System Integration Status and Challenges, Post Project Commissioning Plans to Meet Science Goals

May 27, 2014

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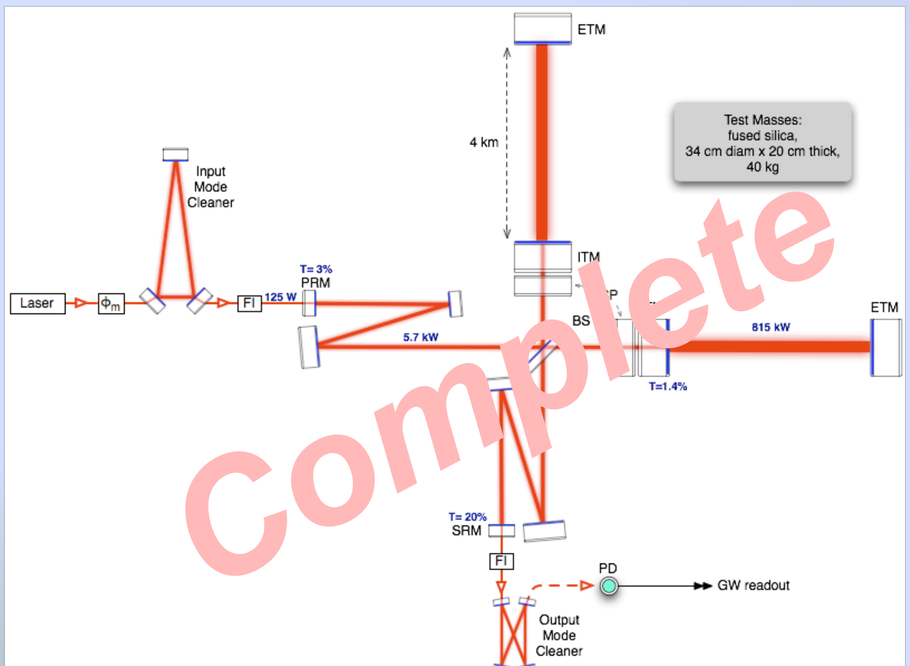
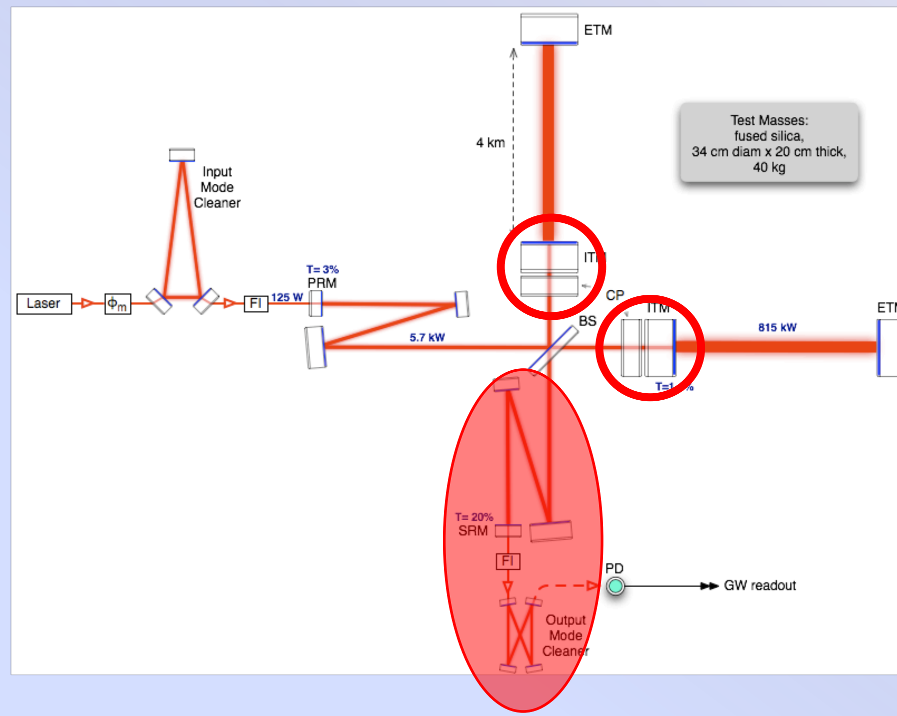
What's left to install

