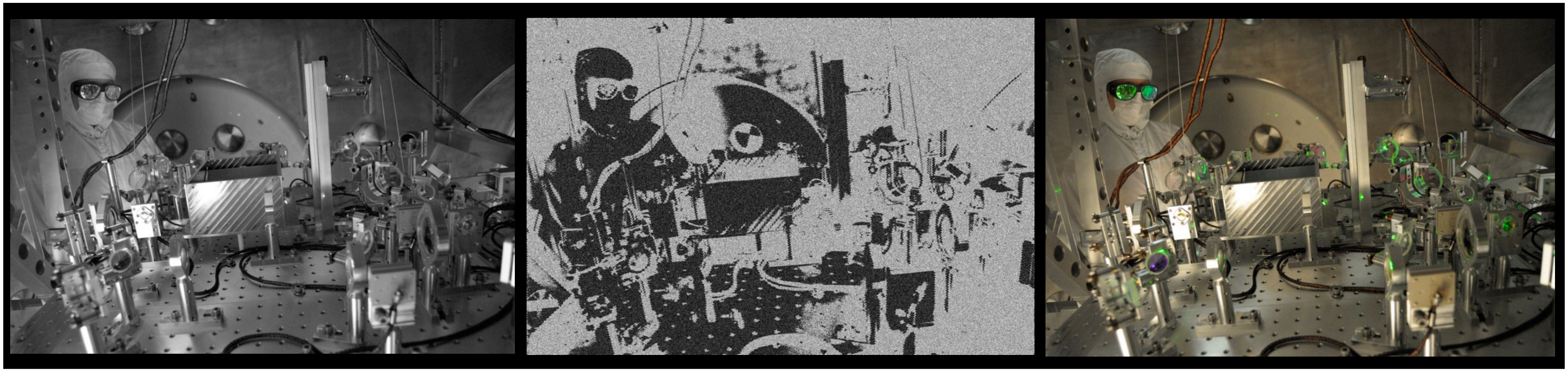
Installing Advanced LIGO: problems, challenges and some solutions

M. Landry
LIGO Hanford Observatory/Caltech

KAGRA Collaboration Meeting
Toyama University
2 August 2013
LIGO-G1300759



Outline

1. A (very brief) introduction to LIGO
2. Organization: project controls, installation planning, documentation
3. Selected topics in installation
4. Problems and some solutions
5. Brief status of integration

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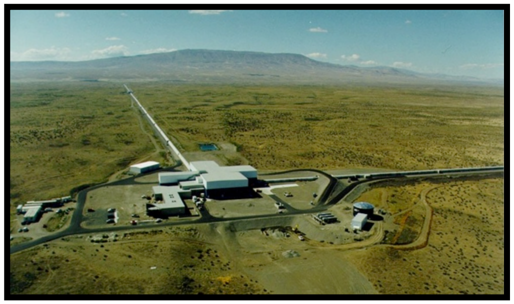
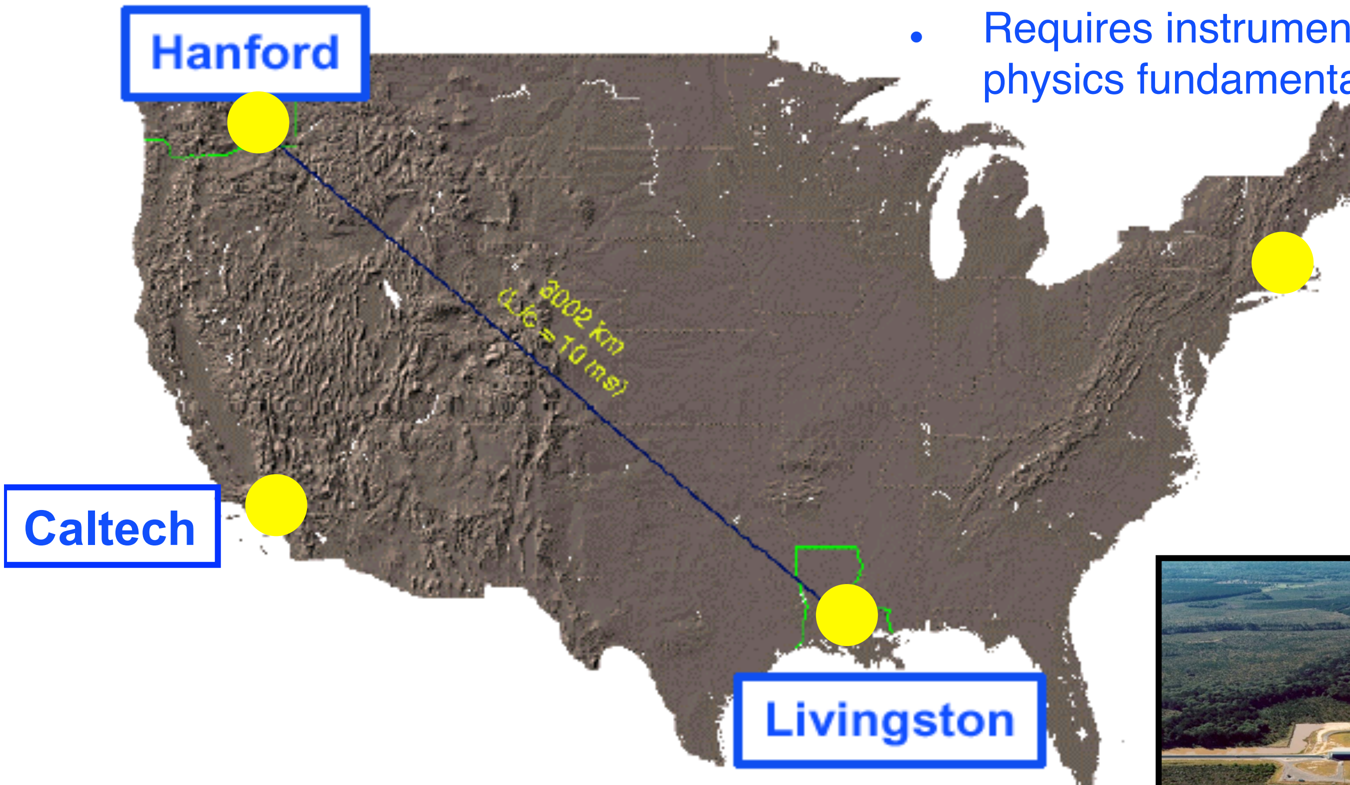
LIGO Laboratory: two Observatories, Caltech and MIT campuses



- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



LIGO

LIGO Scientific Collaboration

University of Maryland 1856

Michigan

University of Strathclyde

Loyola University New Orleans

Montana State University

PAH

University of Washington

Syracuse University Suos Cultores Scientia Coronat Founded AD 1870

清華大學

Tsinghua University

Trinity University

San José State University

University of Wisconsin UWMilwaukee

ANU The Australian National University

LSU

UTB TSC

The University of Western Australia

1764

University of Glasgow

NASA Goddard Space Flight Center

Università degli Studi del Sannio

California Institute of Technology 1891

Northwestern University

Andrews University

Massachusetts Institute of Technology

Southeastern Louisiana University

The University of Texas at Austin

Moscow State University

R·I·T

The University of Adelaide Australia

PAN

Embry-Riddle Aeronautical University

University of Massachusetts Amherst 1863

University of Southampton

PennState 1855

Sigill. Coll. Carleton Northfield, Minn. A.D. 1866

GEO 600

California State University Fullerton

Washington State University

UF University of Florida

The University of Mississippi 1848

Cardiff University

Universitat de les Illes Balears

Charles Sturt University

NAOJ

University of Rochester

University of Minnesota

Southern University Agricultural & Mechanical College

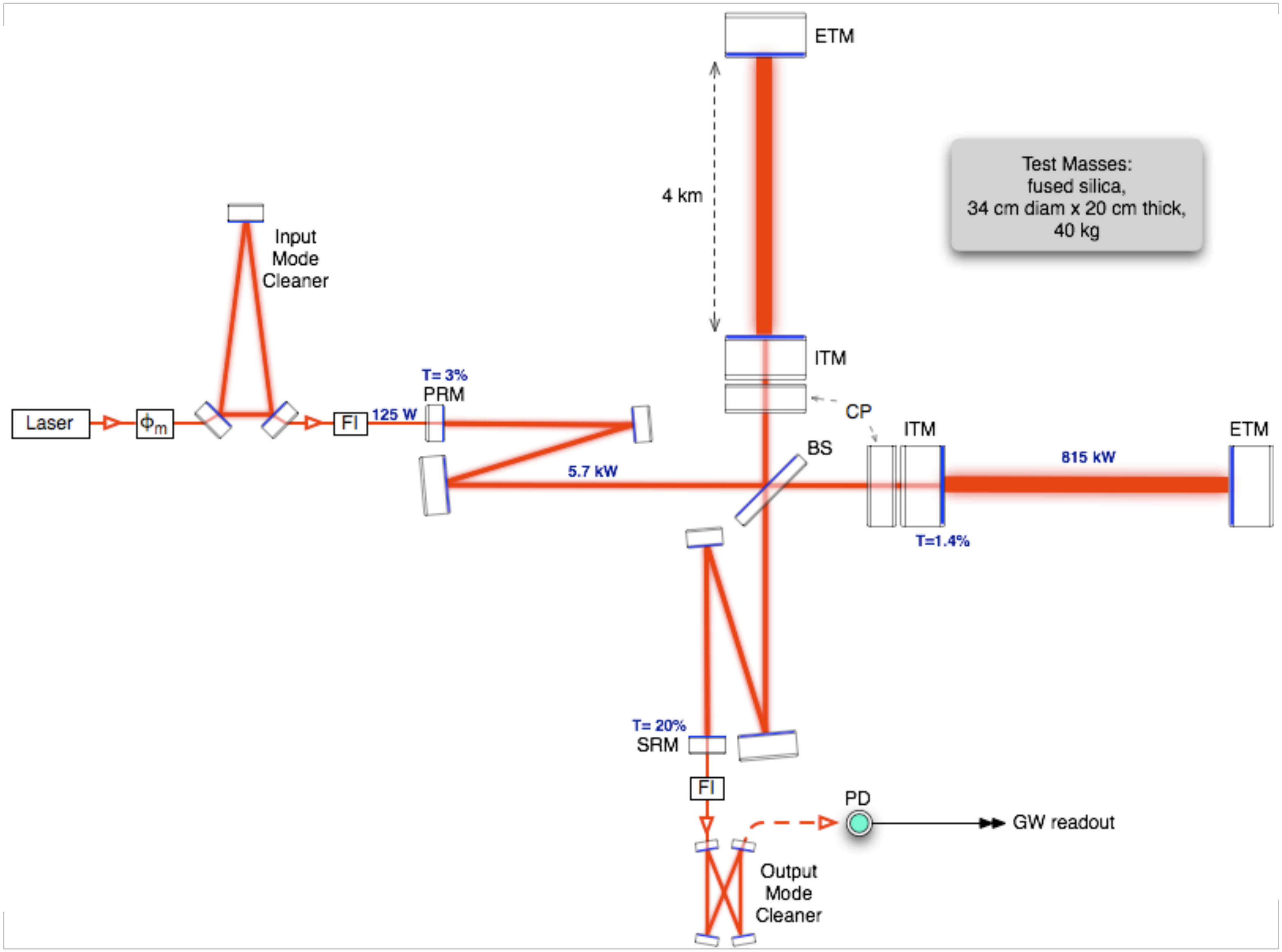
Hobart College

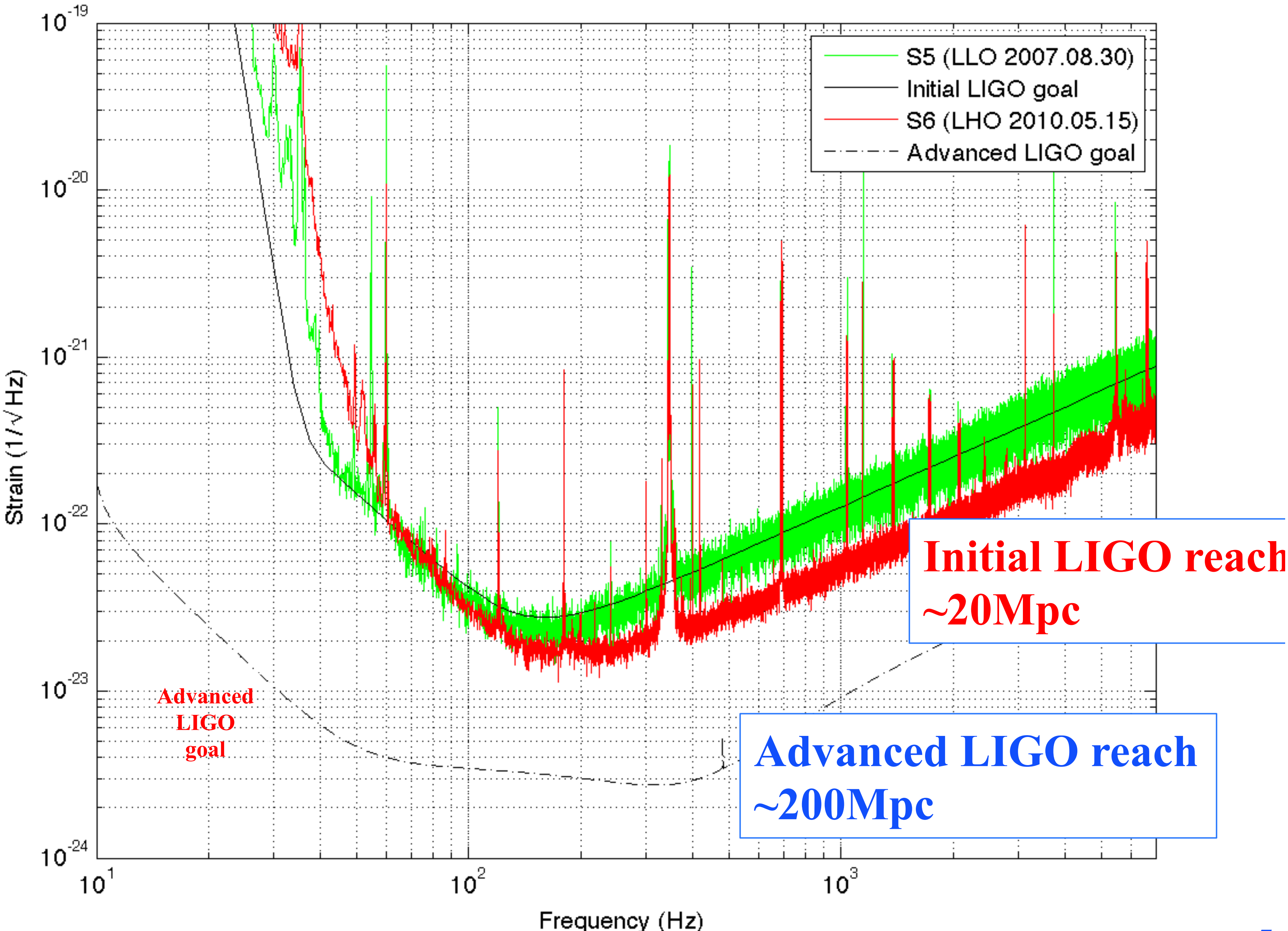
William Smith College 1908

Science & Technology Facilities Council Rutherford Appleton Laboratory

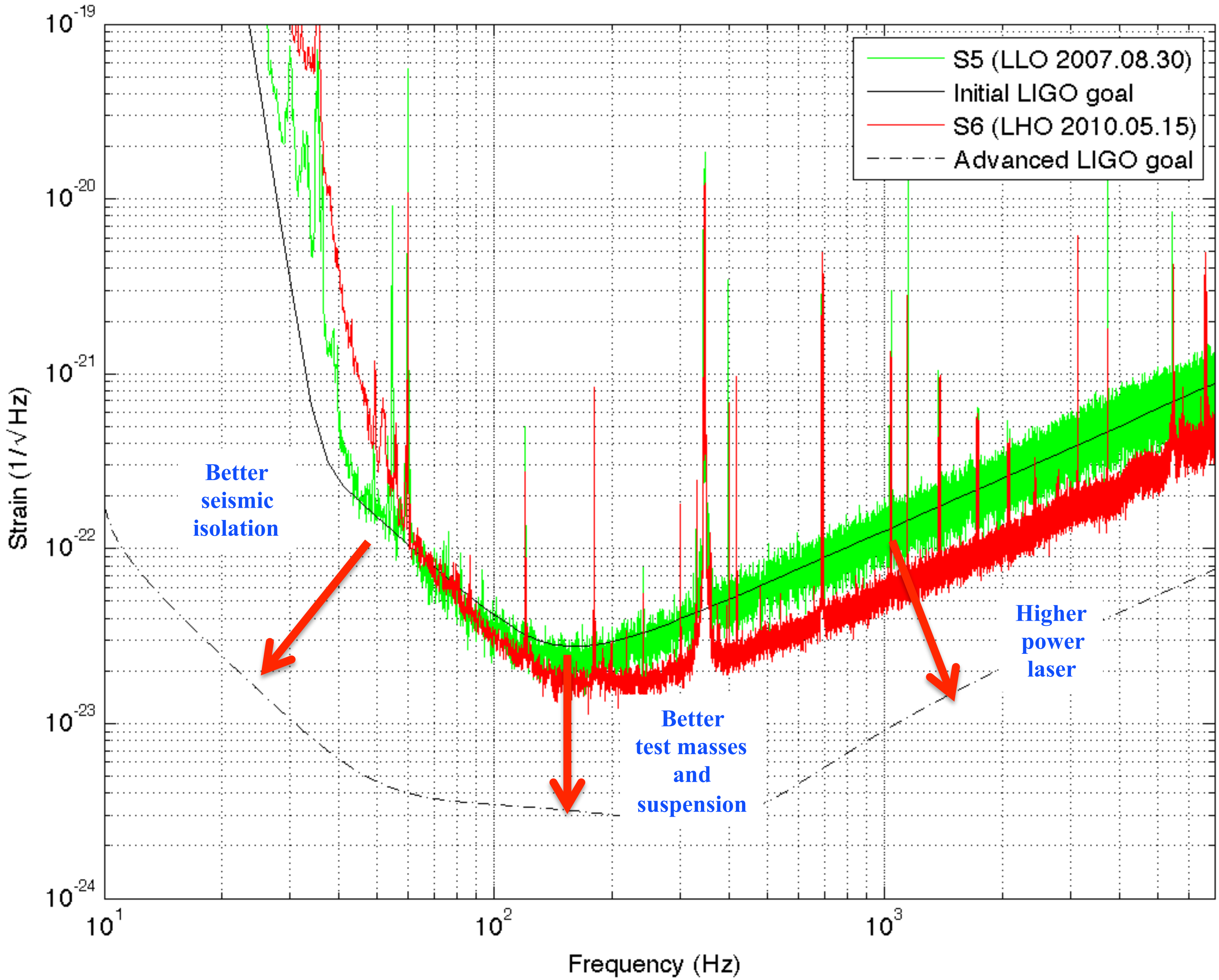
Universität Hannover

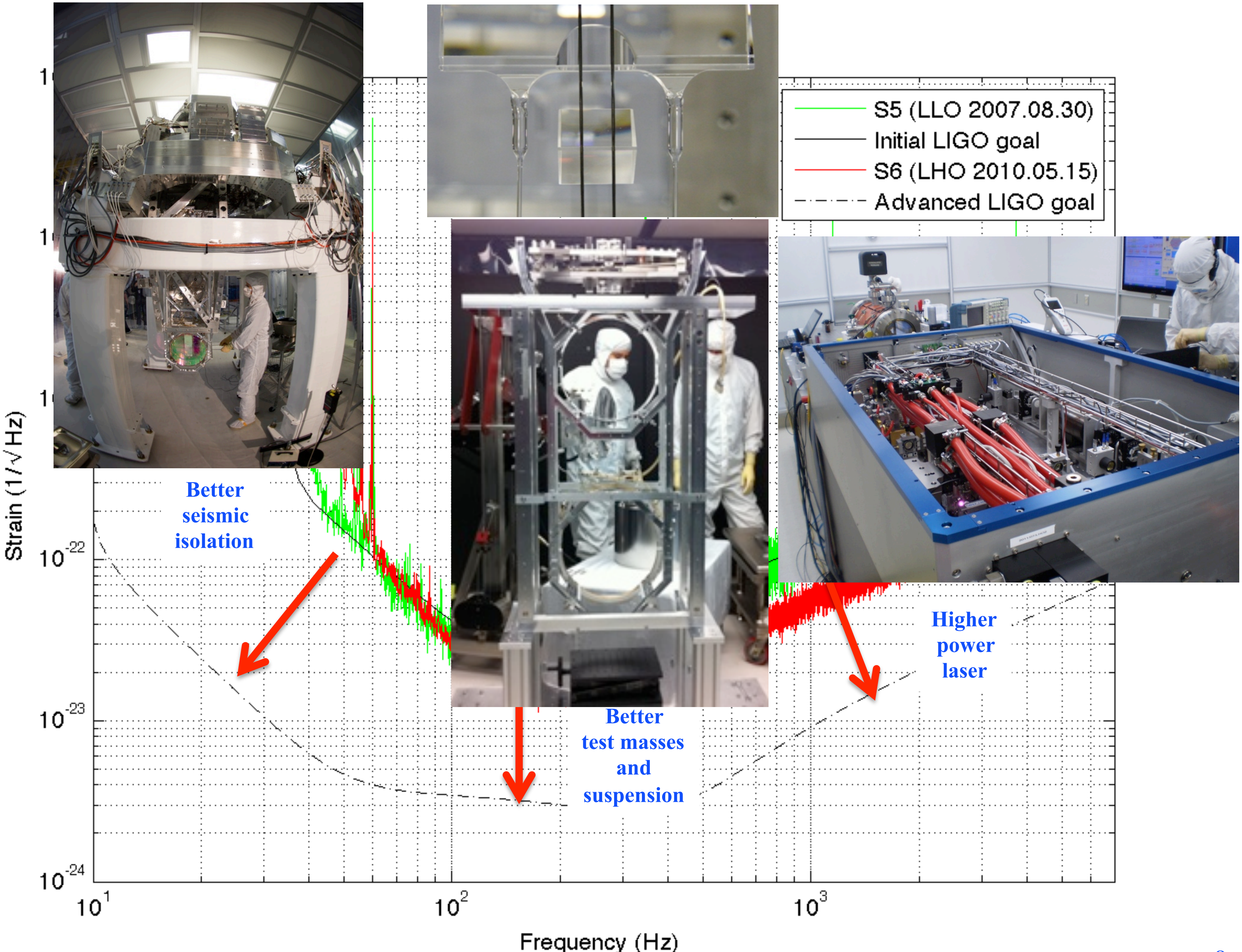
Optical configuration





S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
Advanced LIGO goal
Initial LIGO reach ~20Mpc
Advanced LIGO reach ~200Mpc


