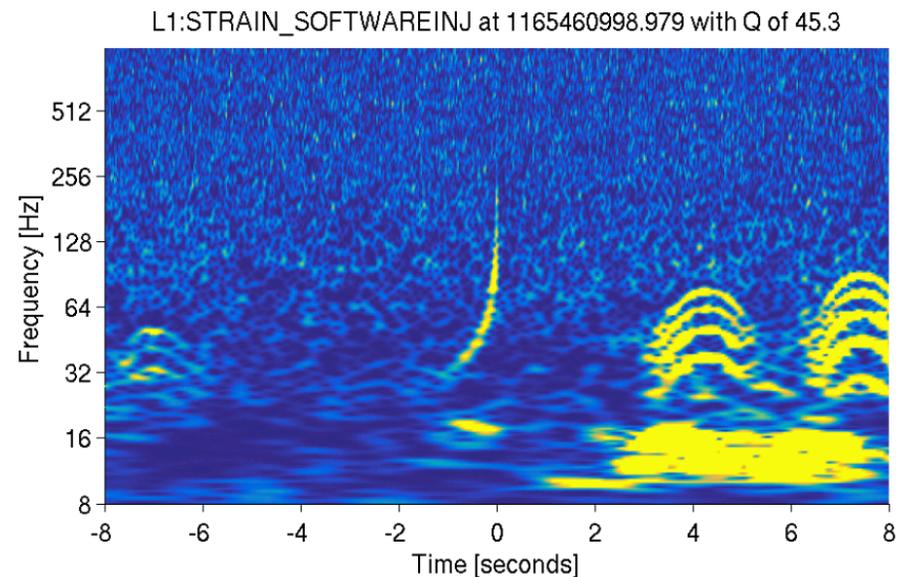
(design was done in parallel)



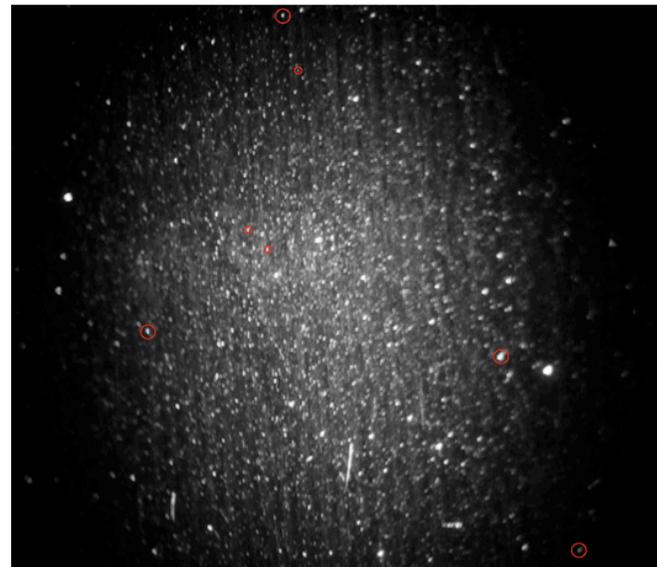
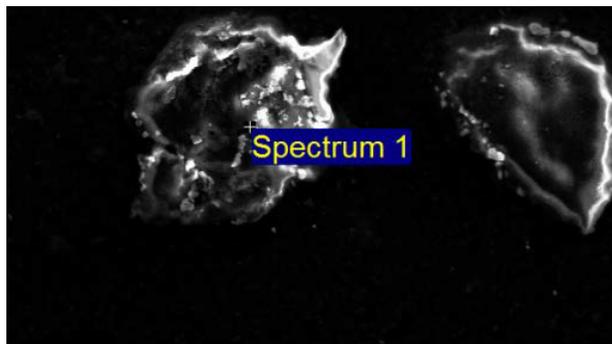
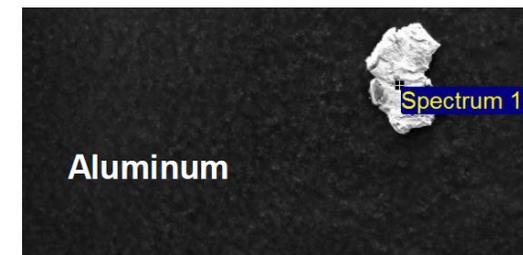
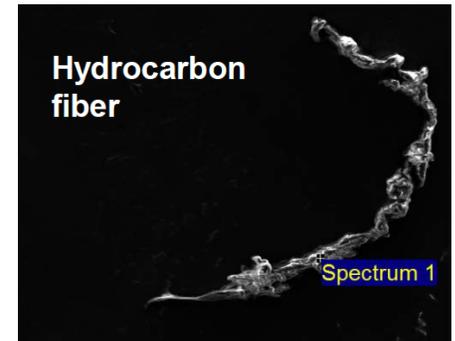
- Bad idea: try to do design on some subsystems while others are cutting metal
- Led to rework, subsystems waiting for parts, thrash to keep 'new, better ideas' from being introduced
- Not *too* much stuff thrown away