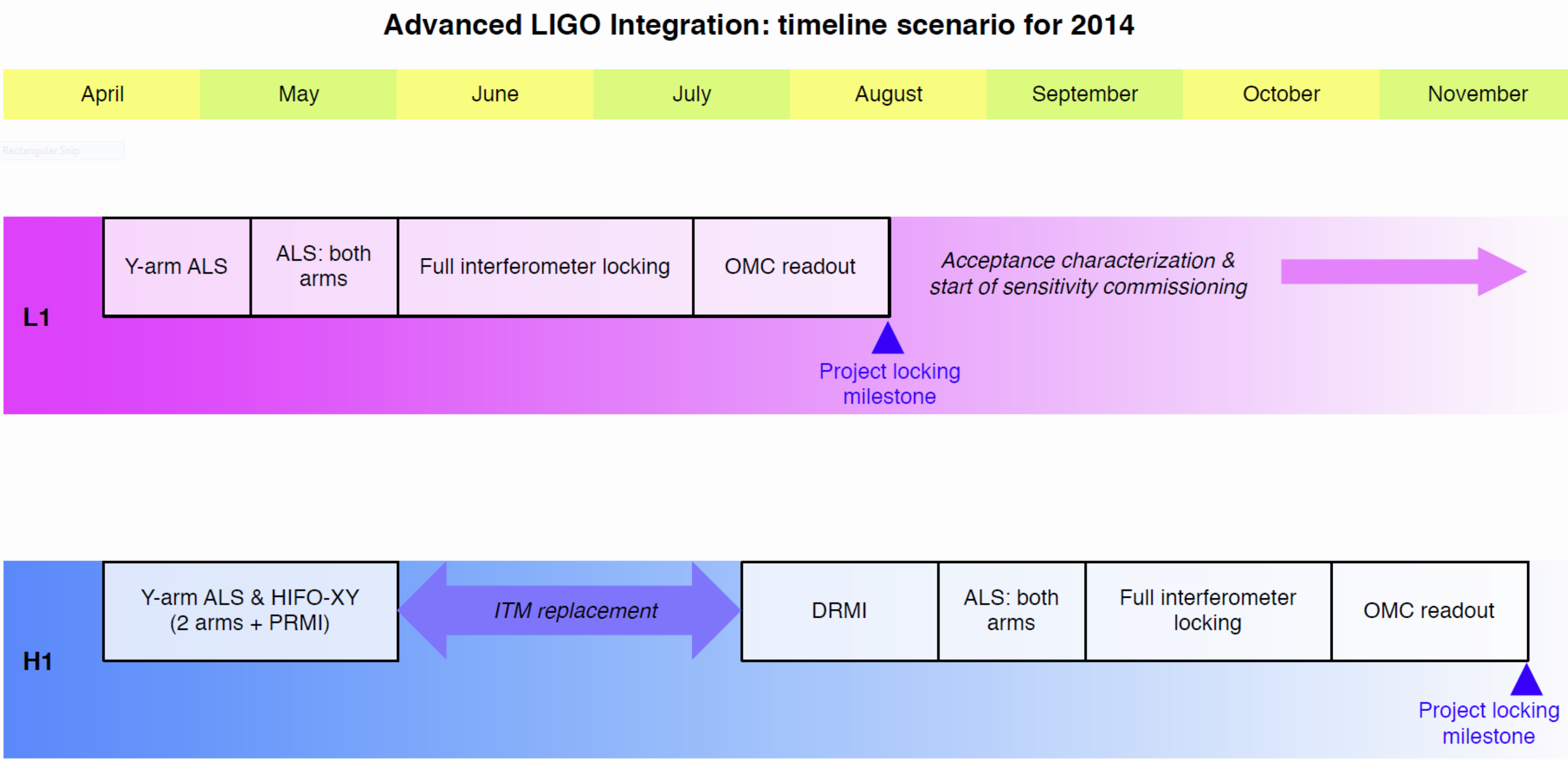
LIGO Livingston



LIGO Hanford



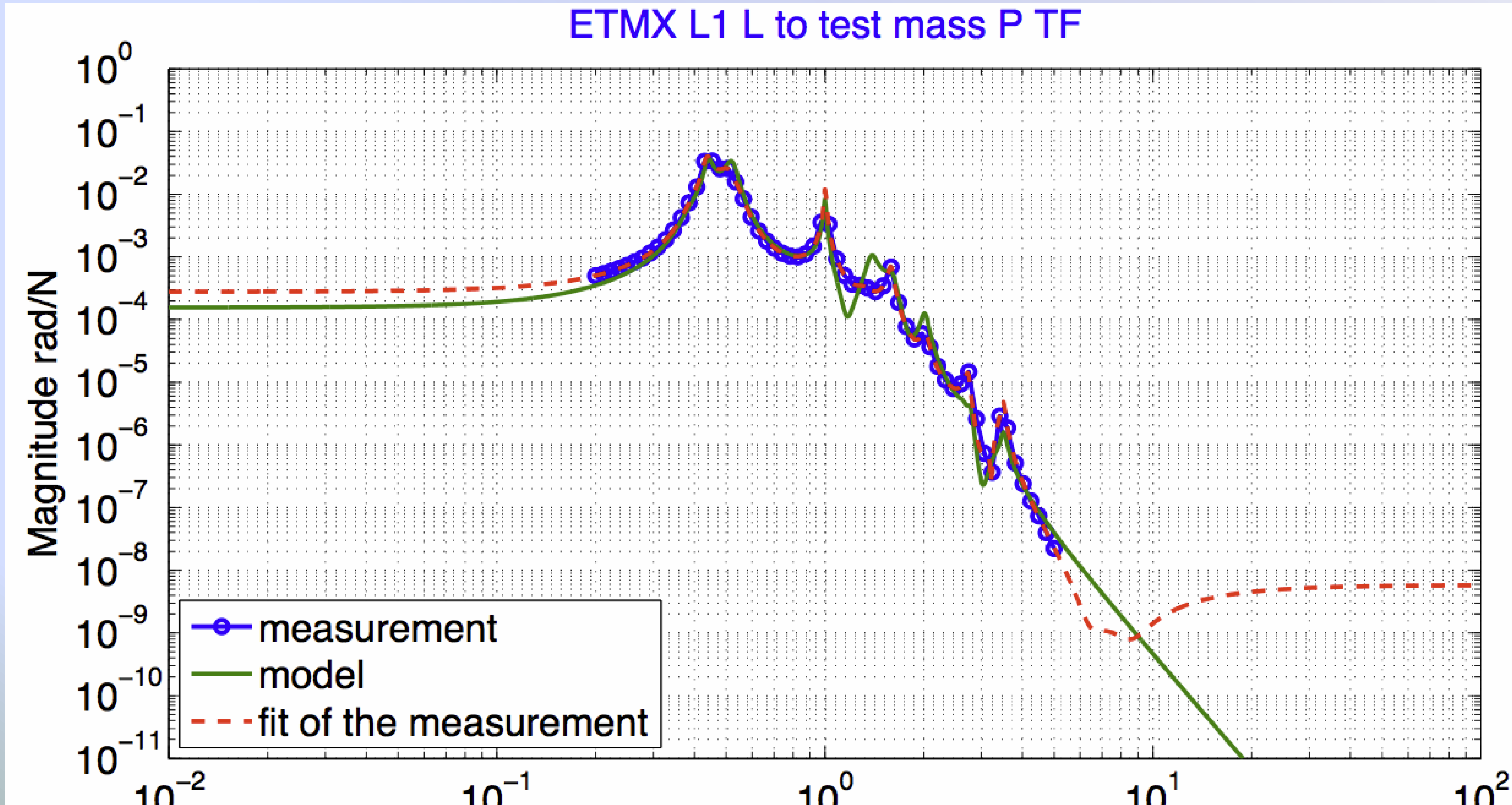
Current Timeline



Achievements

- Pre-Stabilized Laser (PSL) was commissioned and works as designed at both at LHO and LLO
- Input Mode Cleaner (IMC) has been fully commissioned
- All seismic isolators (SEI) work as designed and are fully automated
- All suspensions (SUS) work as designed and are fully automated
- Dual Recycled Michelson (DRMI) has been fully commissioned at LLO
- Arm Length Stabilization (ALS) has been commissioned at both LHO and LLO

Suspensions work as advertized



Past Commissioning Periods

- One arm test (OAT)
  - First arm cavity locked at LHO in summer 2012.
- Input Mode Cleaner Test
  - IMC locked at LLO in fall 2012, and spring 2013 at LHO.
- HIFO-Y
  - Commissioning the first ALS at LHO in summer 2013.
  - Now also completed for H1 HIFO-X, L1 HIFO-X and HIFO-Y.
- DRMI
  - Locked at LLO in summer 2013.
  - Also completed LHO PRMI (without AS port) in winter 2013.