S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Better seismic isolation
Better test masses and suspension
Higher power laser
Strain (1/√Hz)
Frequency (Hz)
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3

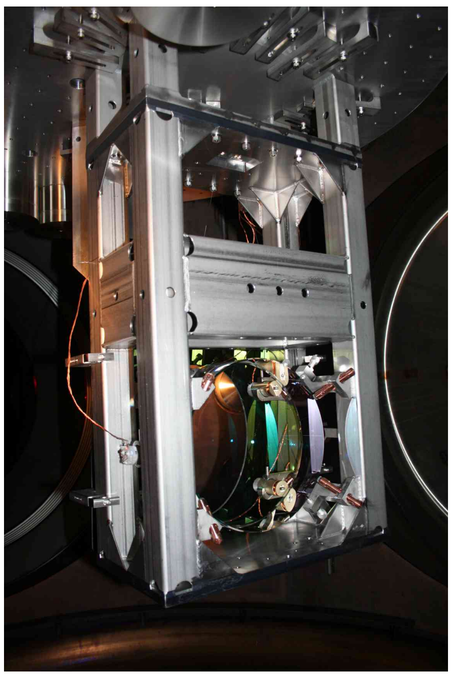


S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
10^-22
10^-23
10^-24
10^1
10^2
10^3
Frequency (Hz)
Better seismic isolation
Better test masses and suspension
Higher power laser

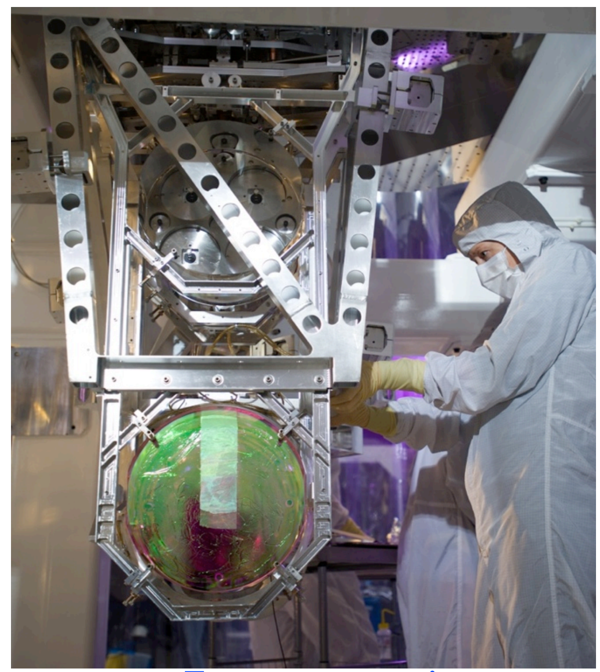
10X more sensitive, >10X harder…

- 14 unique fabricated parts
- 68 fabricated parts total
- 165 total including machined parts and hardware

- 188 unique fabricated parts
- 1569 fabricated parts total
- 3575 total including machined parts and hardware



Test mass suspension
From Initial LIGO



Test mass suspension
From Advanced LIGO

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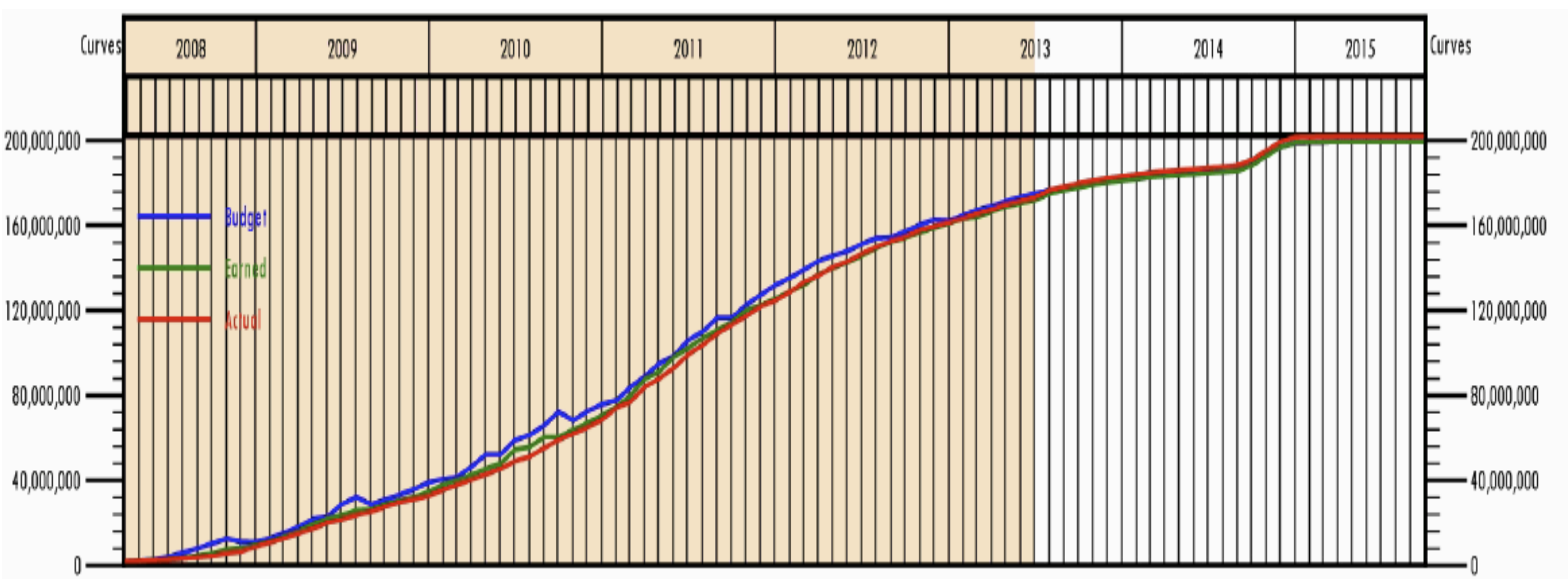
Advanced LIGO support

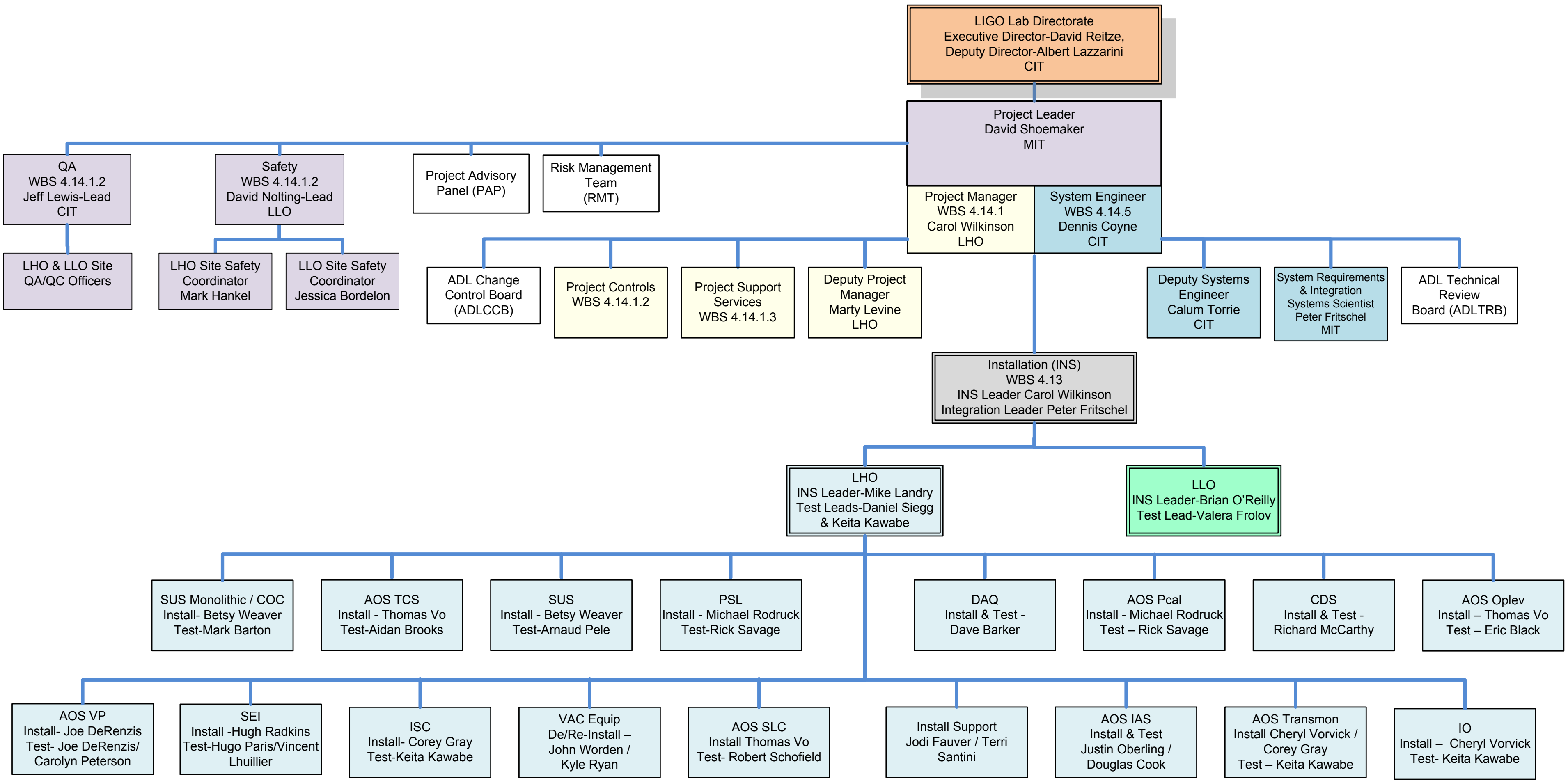
- NSF-supported (~$205M MREFC phase)
  - » Caltech as awardee, MIT and Caltech sharing responsibility institutionally, organizationally, scientifically, and technically
  - » Several US LSC institutions supported on subcontracts from LIGO Lab in Project phase (all US-supported aLIGO work to be on aLIGO MREFC)
- Foreign contributions – from experienced collaborators
  - » Germany – Pre-stabilized laser (value ~$14M incl. development); all equipment delivered; L1 and H1 installed
  - » United Kingdom – Test mass suspensions and some test mass optics (value ~$14M incl. development); deliveries complete, continued training, installation, and risk reduction
  - » Australia – wavefront sensors, optics, and suspensions (value ~ $1.7M incl. development); all procurements made, software in final development, extensive staff visits made
  - » Well integrated into aLIGO organization & project team
  - » Delivery risk retired

Progress

- 86.1% complete – onto flat part of the curve
- Estimate to Complete (ETC) of $28.7M at the end of June 2013
- Remaining contingency is $8.1M (May: 8.3); if acted on all liens, $3.0M remain
- Estimated remaining contingency is 0.6 months for H1 acceptance; for L1, all 7 months of originally allocated contingency plus an additional time



LHO installation org chart

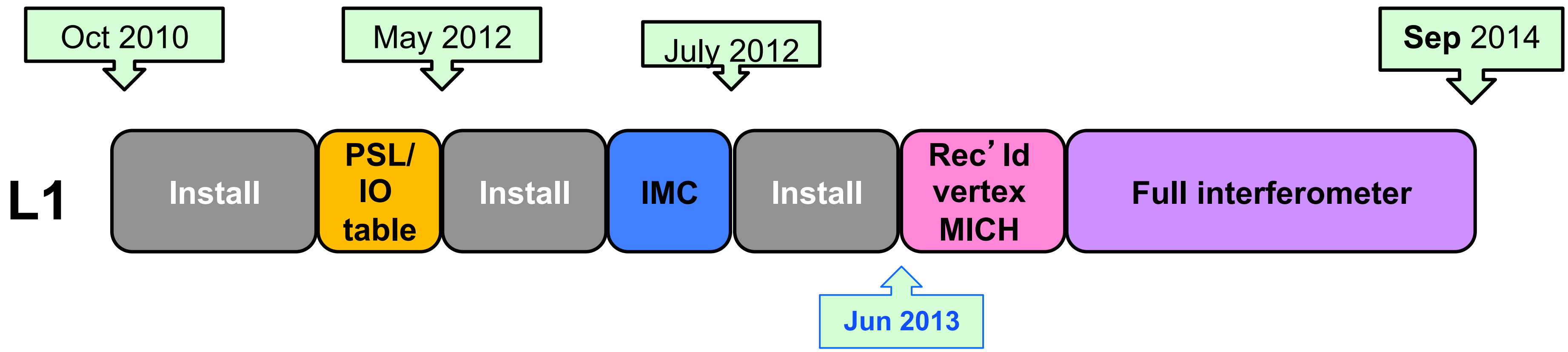


Staff

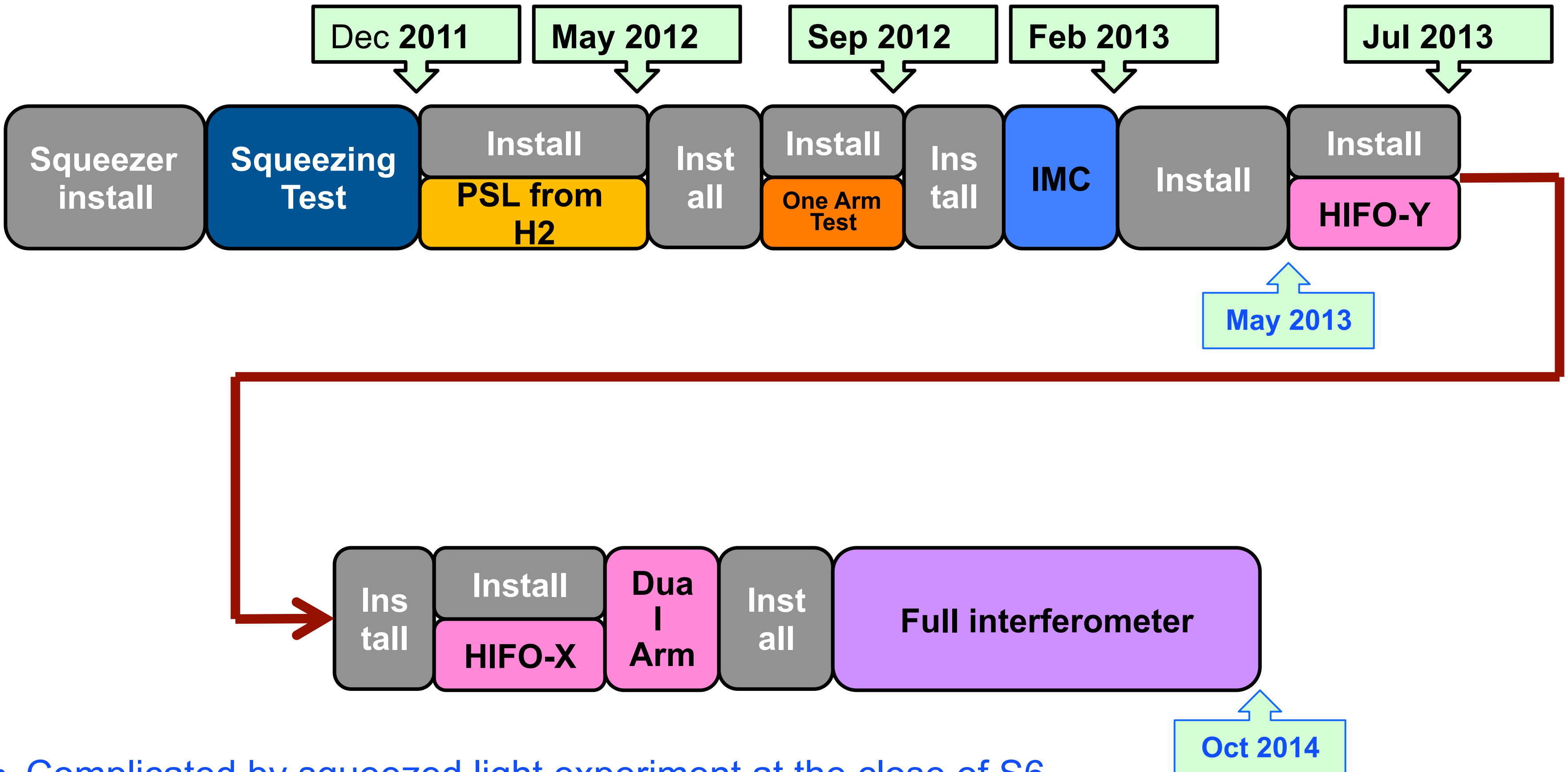
- Steady state science running: ~40 people at each of the sites
- At the peak of Advanced LIGO install ~90 people @ LHO, fewer at LLO owing to single interferometer
- Includes technicians for assembly and clean and bake, engineering, scientists, project controls, facilities, management, i.e. everything
- Also includes riggers/millwrights operating under $3.3M time and materials (T&M) contract. Expertise in rigging, pipefitting, sheet metal, etc. Flexibility in numbers (currently 4 at LHO, 2-3 part time at LLO)
- Visitors: Lab and LSC visitors to sites. LSC on sub-contract

Install Sequence L1

- L1 is pathfinder
- Natural install sequence
- Learn of problems early: interleave integration phases