- Auxiliary optics is the poster child here

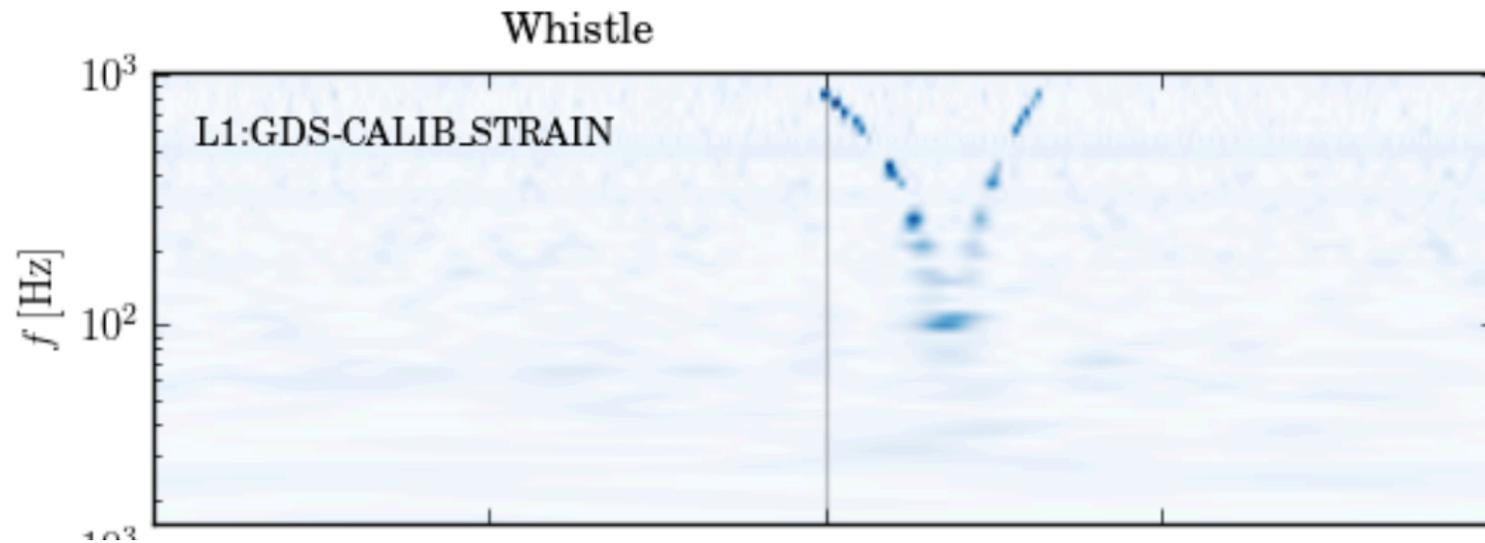
- Lumped together a bunch of stuff as we had in initial LIGO
 - » 1 transport of interferometer output beams,
 - » 2 stray light control,
 - » 3 thermal compensation (including diagnostic wave front sensing),
 - » 4 optical levers for alignment reference,
 - » 5 initial alignment procedure and equipment, and
 - » 6 the photon calibration/excitation system.
- Underscoped cost and labor by about a factor of 6
 - » Moral: make it 3-4 subsystems
- Starved of early design and planning
- Still working on stray light control today



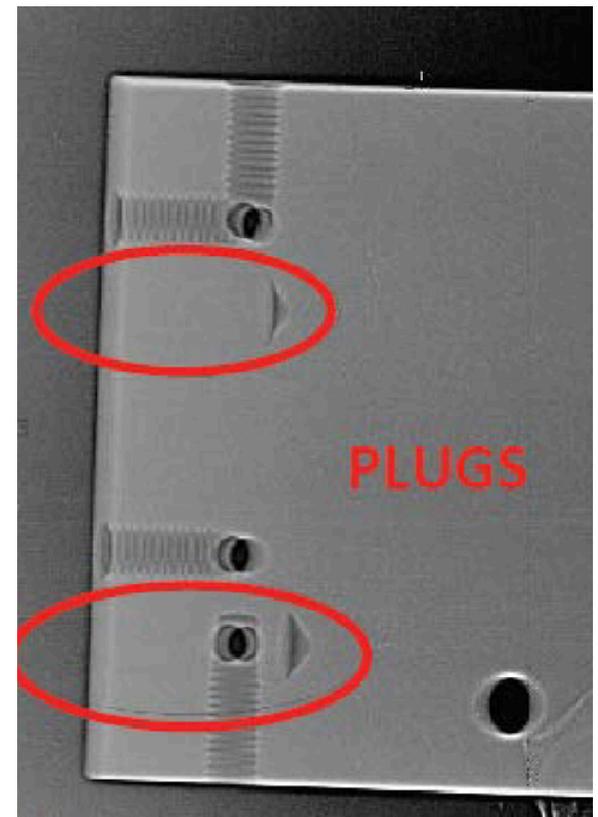
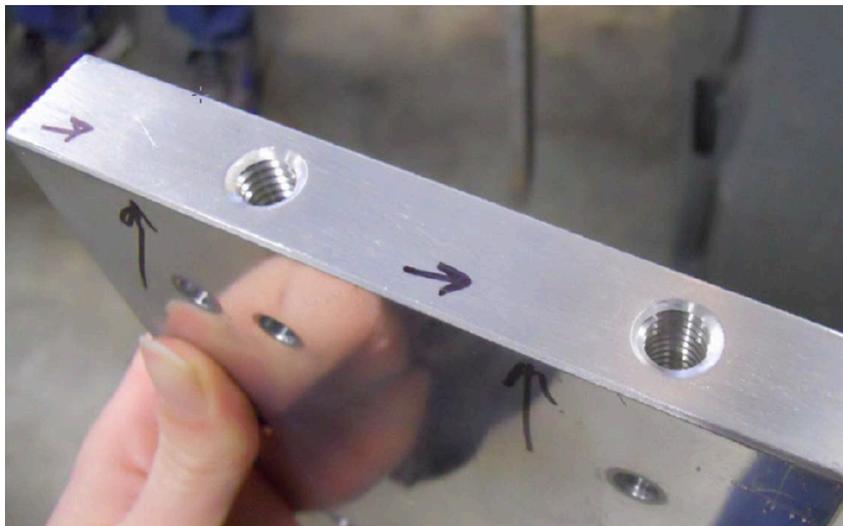
- Still learning how critical cleanliness is
 - » ...point absorbers...
- Knew we needed to scrub the interior of all the chambers
- Did not know how much dirt we dragged in as humans
- Tiger Team (Thanks Calum) attacked this problem
- Changed garb requirements, glove manufacturers, etc.
- Much *much* better now
- ...still not good enough.