Current Commissioning Period

- HIFO-XY
  - First look at arm cavity difference at both sites in spring 2014.
  - Corner station ALS fully commissioned at both sites.
  - Green coating issue resulted in schedule delay.
- Interferometer locking
  - Full lock attempt at LLO on-going.
  - Common mode lock attempt at LHO on-going.

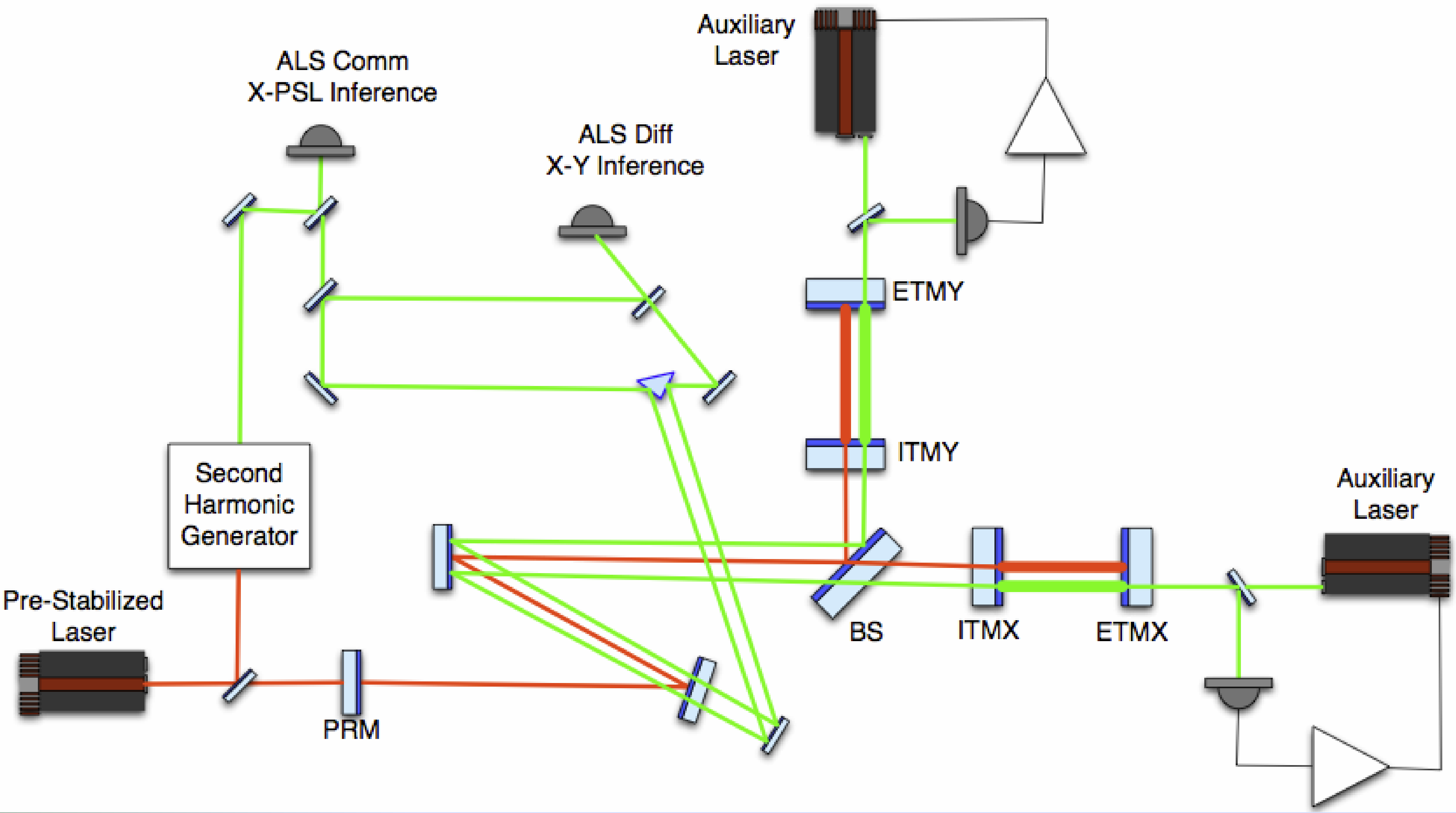
Top Level Summary

- Initial integration testing has progressed quickly
  - All major systems have performed as planned.
  - No show-stoppers found.
  - No true low noise test so far.
  - The only significant delay was due to the green coating issue.
  - Pace may not be sustainable.
- Green coating issue
  - Will not prevent the ALS from working.
  - Additional resources had to be allocated.
  - Robustness will suffer.
- The locking procedure is close to being validated