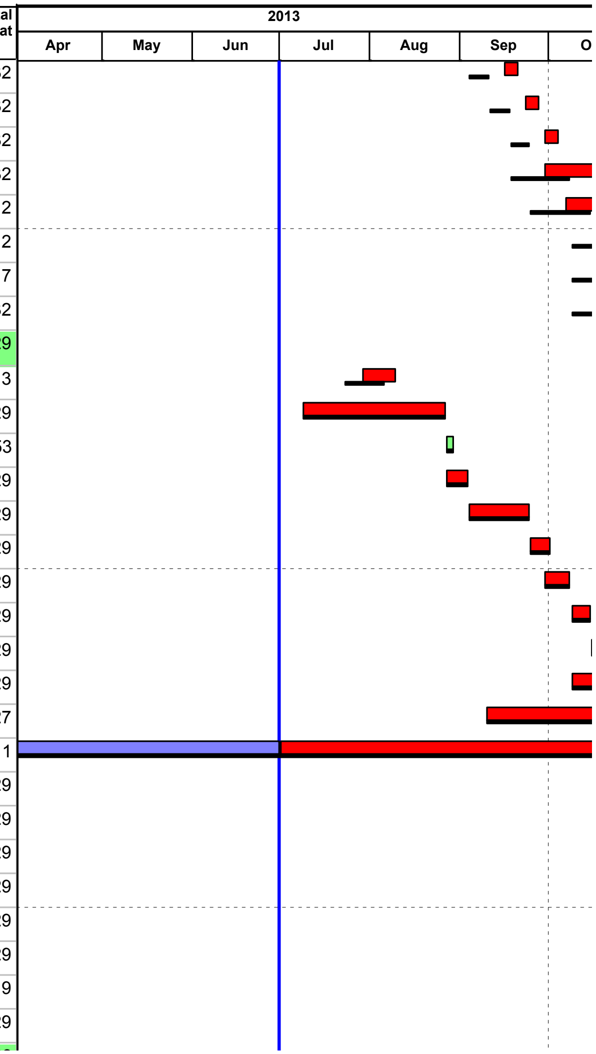
Install Sequence H1



- Complicated by squeezed light experiment at the close of S6
- First de-installed/installed on H2, i.e. second LHO interferometer
- Later, backed out H2 in favour of LIGO India
- LHO is the arm-locking pathfinder

Sample install schedule - LLO

Activity ID	Activity Name	Orig Dur	Rem Dur	Start	Finish	% Comp	Total Float
IN-L1-E1397	INS L1: Install Cartridge in BSC, & Align X- arm (BSC4)	5	5	09-16-13	09-20-13	0%	-32
IN-L1-E3210	INS L1: Vacuum Pump Down X- arm (BSC4)	5	5	09-23-13	09-27-13	0%	-32
IN-L1-E1410	INS L1: Checkout/test HEPI X- arm (BSC4)	5	5	09-30-13	10-04-13	0%	-32
IN-L1-E1429	INS L1: Checkout/test ISC and AOS in ETM X- arm (BSC4)	15	15	09-30-13	10-18-13	0%	-32
IN-L1-E1420	INS L1: Checkout/test ISI X- arm (BSC4)	15	15	10-07-13	10-25-13	0%	-12
IN-L1-E1430	INS L1: Checkout/test SUS X- arm (BSC4)	10	10	10-21-13	11-01-13	0%	-12
IN-L1-E5003	INS L1: AOS TCS Verification Tests, RH Electronics (BSC4)	25	25	10-21-13	11-22-13	0%	-17
IN-L1-E1419	INS L1: Acceptance of (BSC4)	40	40	10-21-13	12-17-13	0%	-32
L1 BSC5		197	154	02-18-13 A	02-18-14		-29
IN-L1-YE1405	INS L1: Install/Test AOS: AC & CRYO Baffle/PCal Y-arm (BSC5)	10	10	07-29-13	08-09-13	0%	-13
IN-L1-YE1315	INS L1: Prep ISI on Stand for Cartridge Assy Y-arm (BSC5)	35	35	07-09-13	08-26-13	0%	-29
IN-L1-YE5000	INS L1: AOS TCS RH Install Components (BSC5)	3	3	08-27-13	08-29-13	0%	53
IN-L1-YE1375	INS L1: Install/Test ETMY Optics, RH & Weld Fibers Y-arm (BSC5)	5	5	08-27-13	09-03-13	0%	-29
IN-L1-YE1380	INS L1: Mate Cartridge Y-arm (BSC5)	15	15	09-04-13	09-24-13	0%	-29
IN-L1-YE5033	INS L1: Align Cartridge Y-arm (BSC5)	5	5	09-25-13	10-01-13	0%	-29
IN-L1-YE5043	INS L1: Install TMS Y-arm (BSC5)	7	7	09-30-13	10-08-13	0%	-29
IN-L1-YE5053	INS L1: Install Payload Y-arm (BSC5)	5	5	10-09-13	10-15-13	0%	-29
IN-L1-YE5063	INS L1: Finalize Cartridge Y-arm (BSC5)	5	5	10-16-13	10-22-13	0%	-29
IN-L1-YE5073	INS L1: ISI Unlocked/Balanced, SEI Testing Y-arm (BSC5)	10	10	10-09-13	10-22-13	0%	-29
IN-L1-YE1570	INS L1: SUS Phase Two Testing ETM Quad SUSs (ETM) (BSC5)	34	34	09-10-13	10-25-13	0%	-27
IN-L1-YE5002	INS L1: Install/Test ETM OptLevs (BSC5)	177	84	02-18-13 A	10-29-13	13%	1
IN-L1-YE1385	INS L1: Install Cartridge in BSC, & Align Y- arm (BSC5)	5	5	10-23-13	10-29-13	0%	-29
IN-L1-YE1590	INS L1: Vacuum Pump Down Y- arm (BSC5)	5	5	10-30-13	11-05-13	0%	-29
IN-L1-YE1390	INS L1: Checkout/test HEPI Y-arm (BSC5)	5	5	11-06-13	11-12-13	0%	-29
IN-L1-YE1400	INS L1: Checkout/test ISI Y-arm (BSC5)	15	15	11-13-13	12-05-13	0%	-29
IN-L1-YE1410	INS L1: Checkout/test SUS Y-arm (BSC5)	10	10	11-27-13	12-12-13	0%	-29
IN-L1-YE1429	INS L1: Checkout/test ISC and AOS in ETMs Y- arm (BSC5)	25	25	11-06-13	12-12-13	0%	-29
IN-L1-YE5003	INS L1: AOS TCS Verification Tests, RH Electronics (BSC5)	30	30	12-13-13	02-03-14	0%	-19
IN-L1-YE1439	INS L1: Acceptance of (BSC5)	40	40	12-13-13	02-18-14	0%	-29



Daily installation meeting

- Since Oct 2010, we have had daily 08:15 installation meetings
- We sort INS priorities, near-term scheduling, staffing and interface issues
- Look for collisions, staff and equipment shortages, solutions
- Short (~30 minutes)
- Work permits may be reviewed

Procedures and checklists

- We have several flavours of installation documents
  - » Complete and detailed procedures
  - » Short, breakout checklists
  - » Safety documents, Hazard analyses
  - » Bug trackers
- First we touch on short, aviation-style checklists

LIGO	LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY ALIGO INSTALLATION PROCEDURE	E1200915 -v1- Document No Rev. Sheet 16 of 27
	WBSC1	Nov 9th, 2012 (1:08pm PT)

4.11 Install Ring Heater

Using G1100850:

- Install Upper Ring Heater Assy (D1001838).
- Install Lower Ring Heater Assy (D1001895).
- Install Ring Heater cables (D1001517).

Completed, approved, checked by:

Date:

Comments

4.12 Install glass masses and weld fibers

- Install the new Main Chain loop as built per D060516
- Position masses and weld fibers as per T050213.
- Perform fiber tests per T1100594.
- Suspend Reaction Chain in double suspension and ali

LIGO	LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY SPECIFICATION	Document No Rev. LIGO-E1300166 V1 Sheet 3 of 3
	Critical lift plan for the aLIGO BSC2 cartridge installation	

Pre-lift checklist:

Task Leader: ___________________________

1. Verbally confirm that team members have introduced themselves to each other and that all have read the procedure, are aware of the hazards and are wearing correct PPE. ________
2. Verbally remind team members of the stop work policy. ________
3. Verbally remind team members to not get under the load once it has been lifted.
4. Confirm that the crane and lifting gear have been inspected. ________
5. Confirm that the cartridge is cleared and disconnected from any cables, etc. _________

Checklists

- Are:
  - » Short: 1-2 pages, 6-12 key items that the team absolutely must perform
  - » Not intended as a cookbook: people have to keep thinking
  - » Intended to encourage teamwork
  - » Living documents, intended to be refined

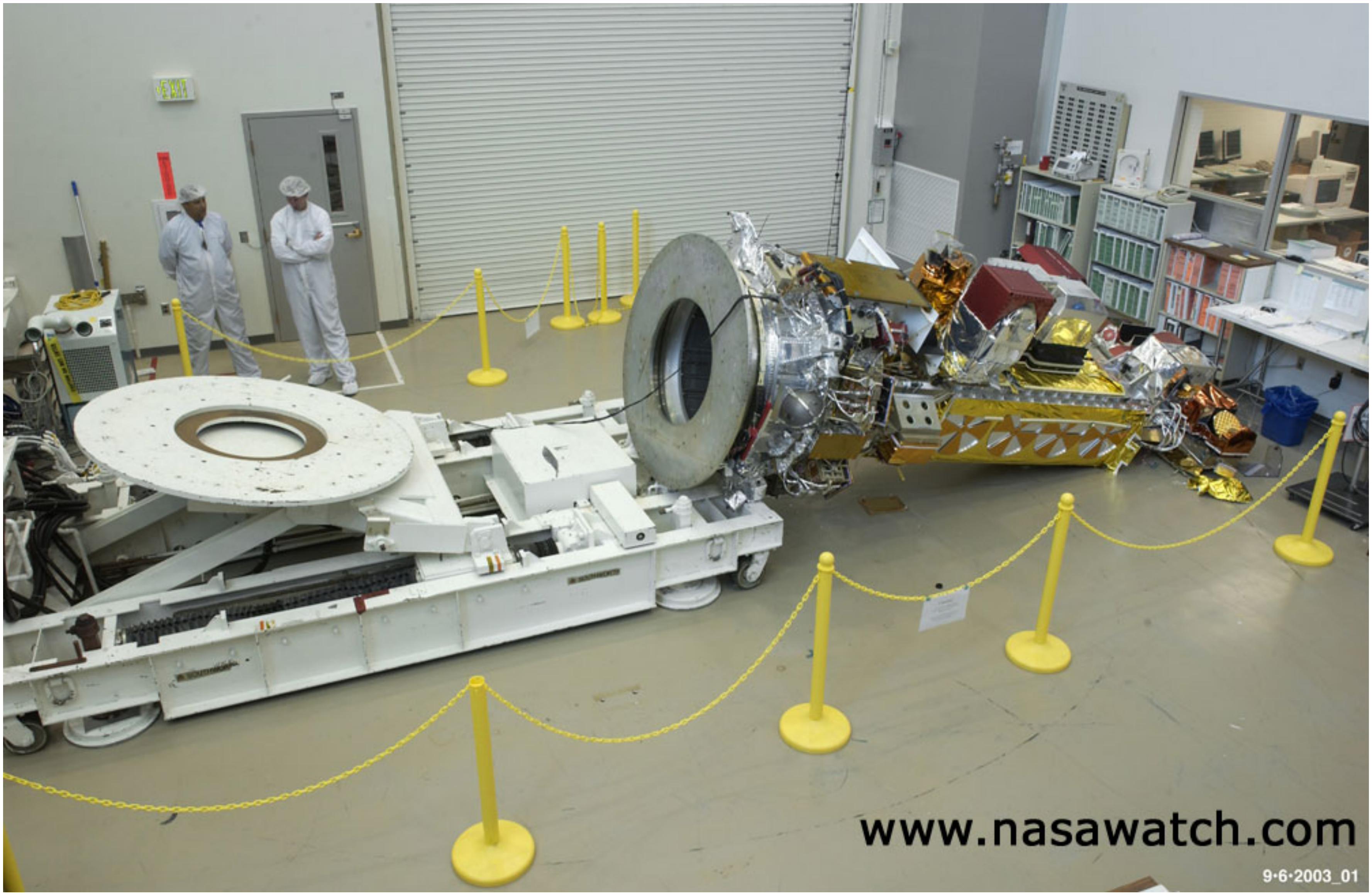
- Are not
  - » Intended as comprehensive with respect to all steps
  - » A recipe whereby you can turn you brain off
  - » A panacea. Things will occasionally go wrong; we have to recognize problems early/respond/react accordingly

A couple of examples*

- Aviation
  - » Long history of using and refining checklists
  - » Cessna engine failure checklist, first bullet: "Fly the plane"
- Surgery
  - » Central line infection checklist: double-digit drops in infection rates, shorter ICU times, fewer deaths
  - » WHO surgery checklists: dramatic improvements in survival rates, infection rates, operating-theatre communications
  - » 20% hold-outs from surgeons: when polled, however, 94% wanted checklists if they themselves were operated on

* From The Checklist Manifesto, A. Gawande (2009)

Adherence



LIGO

Goddard analysis of event

- EARTH SCIENCE MISSIONS ANOMALY REPORT
- Date Released: Tuesday, September 9, 2003
- Source: Goddard Space Flight Center, DATE OF ANOMALY: September 6, 2003
- LOCATION OF ANOMALY: Lockheed Martin, Sunnyvale CA

DESCRIPTION OF EVENT:

- As the NOAA-N Prime spacecraft was being repositioned from vertical to horizontal on the "turn over cart" at approximately 7:15 PDT today, it slipped off the fixture, causing severe damage. (See attached photo). The 18' long spacecraft was about 3' off the ground when it fell.

- The mishap was caused because 24 bolts were missing from a fixture in the "turn over cart". Two errors occurred. First, technicians from another satellite program that uses the same type of "turn over cart" removed the 24 bolts from the NOAA cart on September 4 without proper documentation. Second, the NOAA team working today failed to follow the procedure to verify the configuration of the NOAA "turn over cart" since they had used it a few days earlier.

IMPACT ON PROGRAM/PROJECT AND SCHEDULE:

- The shock and vibration of the fall undoubtedly caused tremendous damage. Significant rework and retest will be required. NOAA-N Prime is planned for launch in 2008.

Safety

- Advanced LIGO safety officer resident at each site
- Stop work policy in force and routinely advertised, e.g.
  - » Trivial slowdowns for clarification of procedure
  - » ~few hour stop works to ensure safe practice, e.g. eLIGO stop work for HAM seismic platform fasteners
  - » ~month stop works for complicated impacts, e.g. fiber breakage
- Detailed assessment of hazards and associated mitigations for given assembly and installation procedures: Hazard analyses
  - » Example on next page
  - » Crews meet at each site to ensure procedures and hazard analyses read and understood

Hazard analyses

6) **Hazard Analysis Severity Table (The number in brackets is a reference back to section 2 summarizing the hazard)**

Item (Ref)*	**Hazard**	**Cause**	**Effect**	**Unmitigated Severity**	**Unmitigated Probability Level**	**Unmitigated Risk Index**	**Comment**	**Mitigation**	**Mitigated Severity**	**Mitigated Probability Level**	**Mitigated Risk Index**
1 (2.1)	Fingers/hand/arm pinching/crushing hazard	Between Cartridge and Support tubes on Test Stand or in Chamber	Injury to personnel	Critical	Occasional	2C		A minimum number (4) of personnel must be trained for and follow safety rules of lifting equipment being used	Negligible	Remote	4D
2 (2.2)	Cartridge impact anywhere other than mounting surfaces.	Interference with support tubes, Test Stand or chambers	Damage to mostly suspended items.	Critical	Probable	2B	Damage concern mostly to suspensions during lift or lower, to stand or chamber	Remove interfering items & lateral moves of cartridge to clear obstacles.	Marginal	Remote	3D
3 (2.3)	Particulate contamination	Debris falling from above: crane etc. Removal of covers/caps	damage to environment	Marginal	Probable	3B		C4 Cloth covers for cartridge and suspended components	Marginal	Remote	3D
4 *(2.4)*	Payload drop hazard	Improper use of interface tooling, linkages, crane	Injury to personnel; damage to equipment	Critical	Remote	2D	3X or better safety factor on all lifting equipment (Industry standard)	Personnel must be trained and follow detailed procedure and checklist.	Critical	Improbable	2E
5 *(2.5)*	Failure of lifting mechanism, power outage	Lifting equipment not serviced or used as per instructions, power outage	Nuisance, lost time	Marginal	Remote	3D	Final weight of cartridge measured, insure crane within operating spec. at all times.	lifting equipment should be inspected and maintained, so that a failure is unlikely. Do not operate at time when a power outage is likely.	Negligible	Improbable	4E
6 *(2.6)*	Crane, structural failure	Overloaded crane, poor crane related maintenance	Injury to personnel; damage to equipment	Critical	Remote	2D		All items to be lifted pre weighed, Test lift, Proper crane maintenance	Critical	Improbable	2E
7 *(2.7)*	Assembly of components at height	On top of, or below Cartridge and above Support tubes	Injury to personnel; damage to equipment	Critical	Remote	2D	-	Use barrier plates and railings as instructed, and personnel must wear safety glasses ,shoes ,hard hats	Critical	Improbable	2E
8 (2.8)	Crane rotation failure	Hook Binds	Wrong orientation	Marginal	Remote	3D		Return cartridge to test stand, repair crane	Negligible	Improbable	4E

Tracking issues

- We employ a web-based tracker of issues on installation, integration, and facilities
- Every Friday, Systems meets with install and integration people to review status

Bugzilla – Bug List

Home | New | Browse | Search | [Search] [?] | Reports | Preferences | Help | Logged in as michael.landry@LIGO.ORG BG | CS | DE | EN | FR | JA | ZH-TW

aLIGO Integration Issue and ECR Tracker

Tue Jul 30 2013 17:27:23 PDT

Status: UNCONFIRMED, NEW, ASSIGNED, REOPENED, ACCEPTED, VERIFIED **Product:** AOS, COC, DAQ, FMP, GC, IO, ISC, PEM, PSL, SCM, SEI, SUS, SYS, TCS

105 bugs found.