- Many radio-frequency oscillators
- Some of them slewing to track interferometer lengths
- Too much RF radiated and carried in grounds
- Enough nonlinearities to mix everything in sight



- QA/QC was invented and executed in house, with a light touch
- Production in the Lab worked out ok
- Had some dramatic problems with subcontractors
- Holes drilled in wrong places, filled with plugs, and *intentionally* hidden
 - » ...found after assembly of seismic isolation systems
 - » Disassembly, new fab, clean, reassemble
 - » Time = money; this cost time AND money
- Next time: heavier touch on QA/QC



- Asked subsystem leaders with experience in initial LIGO to estimate labor and its uncertainty
- Followed with lead system engineers, in general increasing estimates and uncertainty
- Followed with a MonteCarlo study (Thanks, Carol) to estimate a roll-up of costs covering a range of uncertainties
- And...
- Underestimated Labor by something like a factor of 2 – a huge cost for aLIGO (all labor was paid by the Project).
- How did we survive?
 - » Estimates from fab houses collected in dot.com years – all high
 - » aLIGO contracts let after dot.com bubble burst – fab costs were lower than expected.
 - » We got lucky – fab money could pay for people

- Project management infrastructure and software
 - » Required by the NSF to do 'earned value tracking' and to report voluminously on spending
 - » Also needed to be agile for changes – late mirror coatings, LIGO-India shift, etc.
 - » Basic incompatibility for the tools we used (Primavera, Prism)
 - » Also: software needed experts for input, and to interpret output
 - Many project controls people required (\$\$\$)
 - Technical leaders felt disconnected from process
- Project management communication
 - » Because it felt imposed, and project controls people were not savvy on our technology, little buy-in from tech staff
 - » Subsystem leaders did not want to spend time on it and in fact did not have the time – 'Do you want the paperwork or the subsystem?'
- → Project management did not feel like a tool to the team but instead like a burden
 - » (but absolutely necessary)

- Initial LIGO had suffered from having people in a given team at the 4 Lab sites (Caltech, MIT, LLO, LHO)
 - » Disconnects, miscommunication, duplicated effort, travel costs...
- We swore never to do it again...
- ...we did it again.
- No choice: the experts were spread around.
- aLIGO could profit from iLIGO – people either had already worked distributed, or had been at e.g., MIT then moved so already ‘a team’
- (there are also advantages – cross-checking, more breadth in background, teams at observatories had ownership and were not shipped black boxes)

- Much much better than in iLIGO
- But still too little too late
- Spent the last 6 months scrambling to get basic documentation in place
- But lacking a critical scope: running and debugging
- Also need to maintain and refine documentation during running
 - » Extra site burden – needs documentation staff to shadow commissioners
 - » Very, very hard to do real detailed detector characterization if not at a site, limiting severely the number of people who can help
- aLOG is very useful, but could consider a system which also builds and corrects documentation as aLOGs are made using a collection of keywords

- aLIGO had very valuable external committees
 - » LIGO PAC
 - » aLIGO PAP
- They told us again and again:
 - » Make decisions early on imperfect knowledge – take risk
 - » Spend money early to save time (and thus money) later
- We did a little of it but not anywhere near as much as we should have
- Would have had the resources to fix most of the persistent problems if we had.

- But despite all that...

- Completed
 - » within budget
 - » on schedule
- Detections were made
- We are eager to do it again
 - » ...and make new mistakes