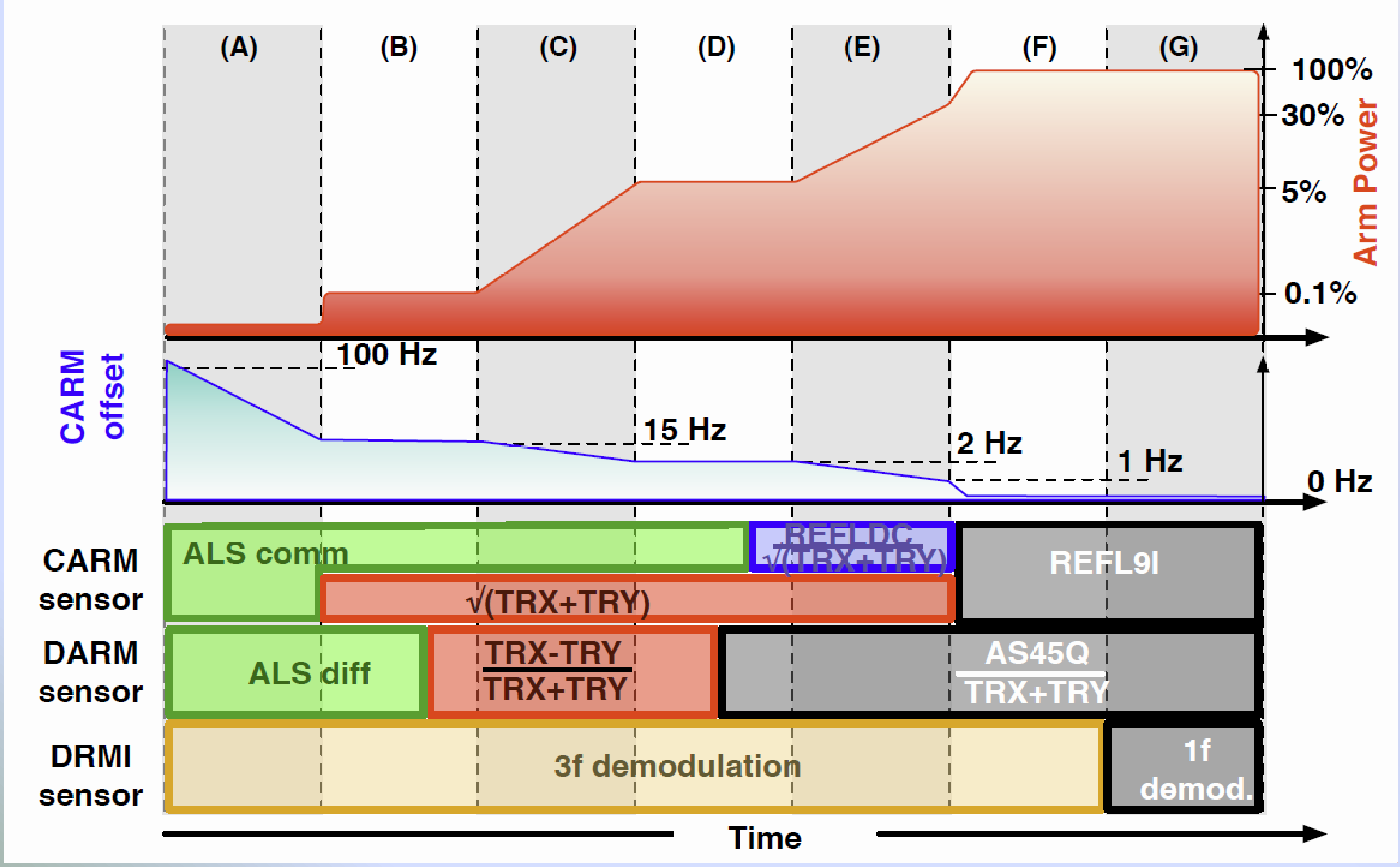
Automation

- Complexity has been a problem
  - Too many variables
    - Hard to know everything
    - Too many steps to achieve simple tasks
    - Too many things can go wrong
  - Great strides are being made to improve automation
    - Script approach (Guardian) and some ALS locking code (TwinCAT PLC)
    - Still substantial work needed to recognize, diagnose and rectify problems, as well as user interfaces
  - Keeping everything under configuration control is a problem
    - How to make sure everything is in the right state?
- Control room tools are not always well integrated
  - Sometimes tedious and repetitive tasks are holding us back
  - Need to make existing tools more useful and efficient
  - Clear-text information/instructions for operators still only rudimentary