ID ▼	Sev	Pri	OS	Assignee	Status ▲	Resolution	Summary
293	maj	Hig	Othe	dwayne.giardina@LIGO.ORG	NEW	---	Help needed to get Fortran compiler working correctly
282	nor	Hig	Othe	matthew.cowart@LIGO.ORG	NEW	---	Test four network switches
281	nor	Hig	Othe	dwayne.giardina@LIGO.ORG	NEW	---	move mlxbd to new network
291	nor	Hig	Othe	matthew.cowart@LIGO.ORG	ASSI	---	Color Copier Printer gives an error
283	nor	Hig	Othe	richard.mccarthy@LIGO.ORG	ASSI	---	CPS Circuit Modification to eliminate a high frequency oscillation
260	nor	Hig	Othe	matthew.cowart@LIGO.ORG	ASSI	---	Livingston Staff webpage is very out of date
257	nor	Hig	Othe	brian.lantz@LIGO.ORG	ASSI	---	Include new 'command' screen using Python/ guardian tools
229	nor	Hig	Othe	dwayne.giardina@LIGO.ORG	ASSI	---	replace UPS batteries
221	nor	Hig	Othe	matthew.cowart@LIGO.ORG	ASSI	---	visitor office iMac stuck on boot up
218	nor	Hig	Othe	peter.king@LIGO.ORG	ASSI	---	flow sensors for diode chiller keep failing
199	nor	Hig	Othe	dwayne.giardina@LIGO.ORG	ASSI	---	order / install new engineering workstation
198	maj	Hig	Othe	garilynn.billingsley@LIGO.ORG	ASSI	---	Power Limit for Optics w/o FC Cleaning (& LLO waiver of to clean MC before closing 6-2013)
194	nor	Hig	Othe	joseph.gleason@LIGO.ORG	ASSI	---	addition of a light shield to the IO/PSL periscope & differences in the periscopes
191	maj	Hig	Othe	janeen.romie@LIGO.ORG	ASSI	---	Droopy Quad top mass blades

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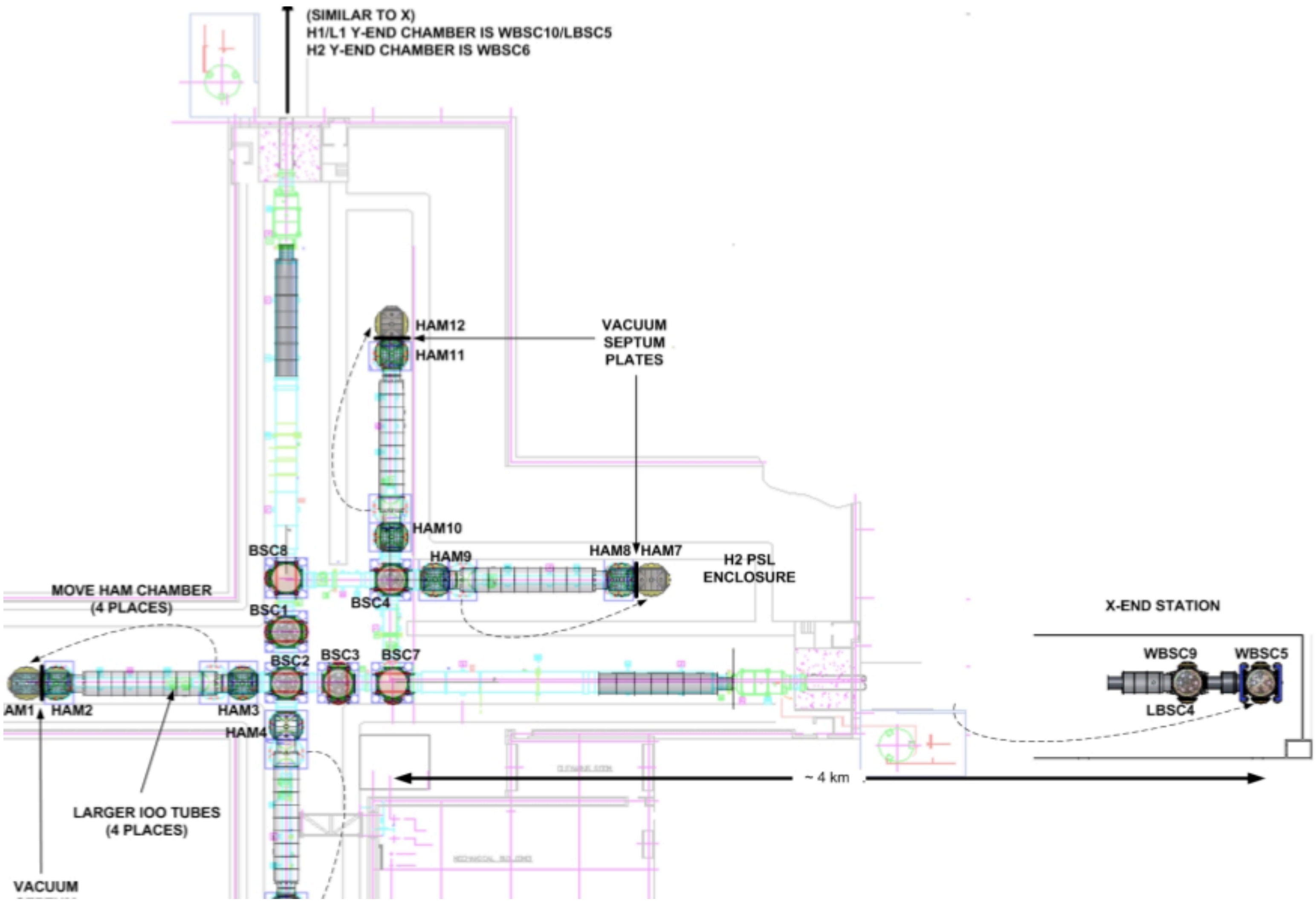
Installation at sites

- Had (and have) to :
  - » deinstall Initial LIGO
  - » Modify the vacuum envelope
  - » Clean in-chamber
  - » Install Advanced LIGO detector components
  - » Commission

Initial LIGO deinstallation

Vacuum equipment modification

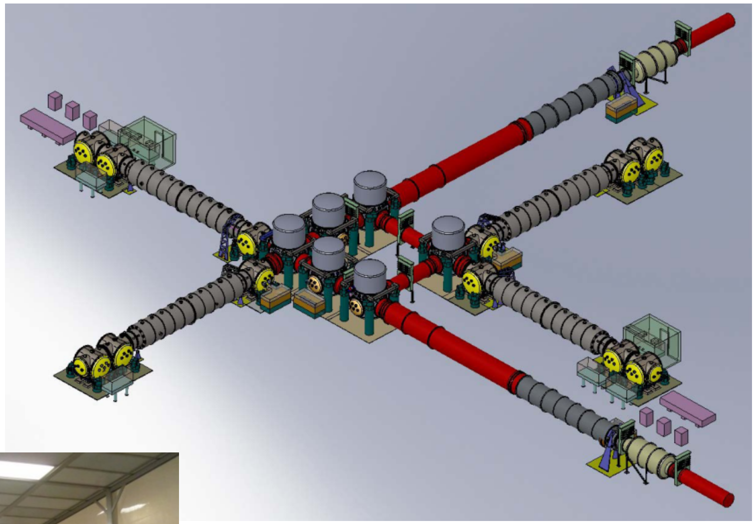


Vacuum mods

- Vacuum Equipment
  - » Problems with testing to qualify cleanliness at required level – working with contractor to resolve

I/O Tube Rollups

Flange Sets



Mid-Station Spool

Vacuum mod highlights

- Major L1 and H2 vacuum modifications in halls: input and output tubes removed, recycled. Two HAMs chambers moved
- Degrouting underneath HAMs: dusty operations in the main hall: next year, deinstallation of H1 will be difficult alongside H2 INS

Extending H2 to 4km

In-chamber cleaning

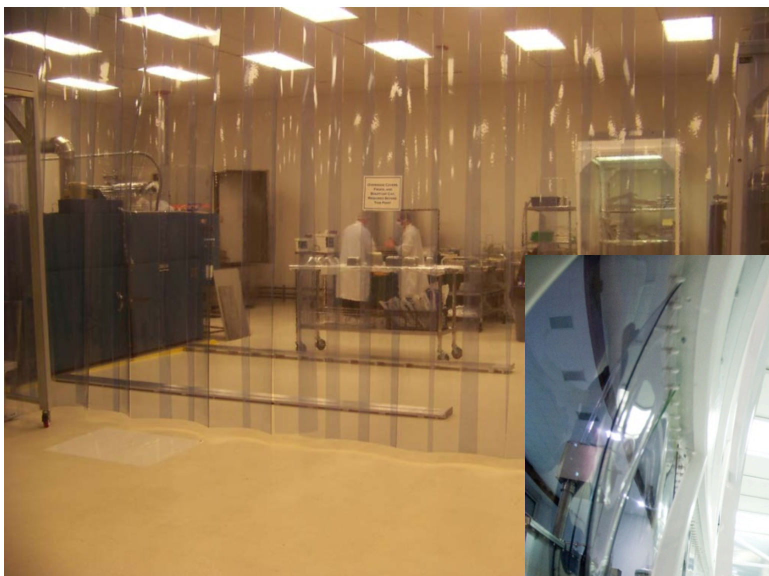
- High in-chamber particulate levels have been observed in Initial LIGO (metal oxides from steel treatment, dusts, Al foil etc)
- Removing oxide layer from interior heat-treated surfaces. Employ
  - » rotary-wire brush with HEPA vacuum assist
  - » dams and barriers
  - » solvent wipedown
  - » i) Fourier transform infrared spectroscopy (FTIR) assessment of hydrocarbon contamination, ii) swipe tests for particle density assessment
- Pneumatic tools used, all lubricants removed (contamination risk; tool failure rates thus high)

In-chamber cleaning

- Was an ongoing R&D effort at LHO since early December 2010
- Tools, brushing/vacuum/wipedown procedures, FTIR (Fourier-transform infrared spectroscopy) assays finalized
- Completed successfully at both sites

Clean and bake

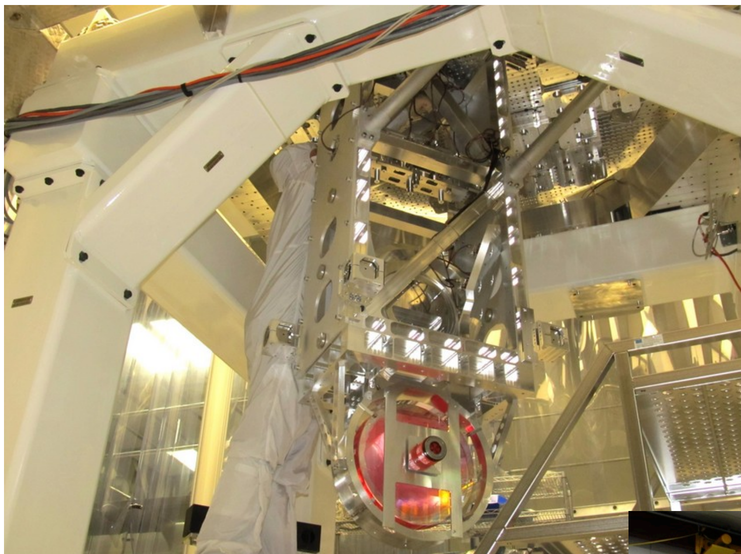
- Clean and Bake for Ultra-High Vacuum (UHV) Service
  - Initially underestimated effort – hired more staff
  - Procured additional vacuum bake ovens required to minimize downtime & meet throughput required
  - Cleanliness certification (by FTIR testing)



Clean & Bake Lab (LHO)

BSC installations

- For LIGO large chambers (“BSCs”), we assemble a cartridge in a given hall, and then crane it into the vacuum envelope

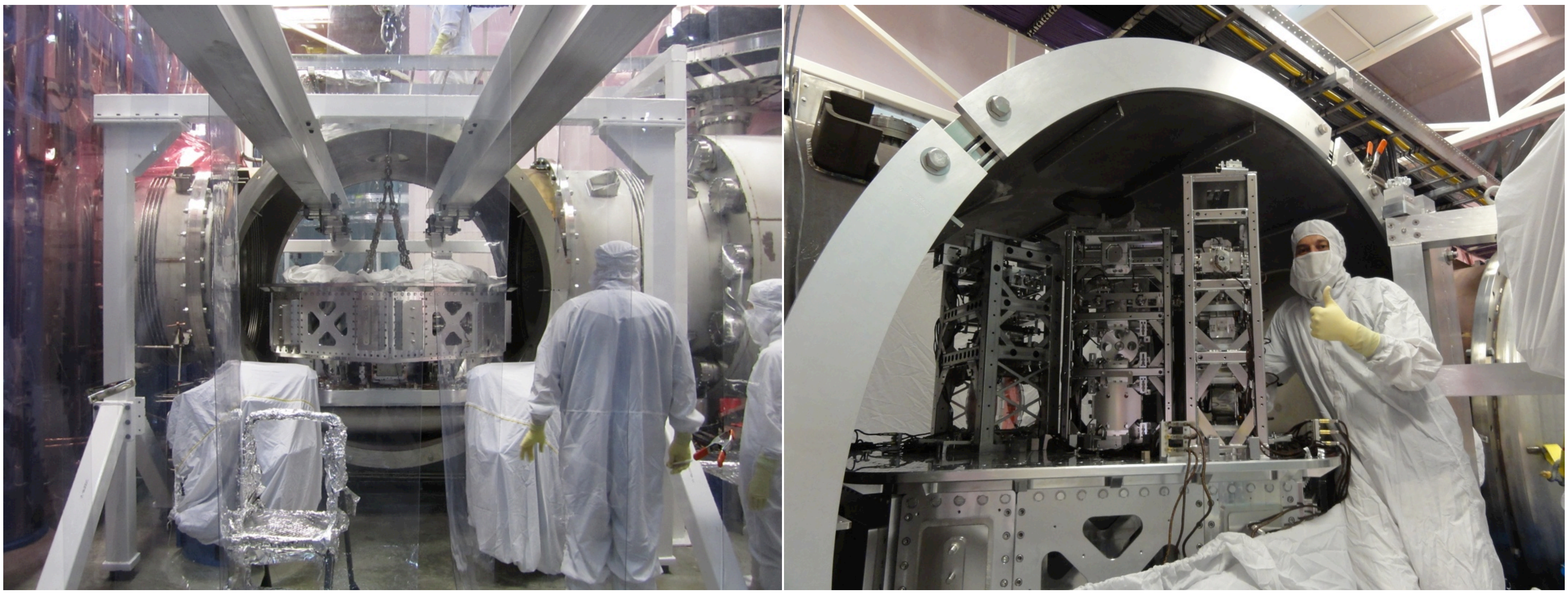


BS

ETMY

HAM installations

- For LIGO smaller chambers (“HAMs”), we install the seismic isolation platform into the chamber, and then populate it in situ



LLO HAM installation

Outline

1. A (very brief) introduction to LIGO
2. Organization: project controls, installation planning, documentation
3. Selected topics in installation
4. Problems and some solutions
5. Brief status of integration

Quality control

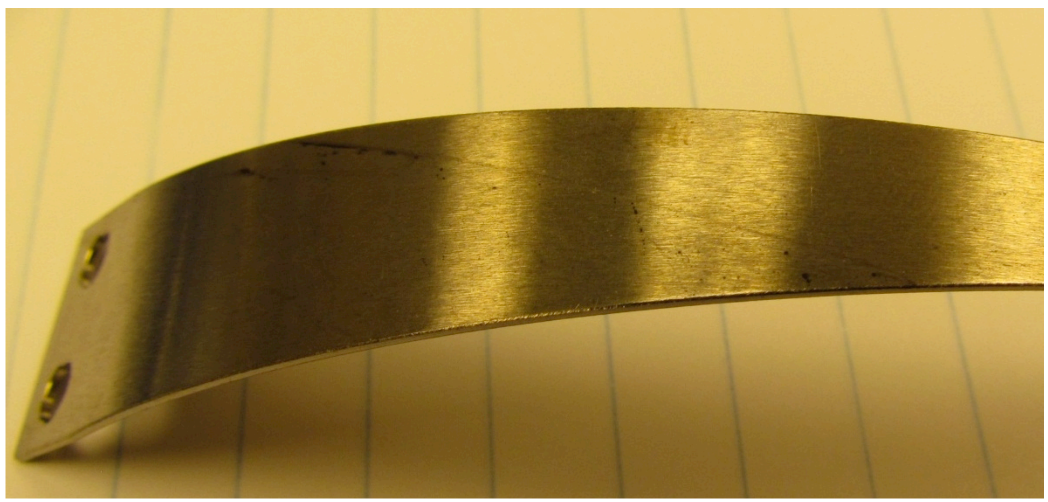
- QAME: Quality Assurance and Manufacturing Engineering group, a subset of Systems Engineering
- Check drawings, visit vendors, source inspect parts, coach designers, receive/inspect/record parts, etc.
- Work now naturally drawing down as designs and procurements finishing
- Some examples of their work
  - » Viewport and feedthrough testing
  - » Corrosion of suspension wires and blade springs

Viewport and feedthrough testing

- QAME: Every viewport in the LIGO vacuum system at each observatory is visually inspected then proof and leak tested. Electrical feedthroughs are also 100% leak tested.

Blade spring corrosion

- QAME: Cantilever Blade Springs were received from an overseas vendor with some spotting/light corrosion marks. There was insufficient time to remake the springs so QAME developed a mechanical and chemical process to remove the corrosion before Ni coating.

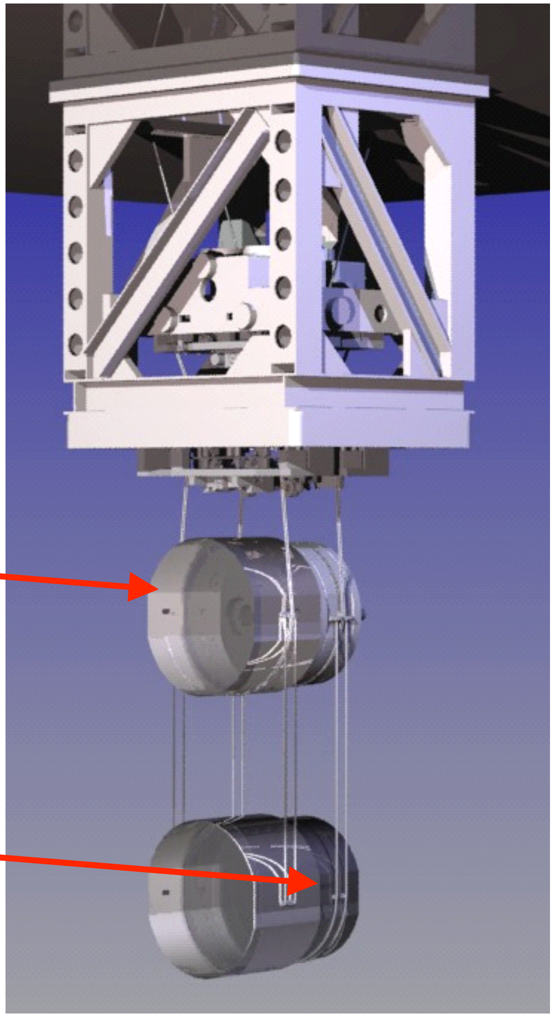


Sample problems

- We consider here a few of the problems we are working through in Advanced LIGO. There are many more, of course

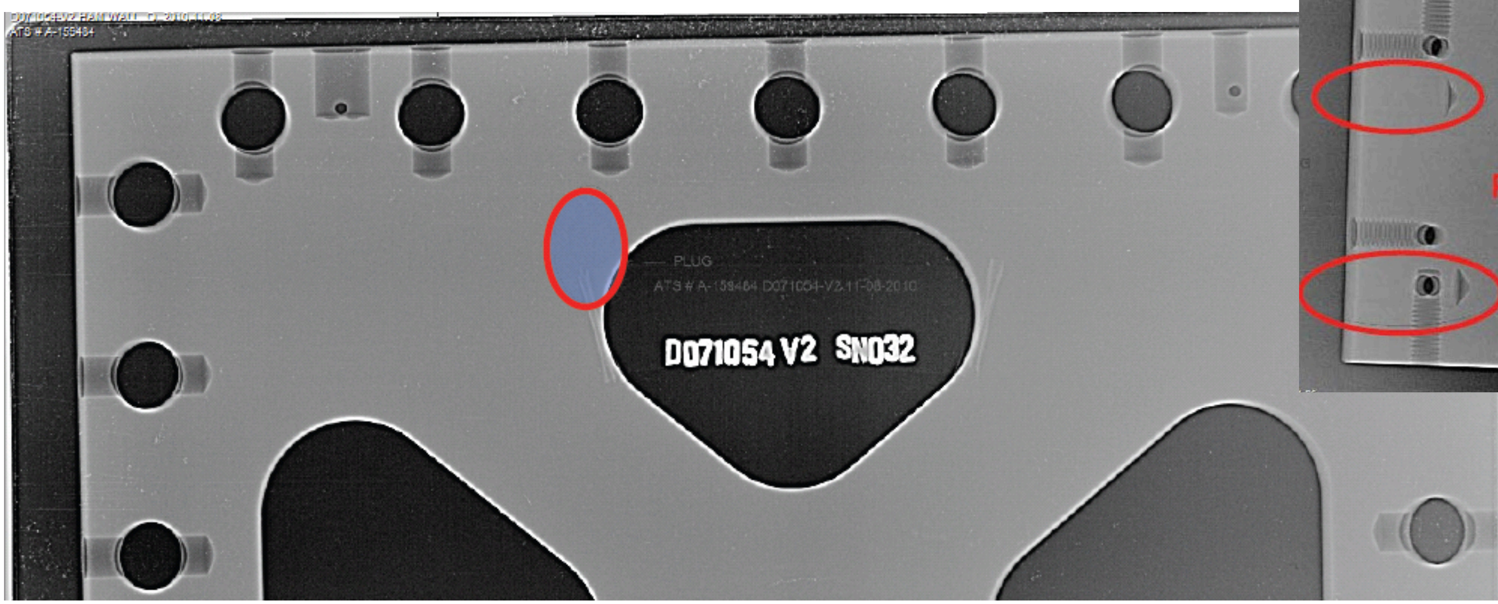
Penultimate mass, i.e. the second-to-last stage that comprises the monolithic structure

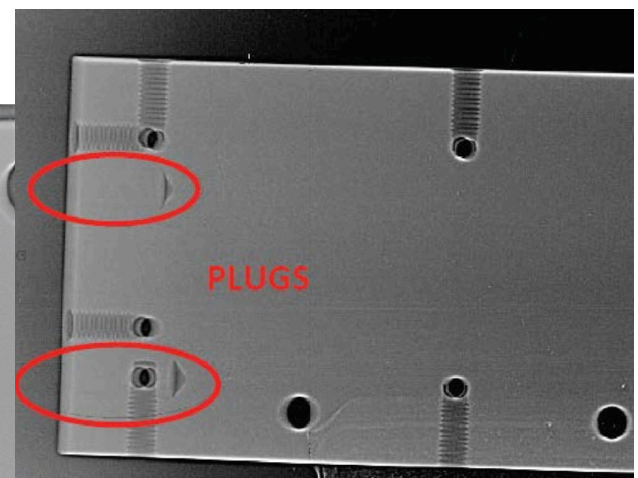
Gap between test mass and reaction mass, a potential site for gas damping



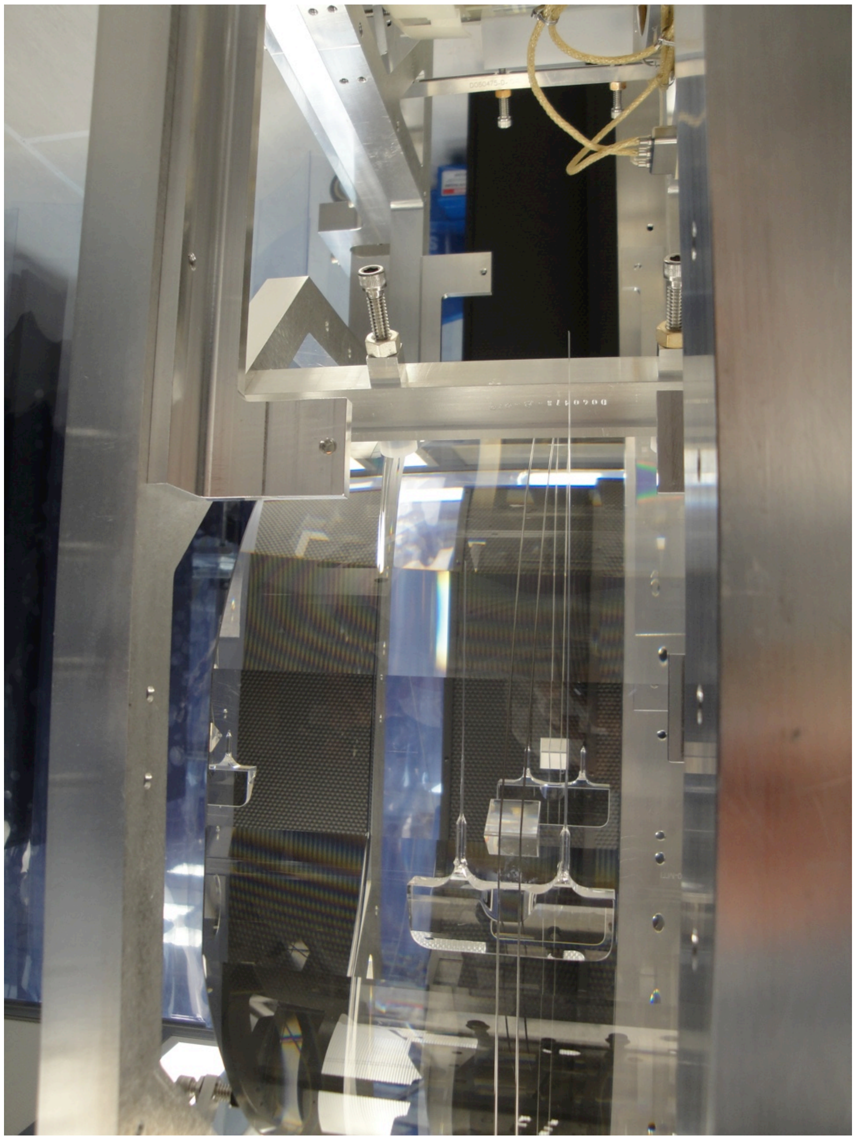
Weld repairs

- Unauthorized weld repairs detected visually in some seismic plates
- Investigated with contractor and x-rays
- At issue is trapped volumes and virtual leaks
- Concluded new parts were required

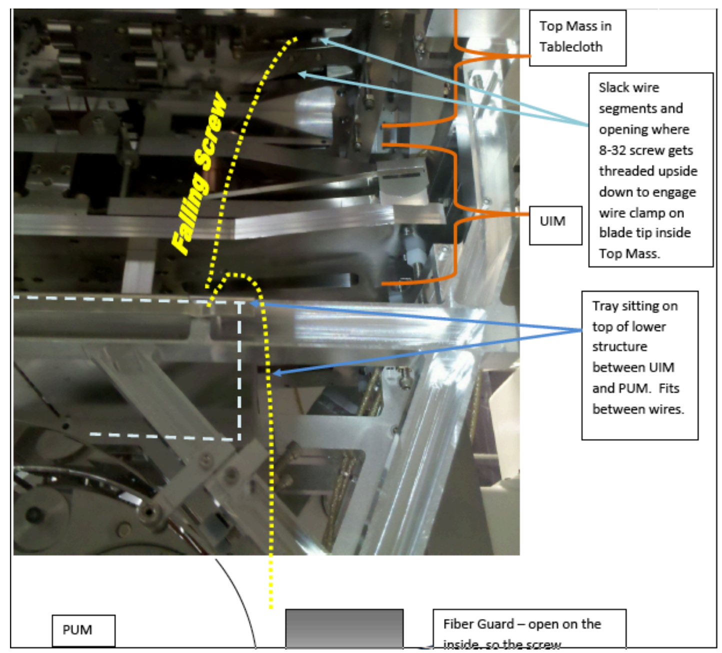




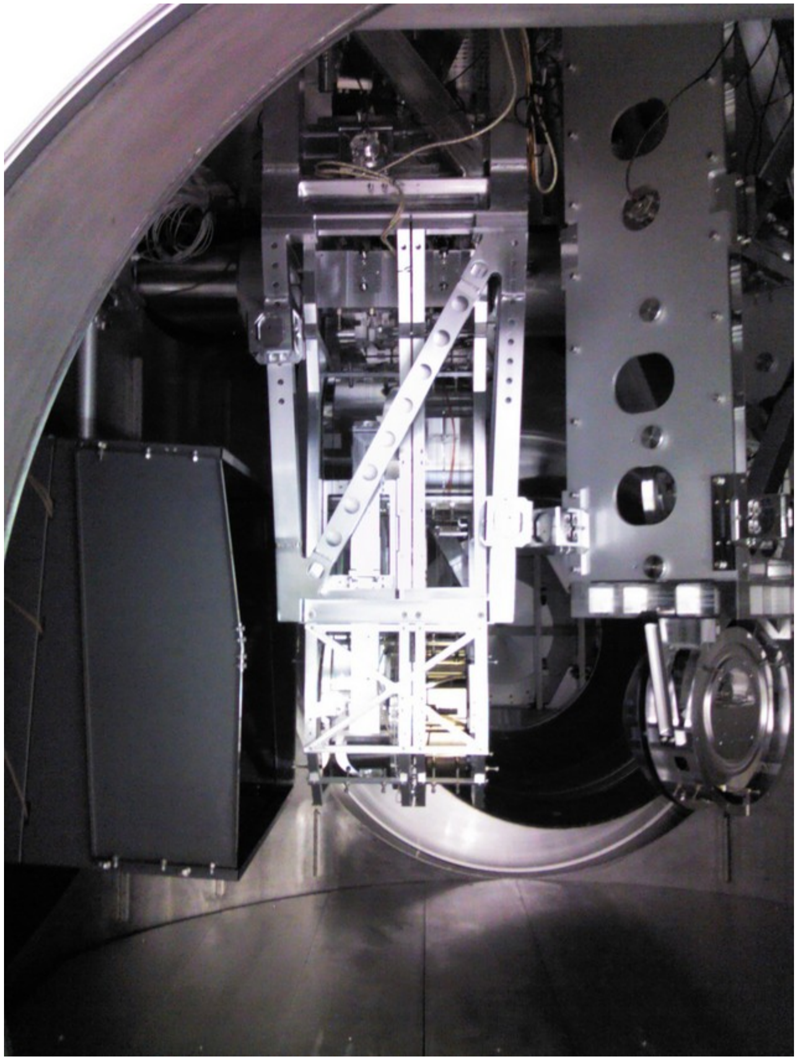
1^{st} ITMY fiber break



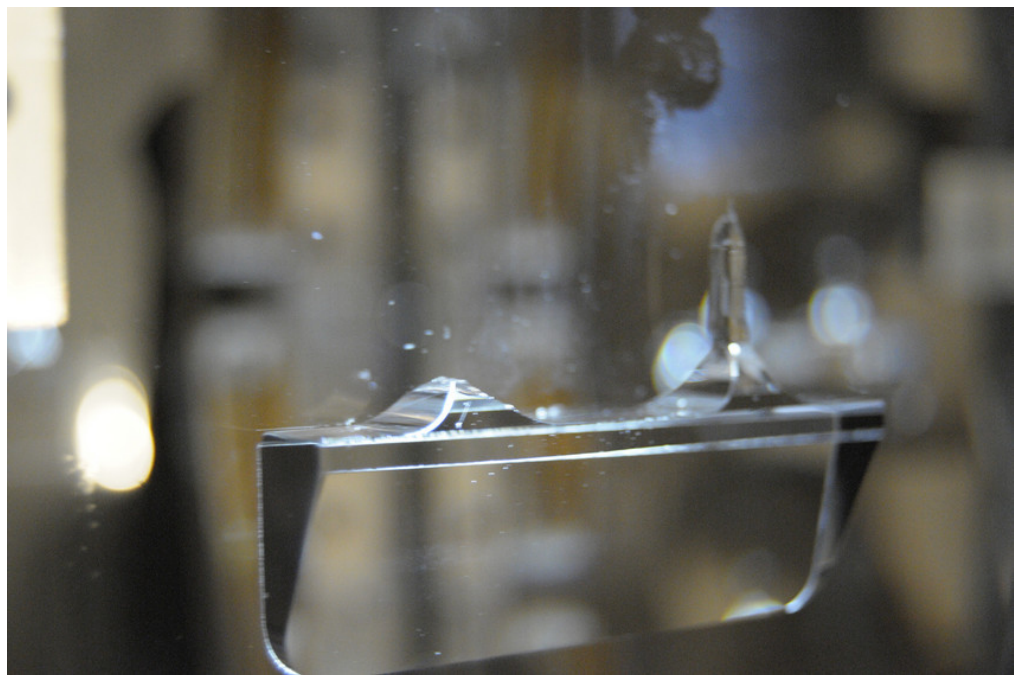
- First test mass successfully welded
- Fiber break when rebalancing on ISI; fastener defeated existing catch-pan
- New tooling, additional catch-surfaces to augment protection for such events fabricated



2nd ITMY (in-chamber) fiber break



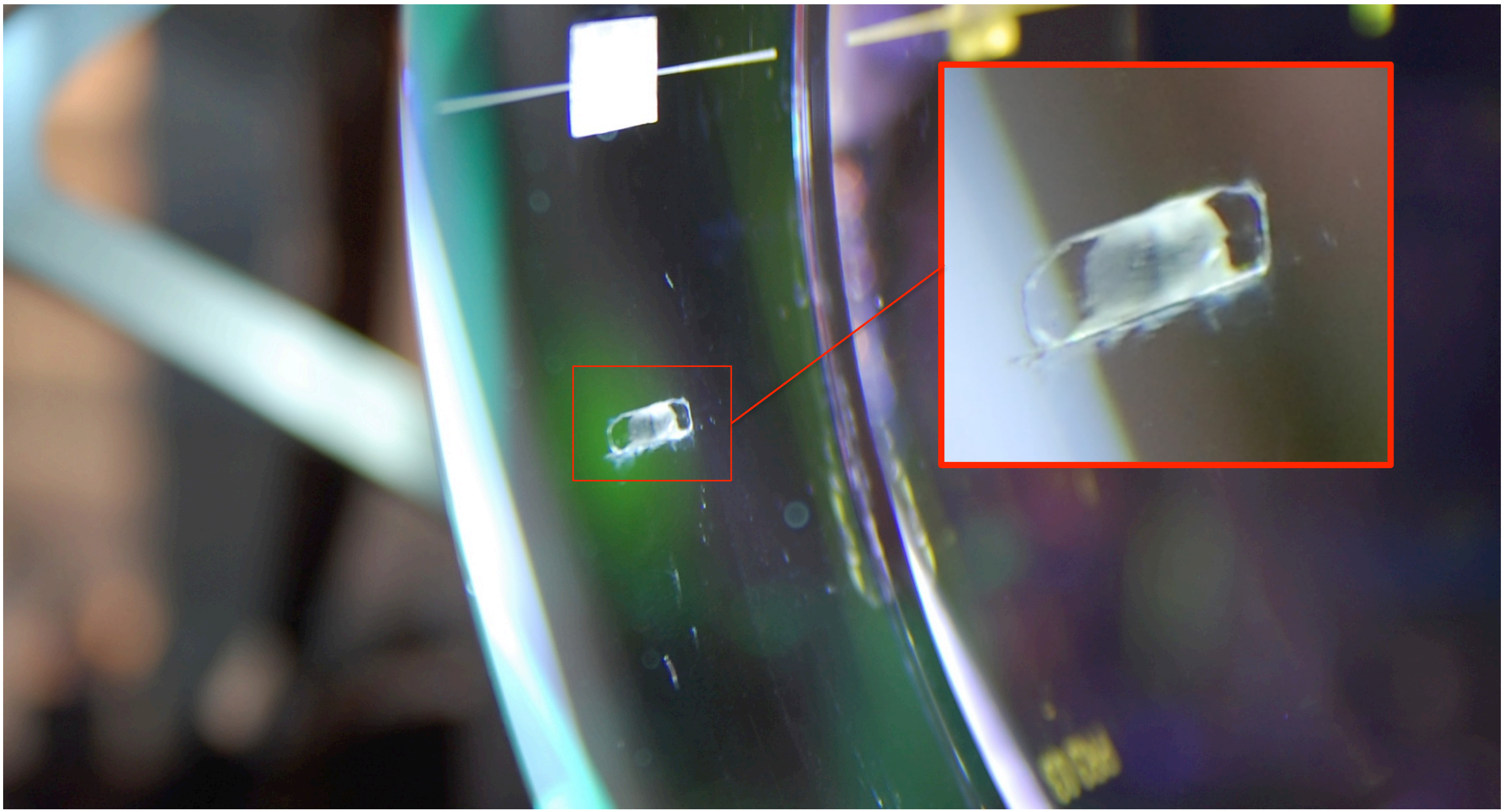
- ITMY fibers broken in shaking incident induced by code bug
- Stop work called; code fixed/reviewed, testing restarted
- Implemented wire hang of ITMY



LIGO

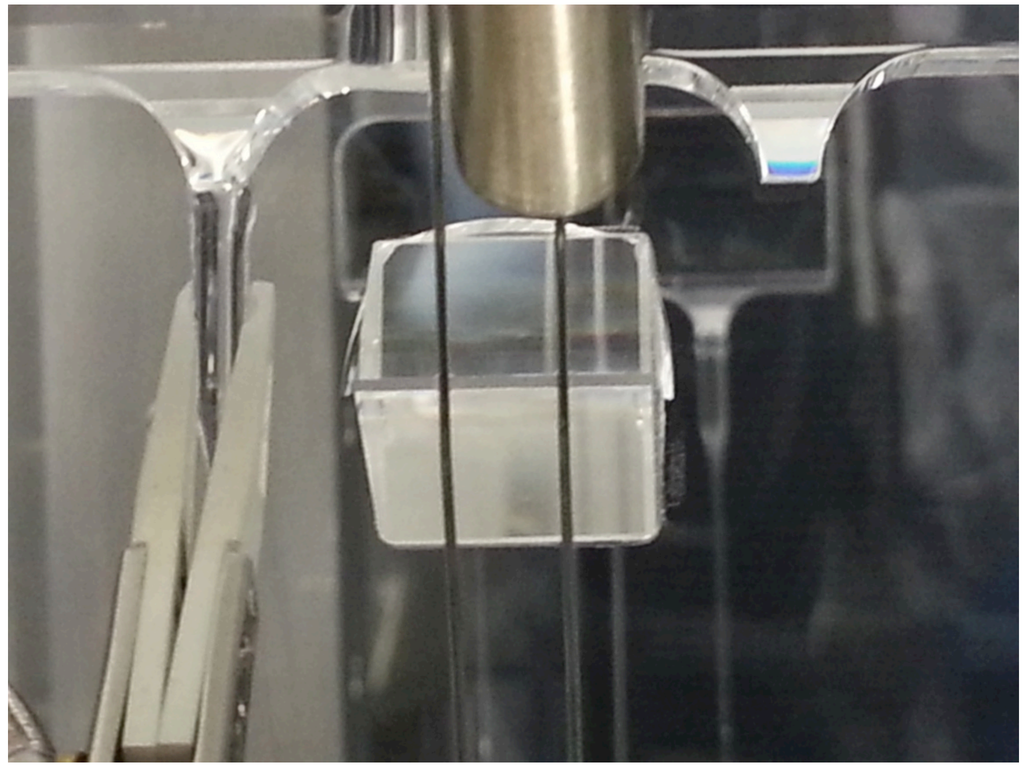
Prism liftoff

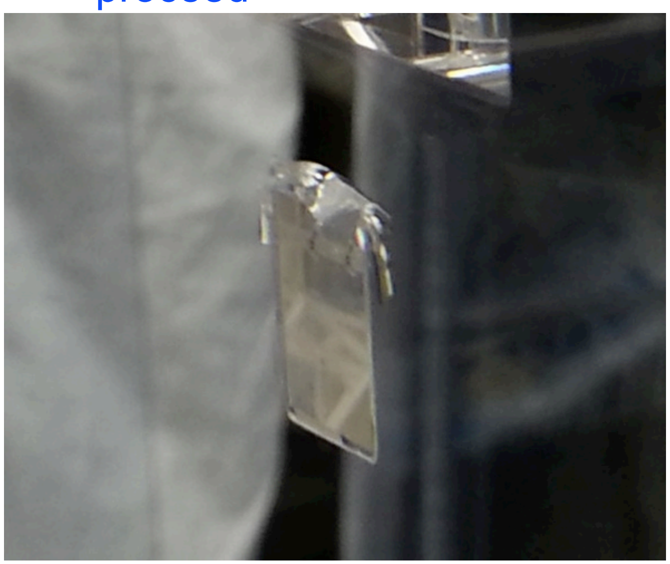
(LLO PR3 secondary prism)



LHO ETMX PUM

- The Penultimate mass (PUM) for ETMx at LHO crack developed at prism which catches metal wires
- Optic suspension continued, and looks ok – we will proceed with this
- A review team assembled, made recommendations for modifications of gluing approach and means to better shield prism from welding heat
- Next suspension is at LLO, able to proceed

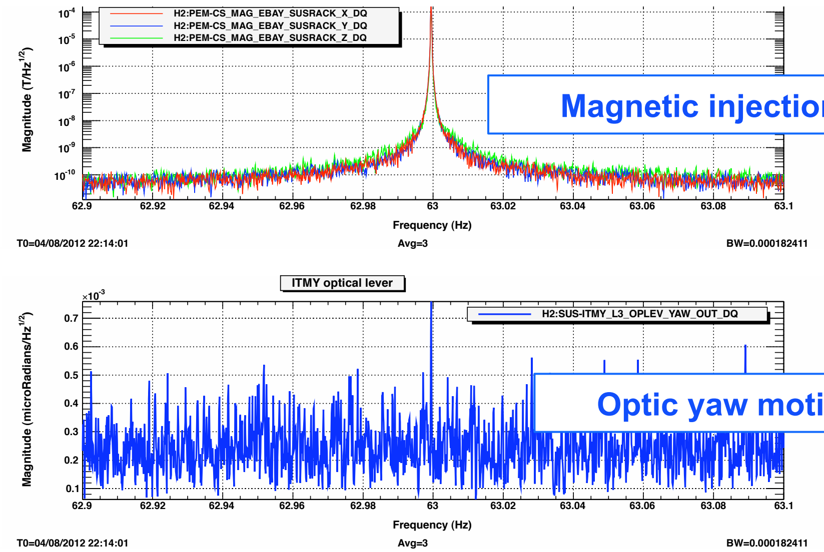




Magnetic coupling

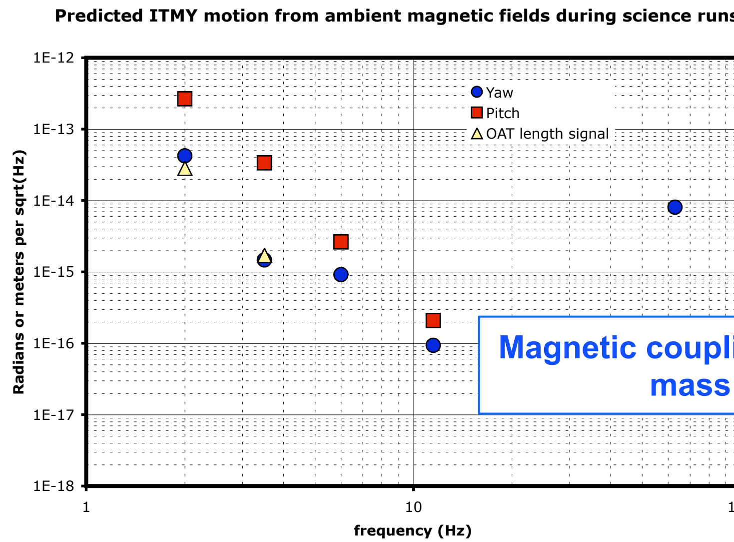
- Suspensions: Excess magnetic coupling observed to test mass motion
  - » Test mass SUS magnetic coupling assessment continues
  - » Ruled out damper magnets and OSEM un-slitted parts as culprit
  - » Investigating reaction masses (cold-worked steel)
  - » Lab and in situ measurements ongoing: next tests at Livingston Aug/Sep

Magnetic coupling, contd.