Arm Length Stabilization

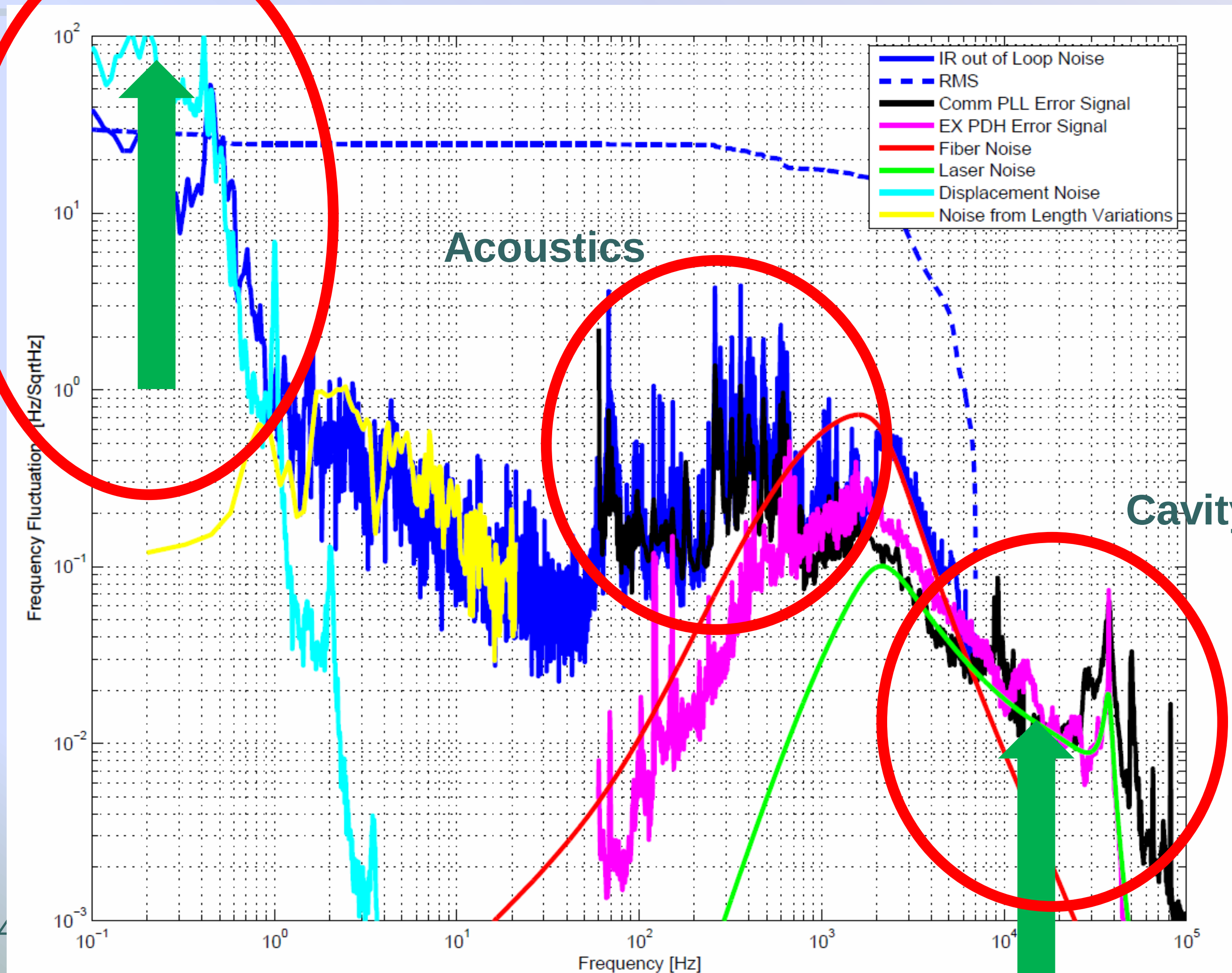


Locking Process



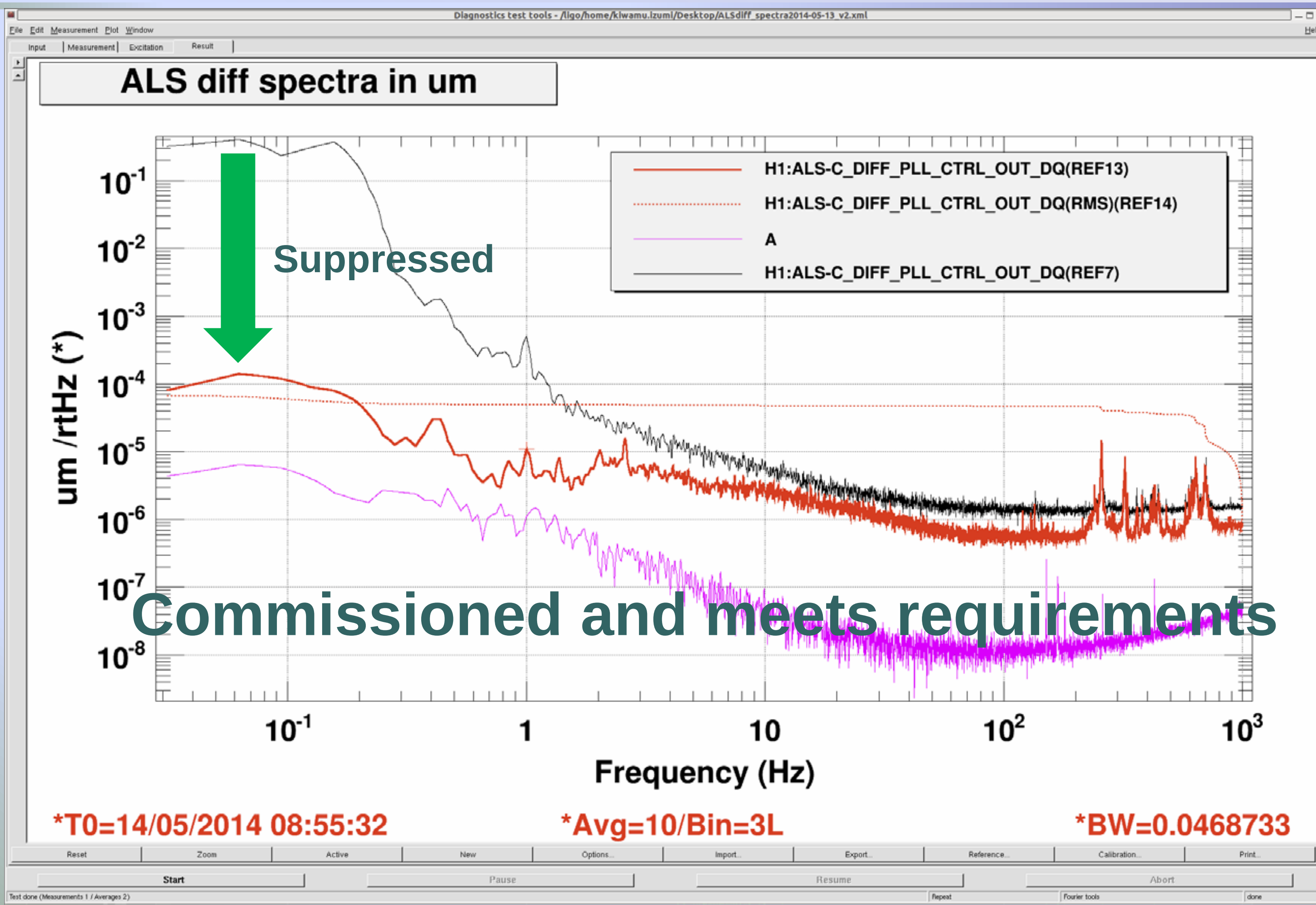
ALS Noise