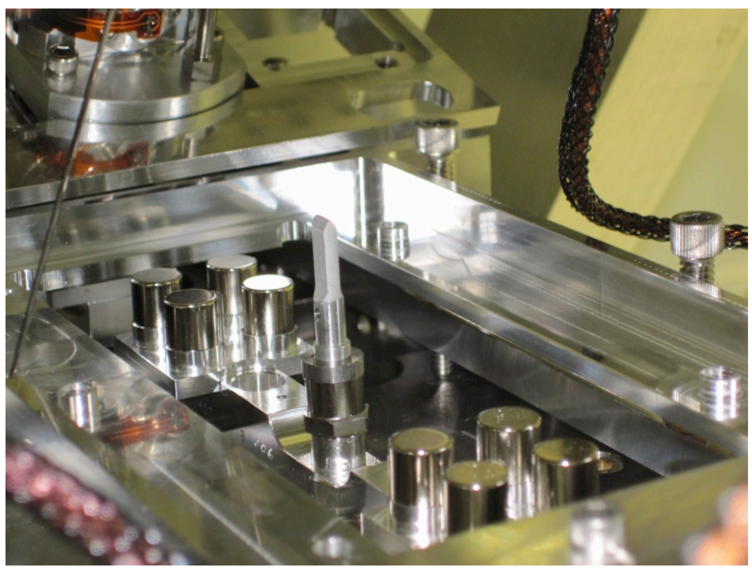


Magnetic injection

Optic yaw motion



Magnetic coupling at test mass

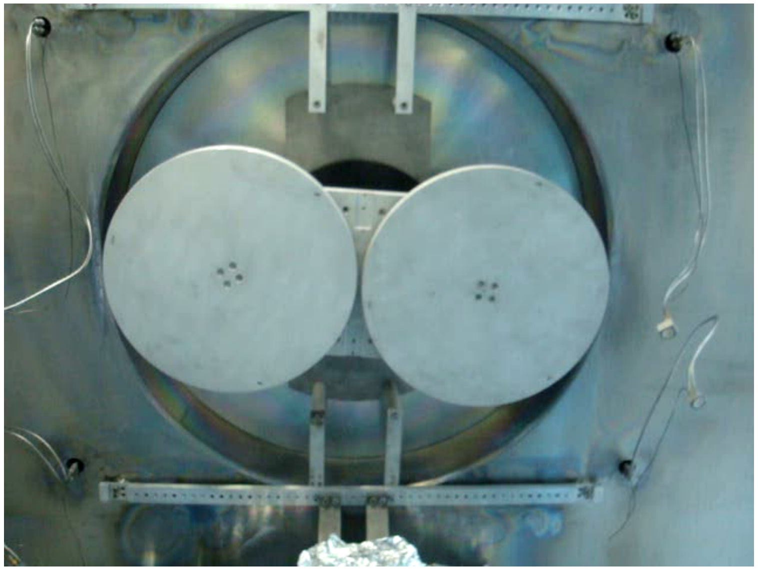


Damping magnets (now vindicated as coupling site)

Core optics delivery/processing

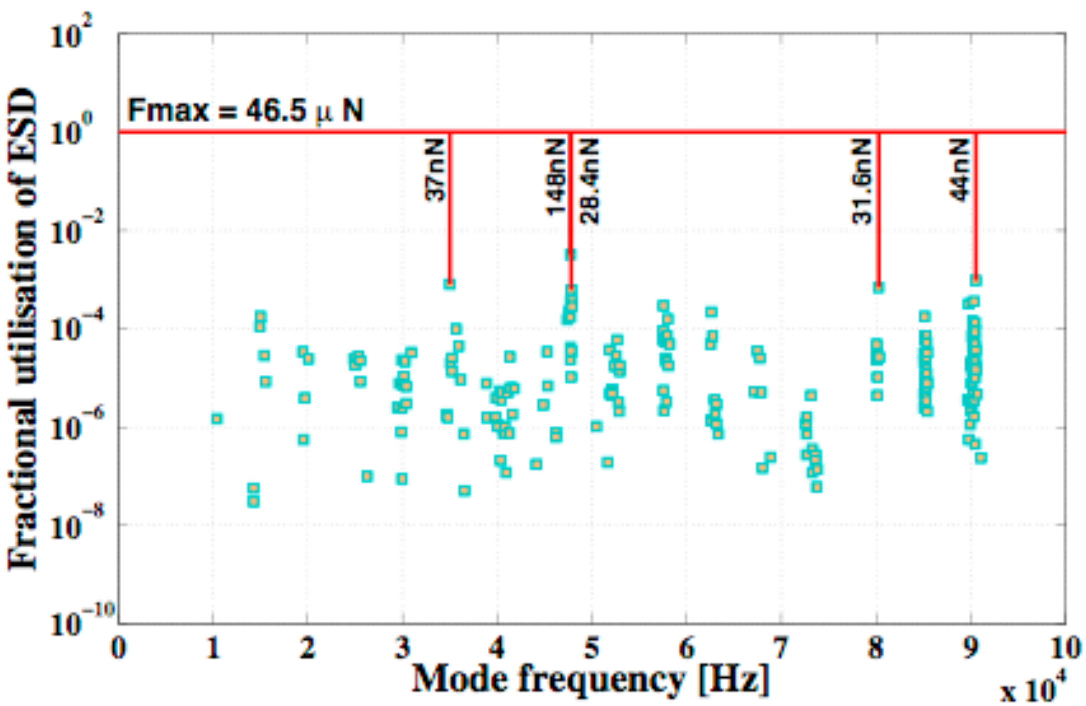
- Core optics readiness remains one of the primary installation risks
- LMA recently shipped one input test mass (ITM) to Caltech for characterization
- Have put both HR and now a first try at AR coatings on final optics, but may need another round of touchup coating
- Depending on the AR coating quality, we may i) weld this optic, ii) wire hang this optic, or iii) wire hang another temporary optic
- Our processing for test mass hangs is always just-in-time (uncomfortable), e.g. our PUMs are processed by one person

Planetary setup
at LMA, France

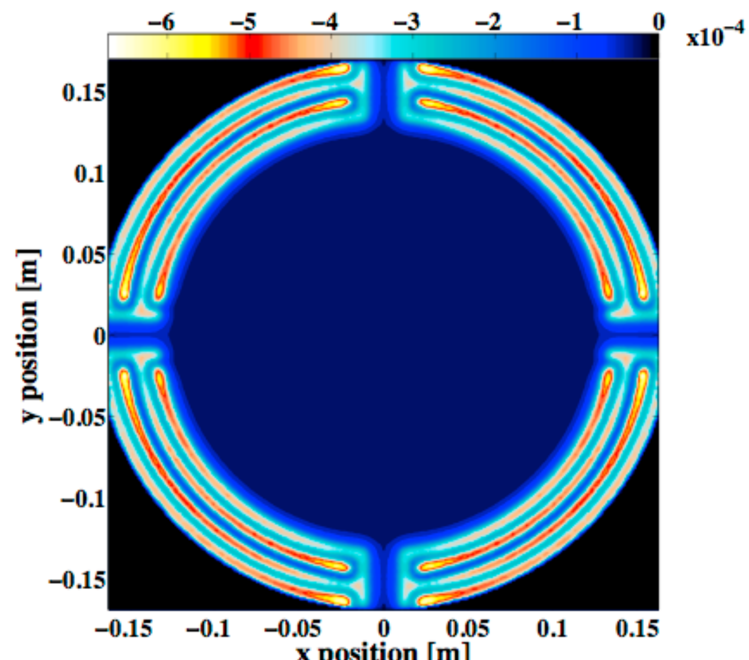


Active acoustic mode damping

- Active damping using the electro-static actuators on the test masses
  - » FEA modeling of actuator force density & acoustic modes



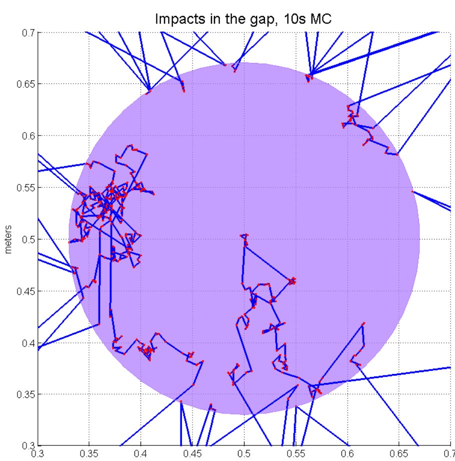
Modeled force density

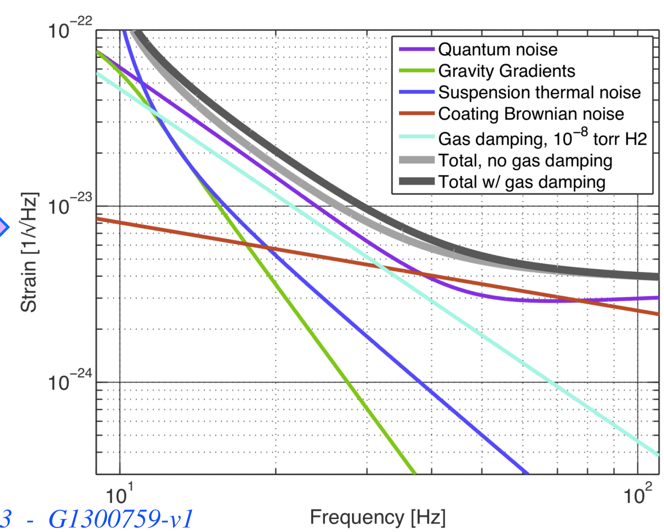


Gas damping

- Residual gas in the gap between Test Mass and Reaction Mass produces increased damping of the TM pendulum motion
  - » Increased damping means higher suspension thermal noise, could be important for frequencies below about 50 Hz
  - » Monte Carlo simulations following gas particles in the gap used to calculate force noise

Simulation of a gas particle interacting with the TM-RM gap





Mitigation of gas damping

- Gap between ITM & Compensation plate (CP) was increased from 5 mm to 2 cm
  - » Reduced the thickness of the CP
  - » Minor changes to accommodate in the quad suspensions
  - » Electrostatic drive (ESD) force reduced as a consequence, but there was margin to spare for the ITMs
  - » Force noise reduced by factor of 2.6
- ETM-Reaction mass gap is a different issue
  - » Rely on ESD force for lock acquisition & global control: don't want to reduce the force before we get experience with what we really need
  - » New reaction mass geometries could reduce damping and retain ESD force
  - » Solution could be a combination of new ERMs and more pumping; will be taken when we know more about required force & chamber pressure

Contamination control

- Just one of the many critical roles played by the Systems group
- Substantial effort to
  - Identify components of contamination
  - Implement mitigation approaches
  - Monitor contamination
  - Determine impact of contamination

"[Improvement through] …the aggregation of marginal gains…"

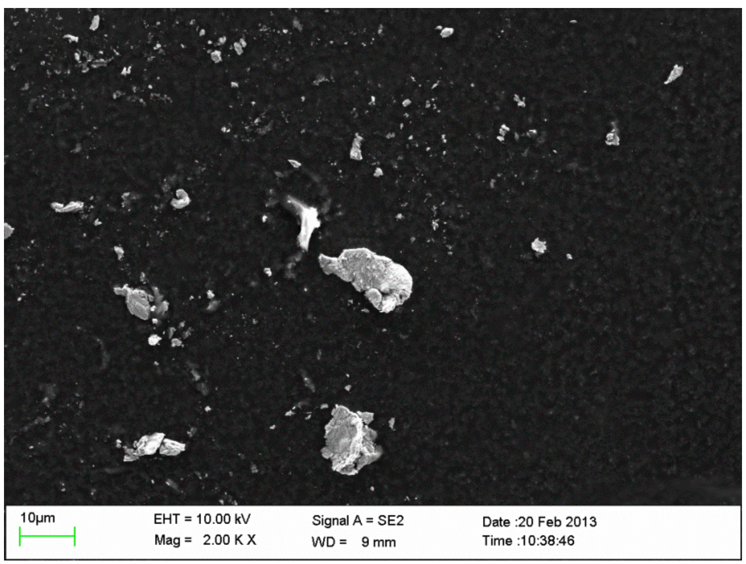
-Dave Brailsford, Team Sky (UK)

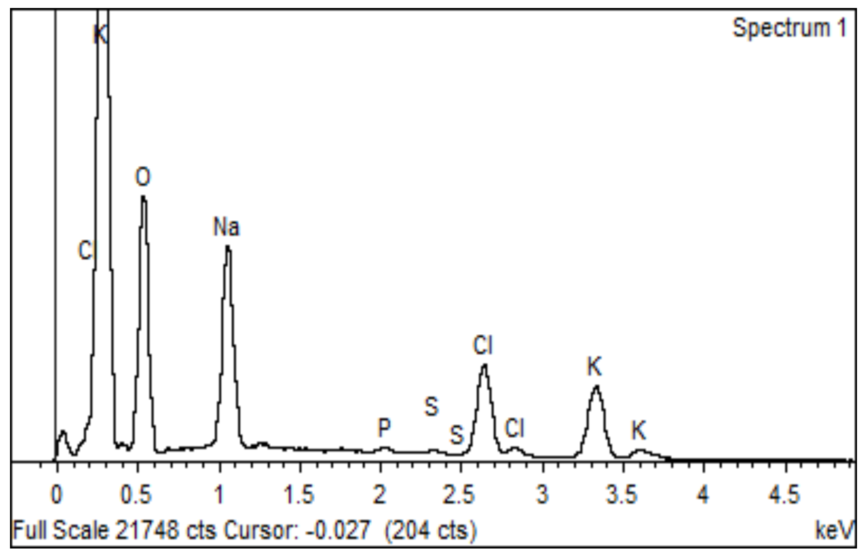
Problematic particulate contamination

- Particulate experiments in Caltech optics lab
  - » Exposure of dirty coatings to intensities found in Mode Cleaner
  - » See 'cratering' around dirt at low equivalent power into MC
  - » Currently limiting input to LLO DRMI to ~1 watt
  - » Not clear how to connect with eLIGO, early aLIGO high power tests and the continued satisfactory performance of the MC then
- Continued measurement, modeling, observation, mitigation

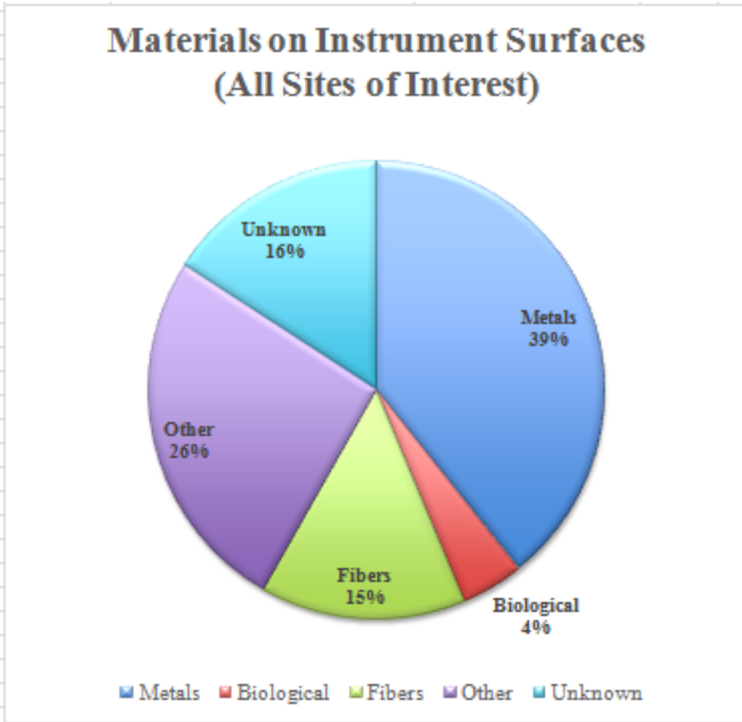
Contamination control actions: particle analysis

- A large collection of “FBI samples” (double sided carbon tape) of particulate contamination has been assembled and photographed and analyzed in a Scanning Electron Microscope (SEM) to build a database of contaminants.





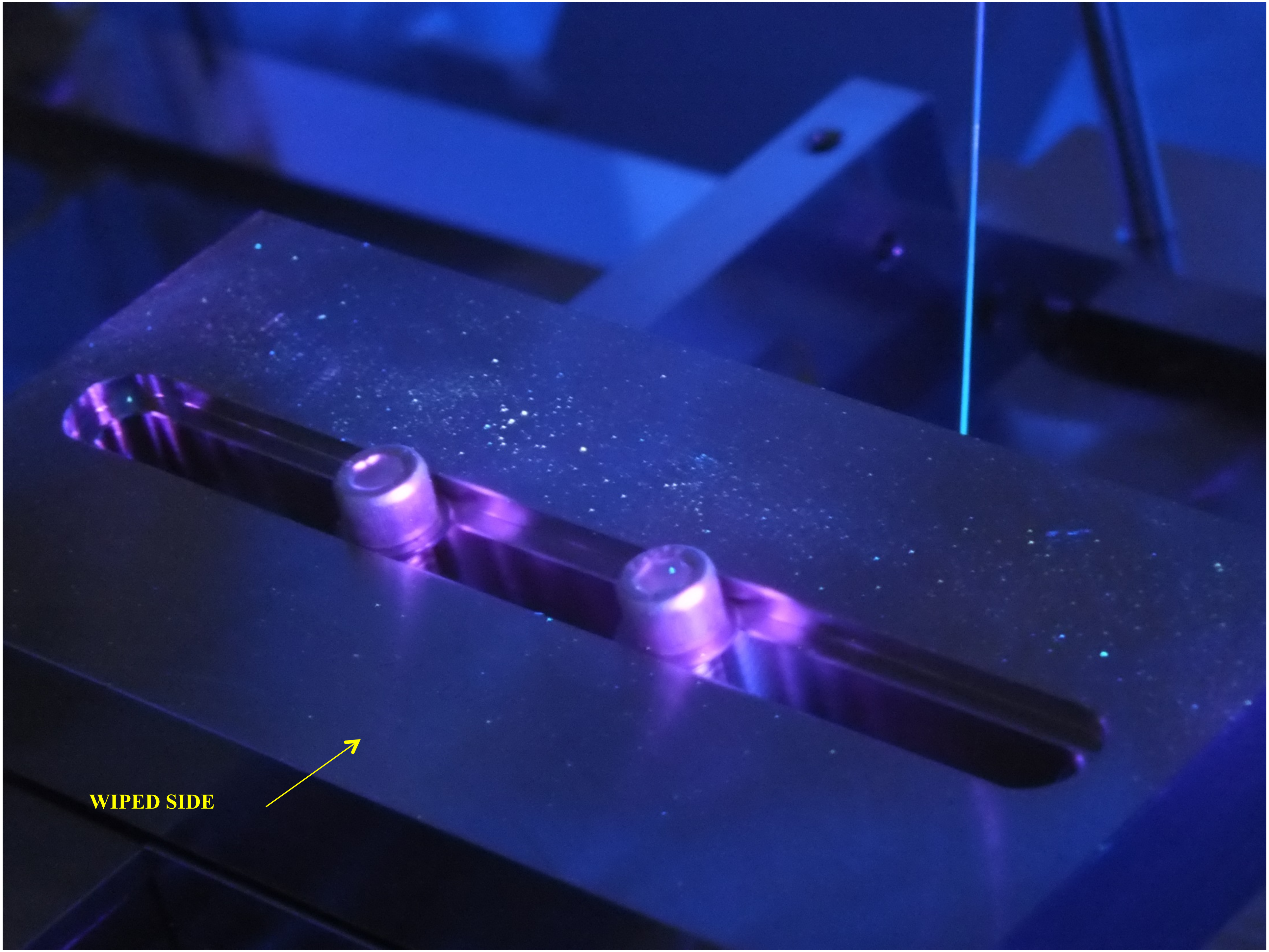
Cleaning on the Go



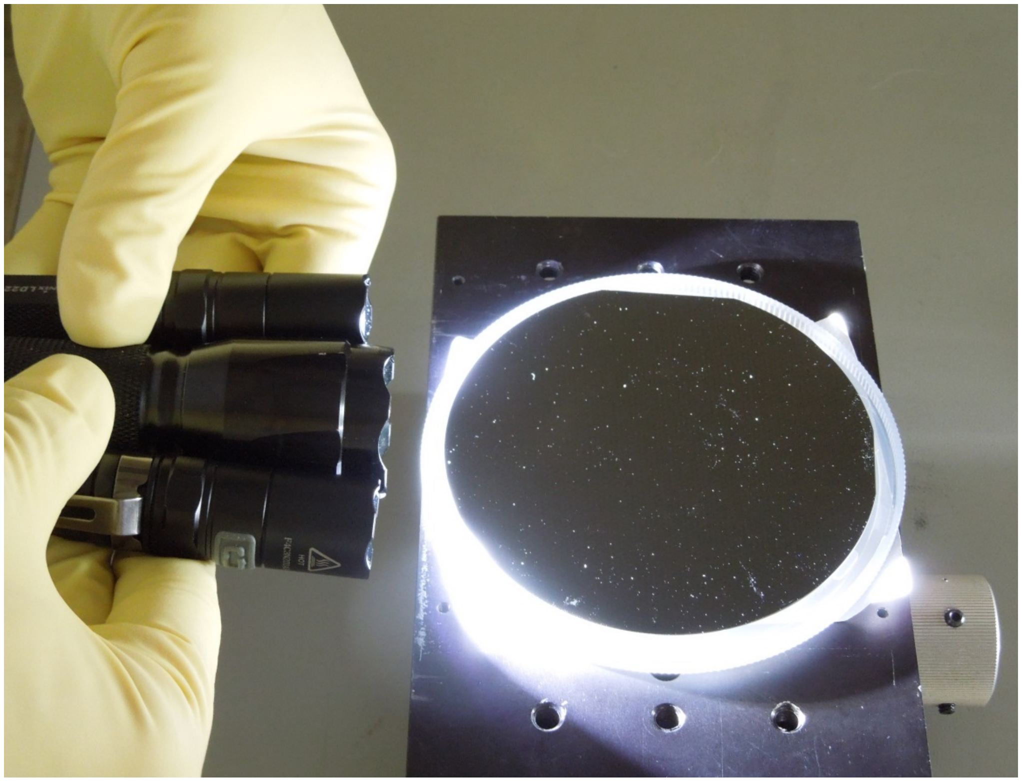
MATERIALS ON INSTRUMENT SURFACES (All sites of interest)

Group	Material	Number of Specimens	Total
Metals	Aluminum	21	62
	Aluminum Oxide	0	
	Copper	2	
	Iron	1	
	Iron Oxide	2	
	Silver	5	
	Stainless Steel	6	
	Steel	14	
	Titanium	1	
	Titanium Oxide	1	
	Zinc	2	
	Zinc Oxide	4	
	Zinc/Nickel Plating	3	
Biological	Hair	1	7
	Saliva	1	
	Skin	0	
	Sweat	3	
	Sweat and Saliva	2	
Fibers	C3	6	23
	Glove Liner	2	
	Jeans	1	
	Unknown Fiber	4	
	Wipe (any type)	10	
Other	Cable	2	41
	Carbon	21	
	Concrete Floor	0	
	Fused Silica	4	
	Glove (print or piece)	14	
	Grease	0	
	Viton	0	
Unknown	Unknown	24	25
	Unknown Salt	1	

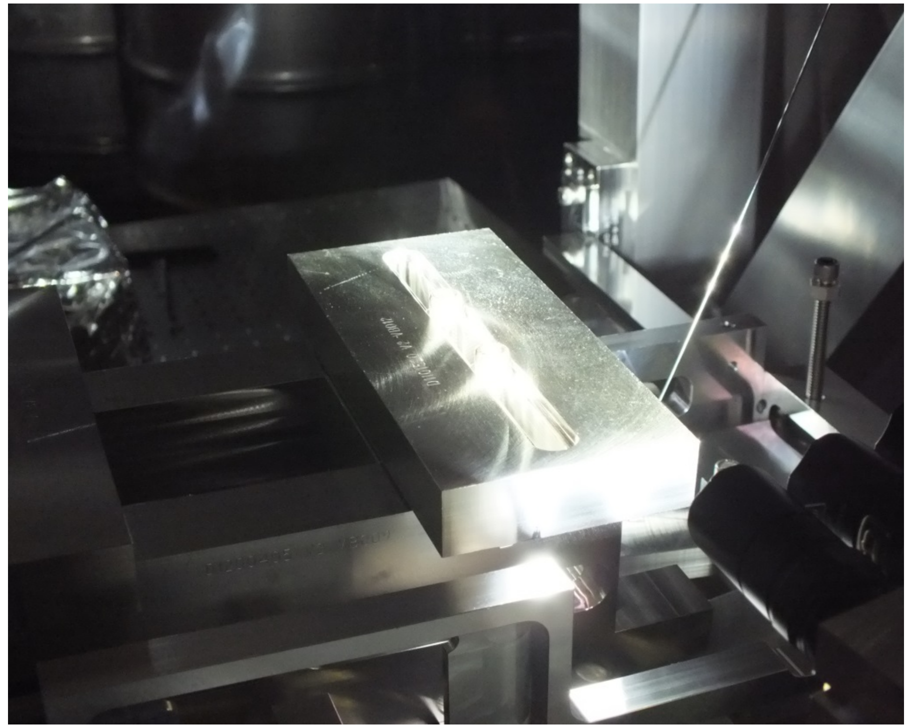
- It is clear from tests that a large portion of the contamination comes from the assembly and installation processes performed by us the humans.
- Therefore to combat this "Cleaning on the go" has to become part of our in cleanroom and in chamber processes.
- "Cleaning on the go" should be encouraged and performed using the tools described below.
  - » When performing localized cleaning (e.g. a stage of a suspension structure), one should check the status of the optic and at least ensure that the lens cap is in place prior to starting.


WIPED SIDE

Items illuminated by flashlight array – real dust from the sites



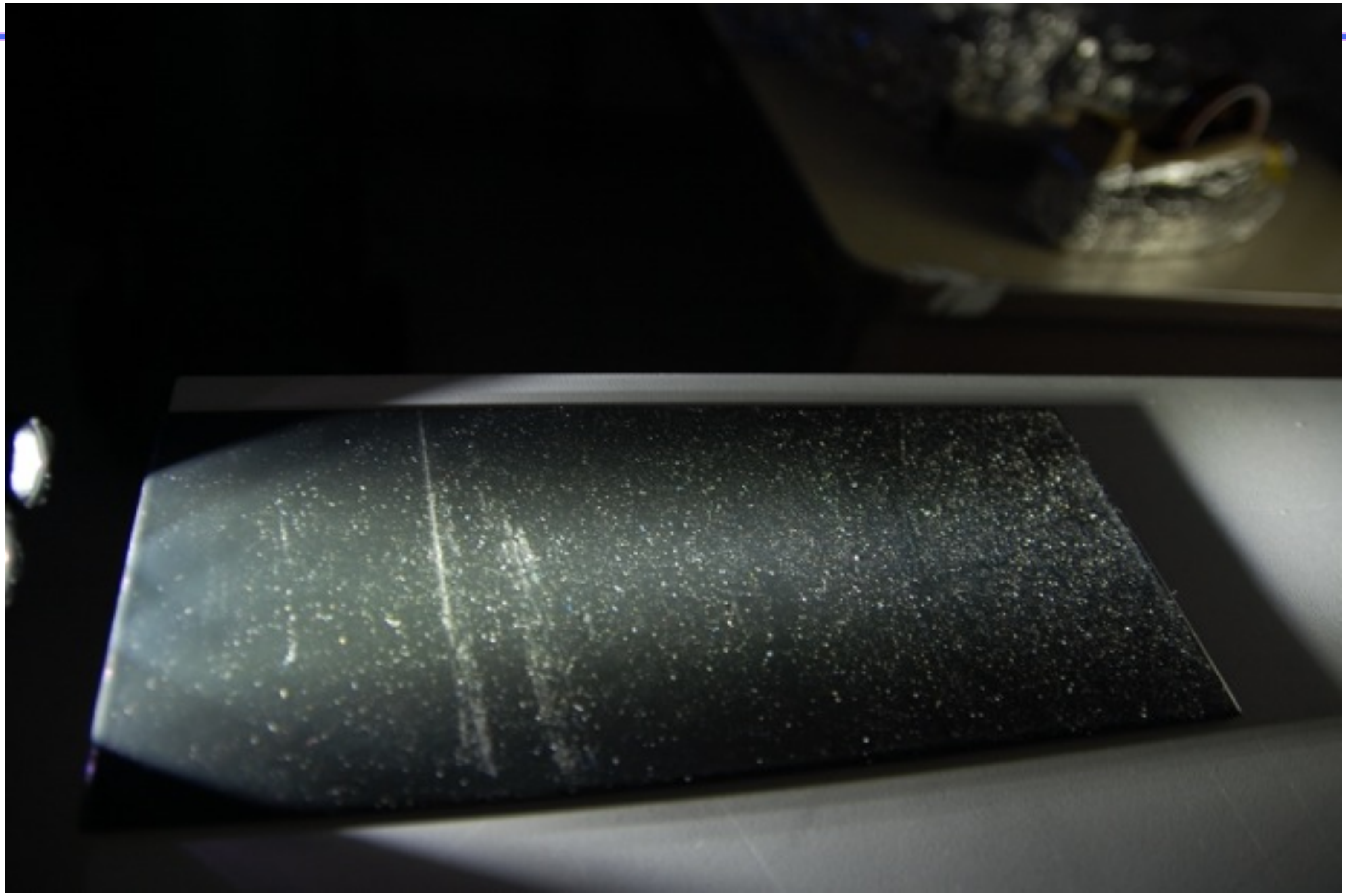
Flashlights illuminating a wafer at grazing incident. The wafer has real dust from the sites on it. Refer to LIGO-E1300183



Flashlight array illuminating (at grazing incident) the same TMS part which is shown above under UV-A blacklight.

Without flashlight array

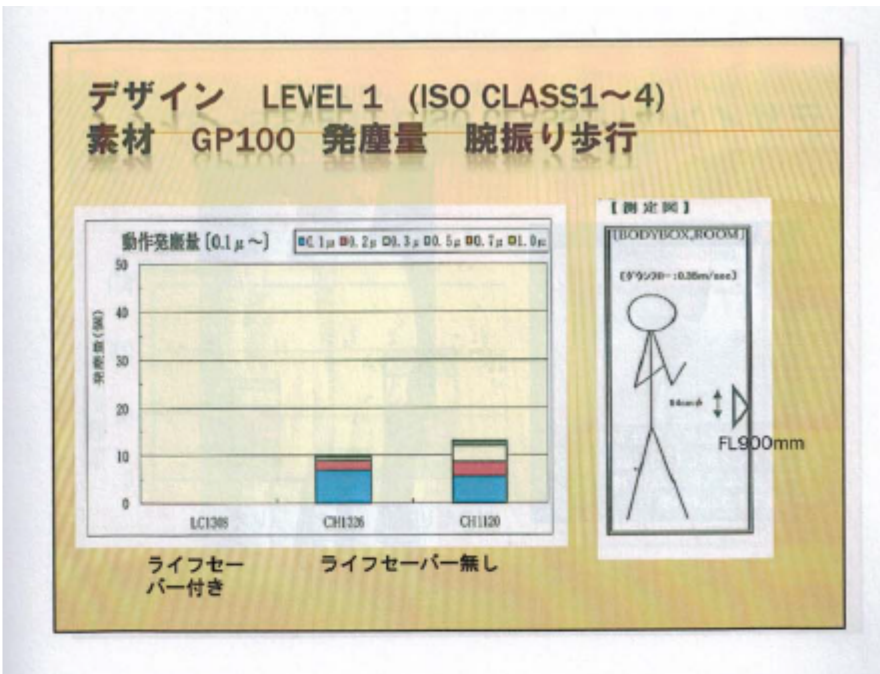
With Flashlight array



***This is not dust from a site, it is dust collected in an open lab space at Caltech i.e. from room 318 in Downs**

KAGRA HEPA suit

- Below is is the particulate count comparison with the HEPA suit mentioned above (left on the plot) and two other types without HEPA (middle and right) when the worker was walking.



Clean Coverall with Integrated Hood (downflow type)

CLOSE ✕

Beamtube leak at LLO

- Not specifically an Advanced LIGO problem, but worth mentioning
- LLO y-beamtube has developed several small leaks
- Associated with rodents living (and urinating) in the beamtube insulation
- Several fixes made
- Will strip insulation at both sites
- New insulation required

Outline

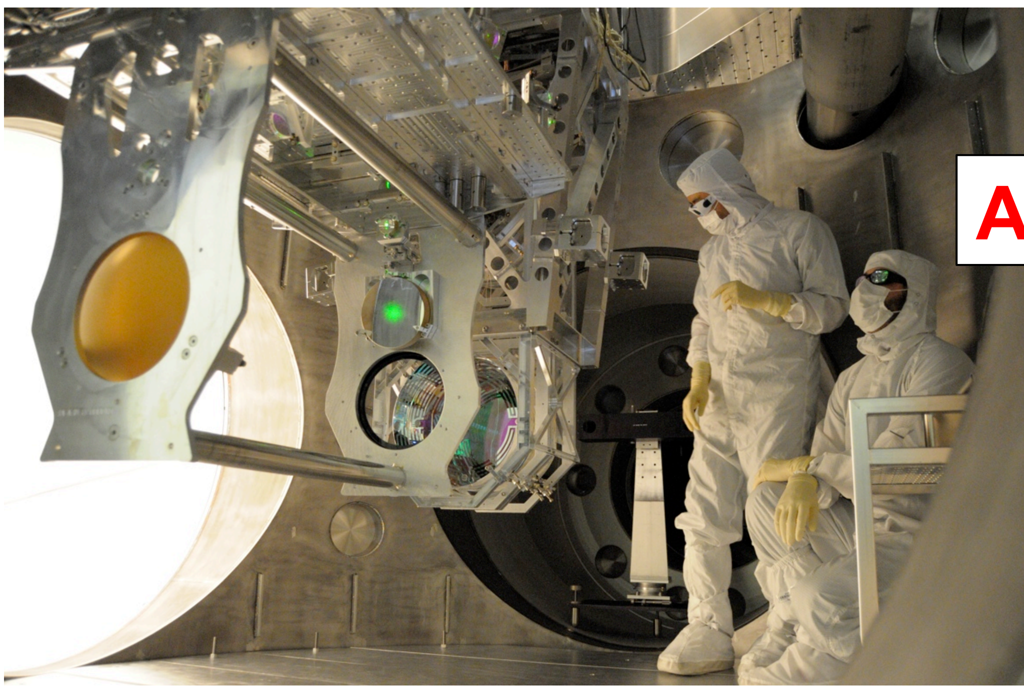
1. A (very brief) introduction to LIGO
2. Organization: project controls, installation planning, documentation
3. Selected topics in installation
4. Problems and some solutions
5. Brief status of integration

Integration

- So at this point you might rightfully ask, “what’s worked?”
- Many things of course work mostly to plan, here we’ve highlighted issues
- Let’s close with Integration status, or, commissioning
- *To the extent integration has moved quickly, it is a reflection on the entire team and the groundwork in design, test, review, clean and bake, assembly, installation, alignment, facilities support, etc.*

H2 single arm

- New lock acquisition strategy developed for aLIGO
- Arm Length Stabilization system controls each arm cavity, putting them off-resonance
- The 3 vertex lengths are controlled using robust RF signals
- Arm cavities are brought into resonance in a controlled fashion
- *Therefore, commissioned single 4km arm*

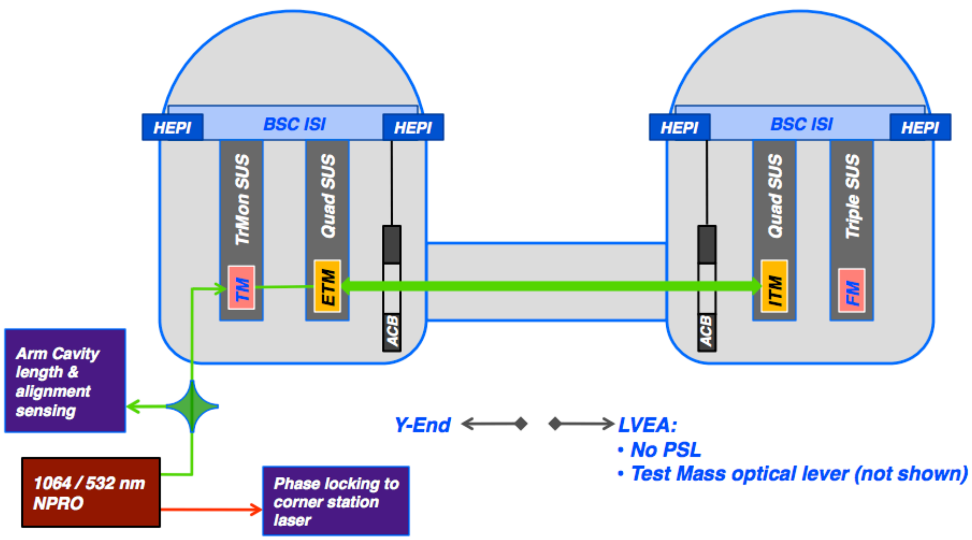


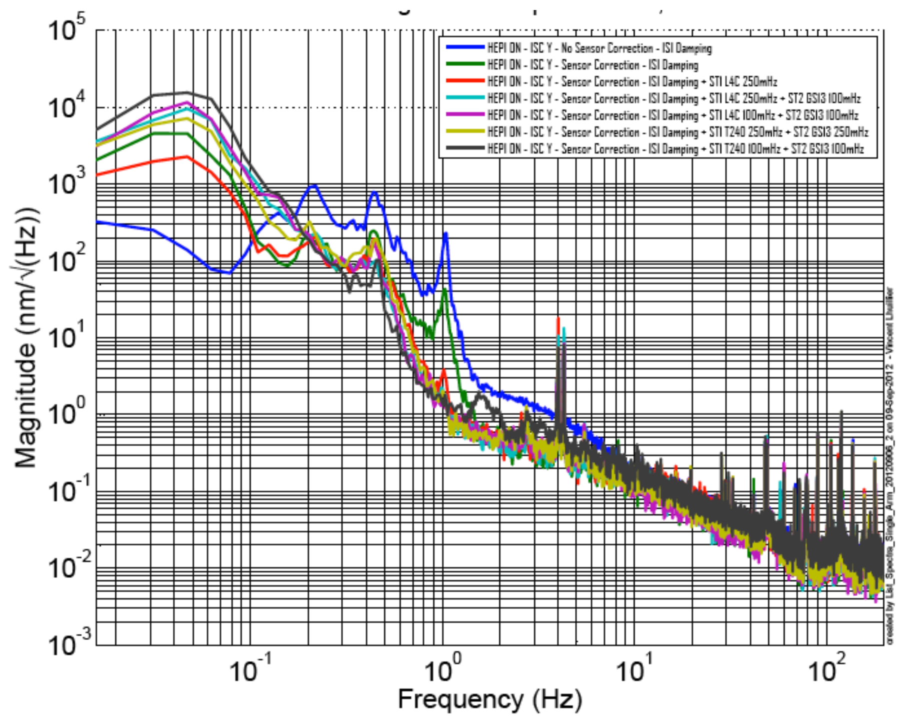
At End Y

Corner ITMY install

H2 single arm, contd.

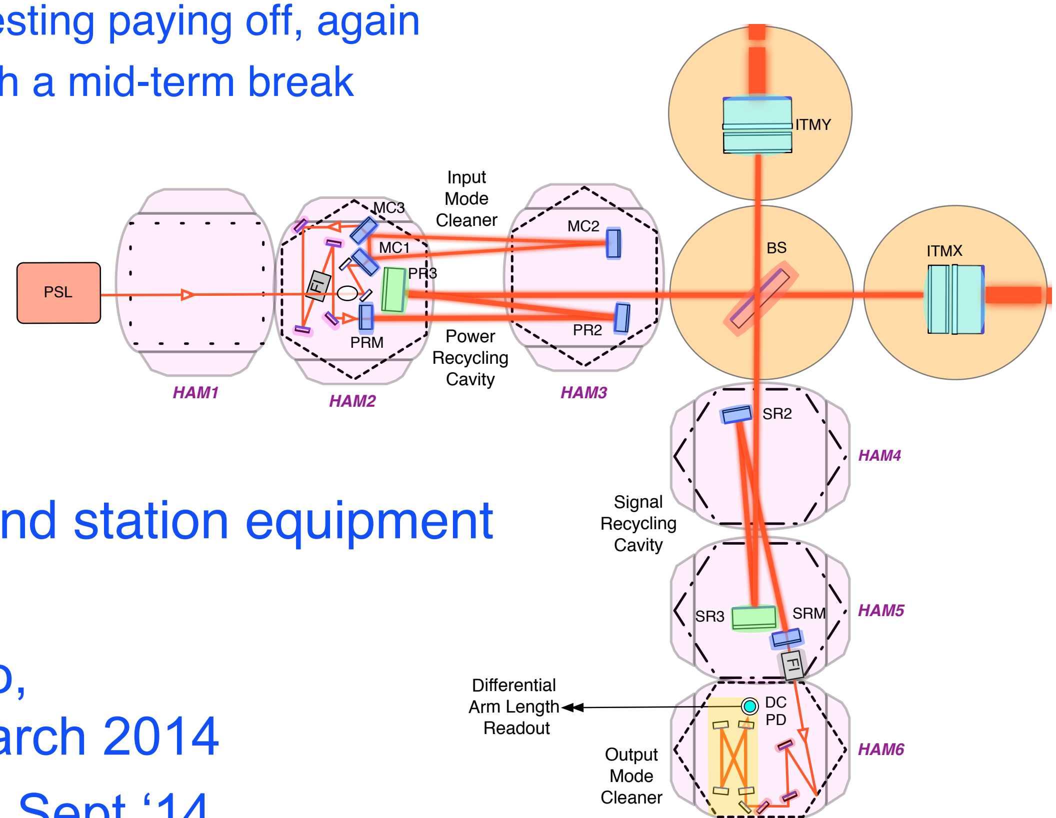
- Several days to align 4km Fabry Perot cavity, after which it was rapidly locked on resonance
- Proved a successful integrated test of elements of SEI, SUS, Transmon, ALS, Controls, Oplevs, TCS, ISC
- Sep 13, 2012 marked the end of the single arm test





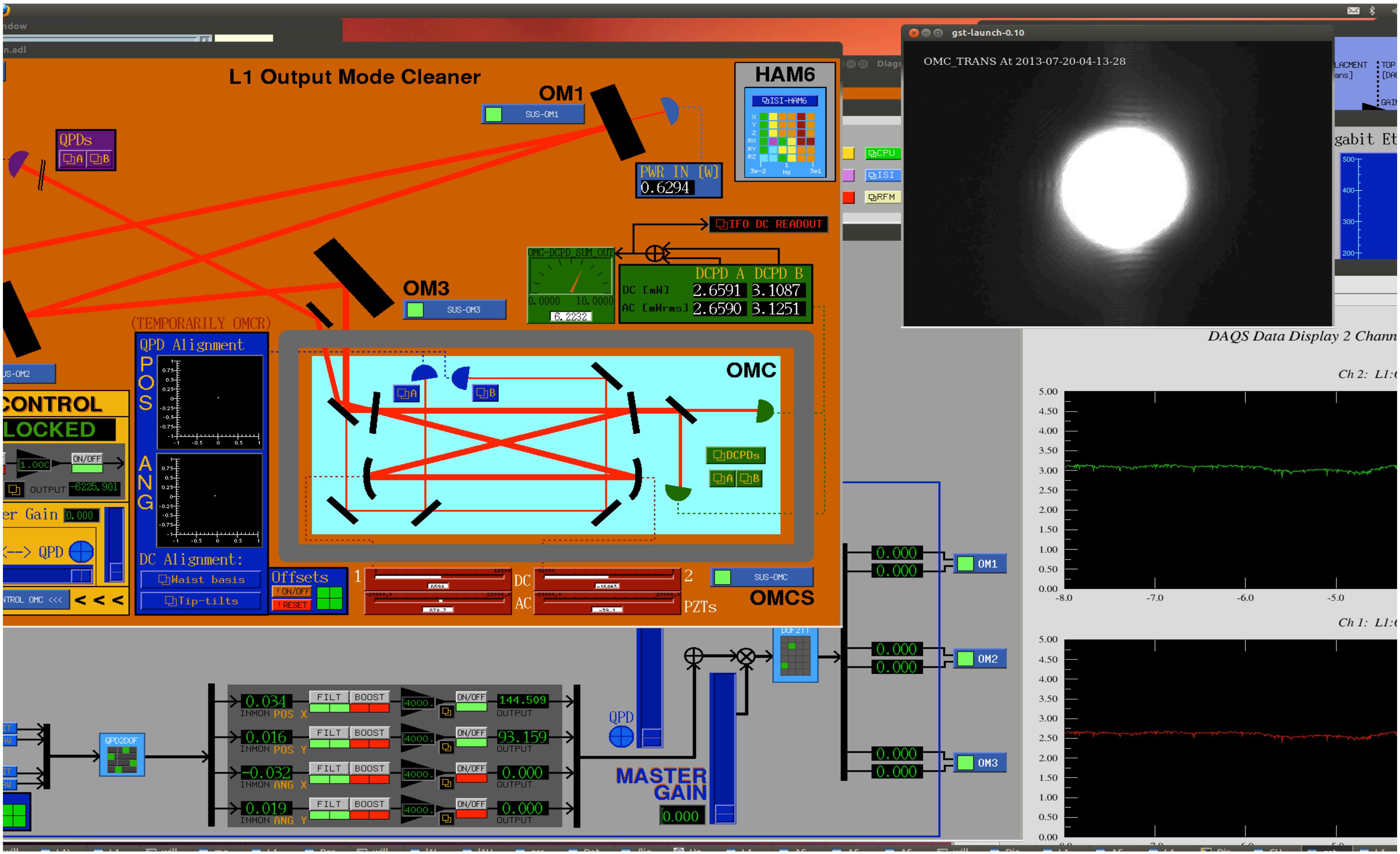
Underway at Livingston

- Dual-recycled Michelson Interferometer ('DRMI')
  - All parts in place for this stage (not all chambers complete)
  - So far, PRMI (power recycled Michelson) locked, first calibration
  - Threading beam through the Output Mode Cleaner as we speak
  - Good progress rate to date – testing paying off, again
  - To continue to end-October with a mid-term break



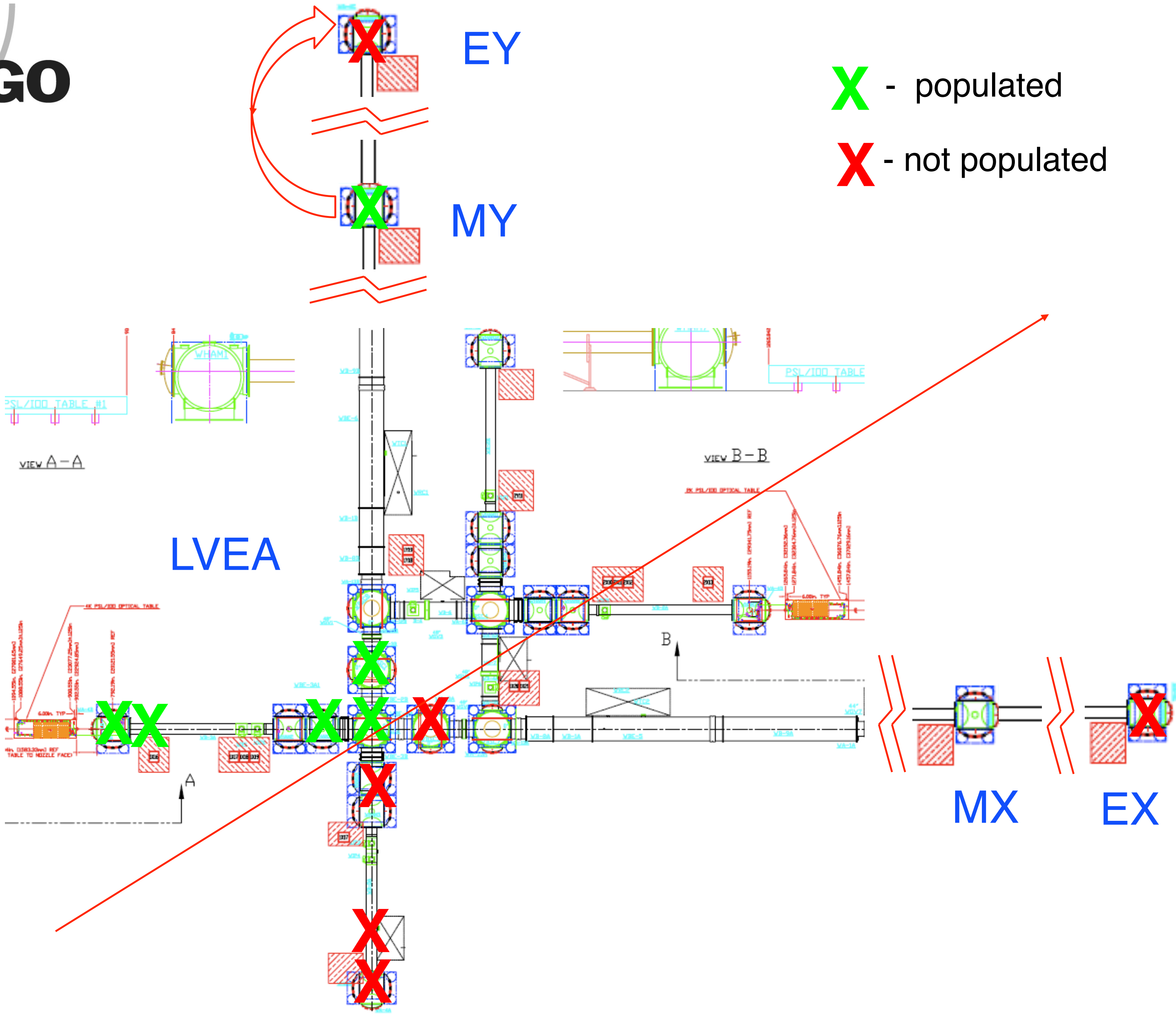
- Parallel installation of X, Y End station equipment
- Followed by HIFOs
- All systems to be ready to go,
  full lock testing starting in March 2014
- Full Interferometer Accepted Sept '14

LLO OMC locked



HIFO-Y

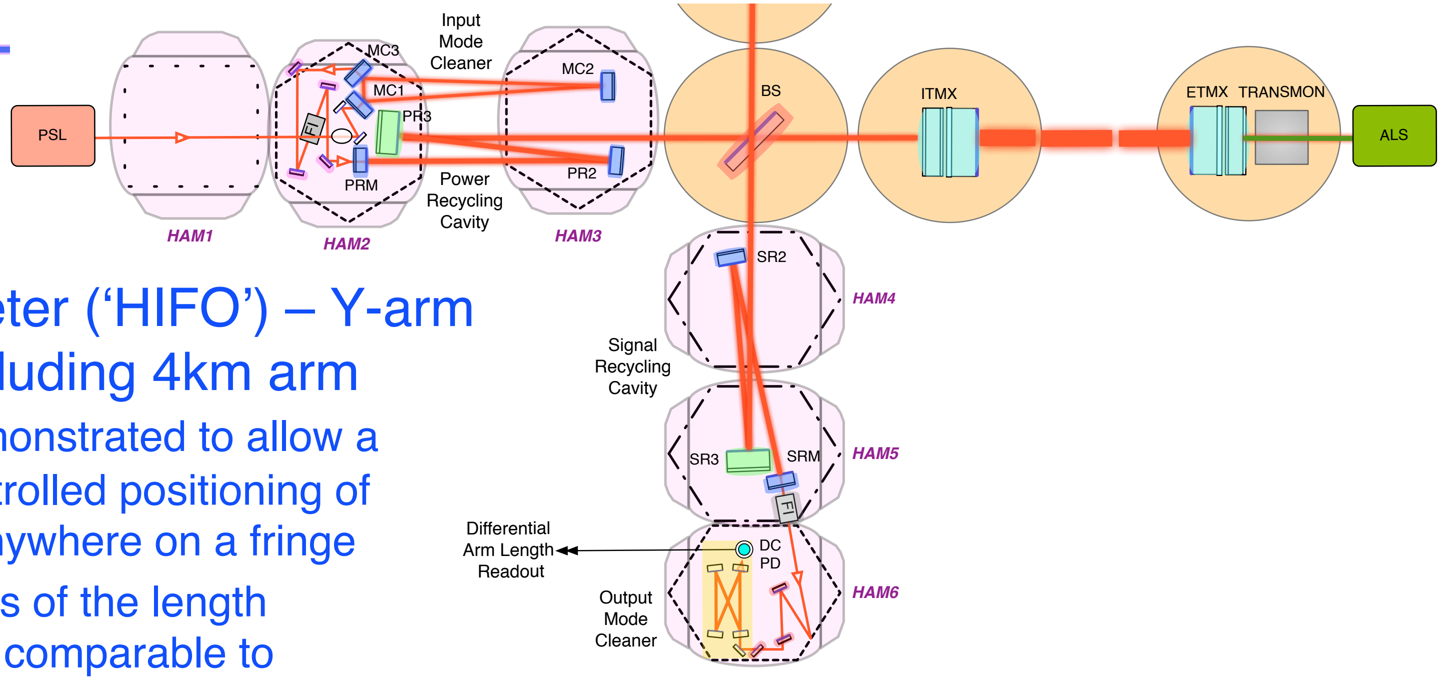
- Old install plan: LLO as pathfinder, moving towards full installation at corner – dual-recycled Michelson test. *At LHO, post-single arm, mirror this plan, albeit phase-delayed*
- Modified LHO one: exploit the existing single-arm further, and quickly learn more about lock acquisition
  - Install Beamsplitter
  - Move ITMY from H2 BSC8 to H1 BSC1
  - Complete HAM2/3 installation, make IMC test
  - Install in HAM1
  - Make *half-interferometer test, or HIFO-Y*
- In this way, continue have early look at new beampaths, hardware, software etc. Profitable commissioning for both LLO *and* LHO



X - populated

X - not populated

HIFO-Y complete at LHO

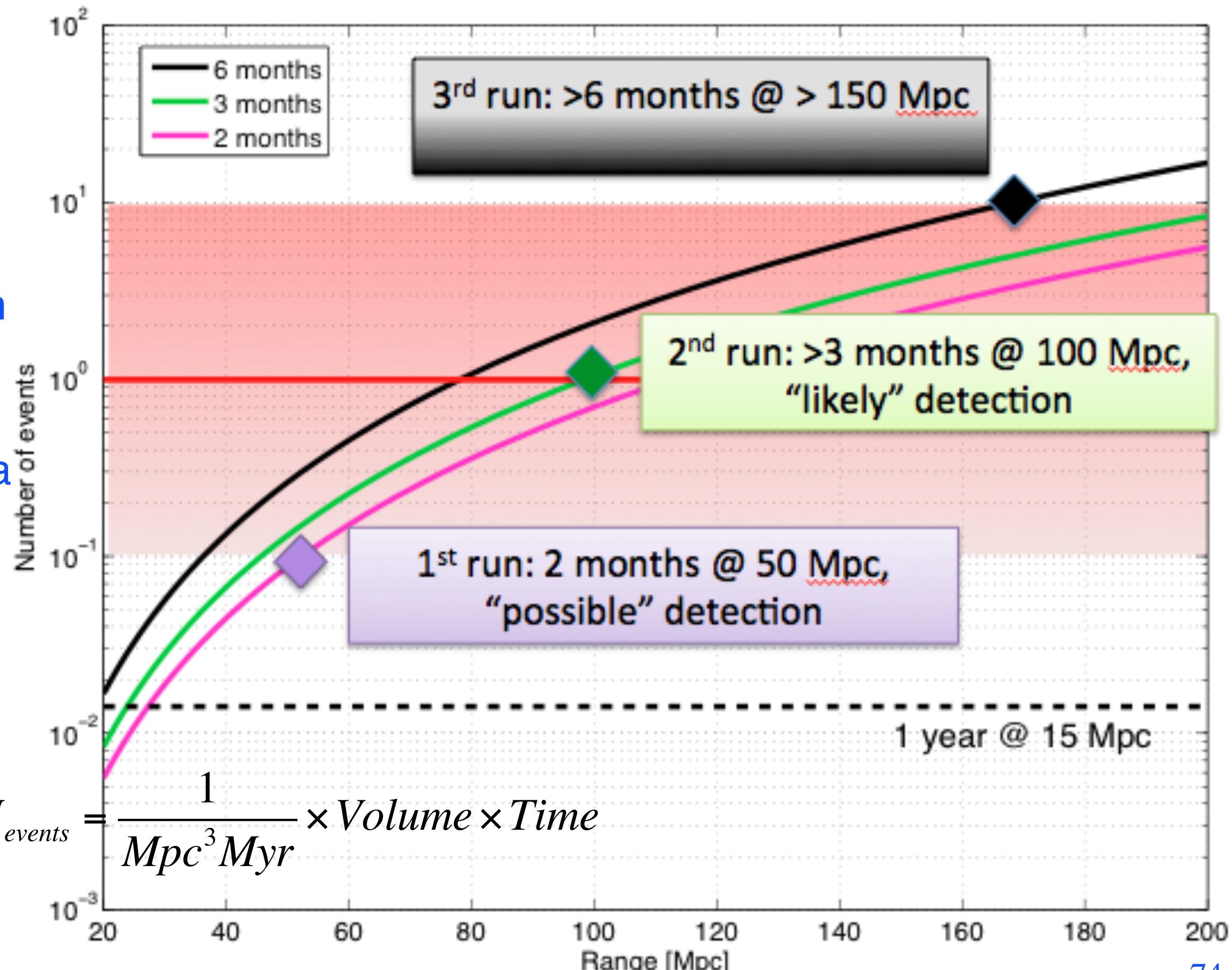


- Half-Interferometer ('HIFO') – Y-arm components including 4km arm
  - » Green light demonstrated to allow a continuous controlled positioning of 1.06μ cavity, anywhere on a fringe
  - » And, fluctuations of the length ~3 Hz RMS, so comparable to coupled cavity resonance width (1 Hz ultimate goal, but looks attainable)
- Now being used to characterize SEI, SUS; some alignment and readout instabilities
- Intensive work on end stations, to enable….
- HIFO-X and DRMI in some order (ITMs – wire or silica hang?)
- All systems to be ready to go, full lock testing starting in June '14
- Full Interferometer Accepted October '14

Current guess for sensitivity evolution, observation

- Vertical scale is the number of binary inspirals detected
- Rates based on population synthesis, realistic but uncertain
- LIGO Scientific Collaboration (LSC) preparing for the data analysis challenge
- Close collaboration with Virgo
- Early detection looks feasible

- [arXiv:1304.0670, arXiv:1003.2480]()



$$N_{events} = \frac{1}{Mpc^3 Myr} \times Volume \times Time$$

Summary

- Advanced LIGO began installation on Oct 20, 2010
- We’ve slipped in schedule and made mistakes along the way, but the installations into the vacuum envelope are less than a year away from completion
- After that, integration towards full lock takes place
- Acceptance and project end expected ~Oct 2014
- More commissioning, then initial science running in both 2015 and 2016