Alignment couplings



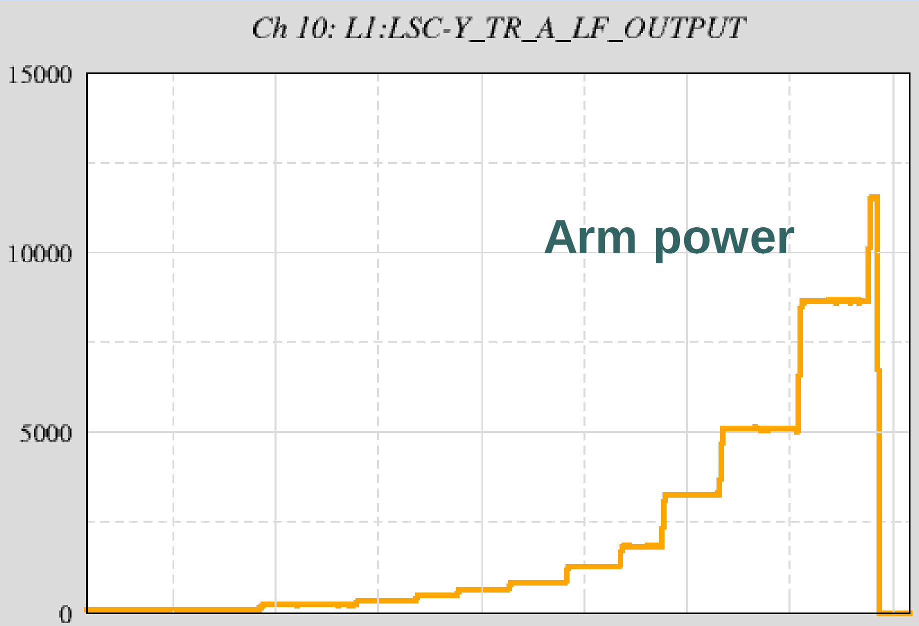
Cavity filtering

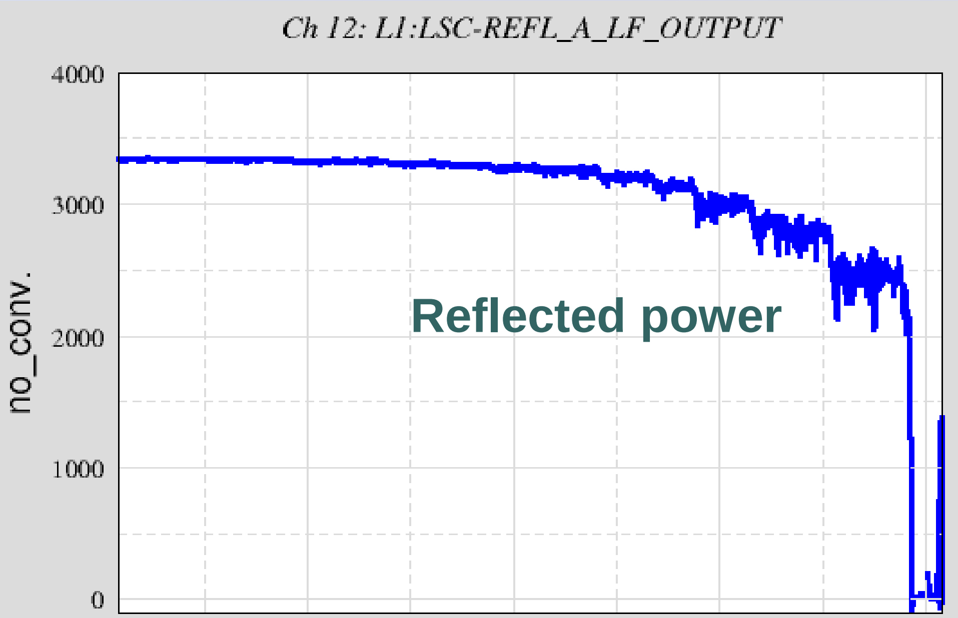
Differential Mode ALS



Current Effort

- LLO succeeded in reducing the CARM offset to 30 pm. (all five DOFs were locked by IR signals.)
- Close to the fully locked interferometer





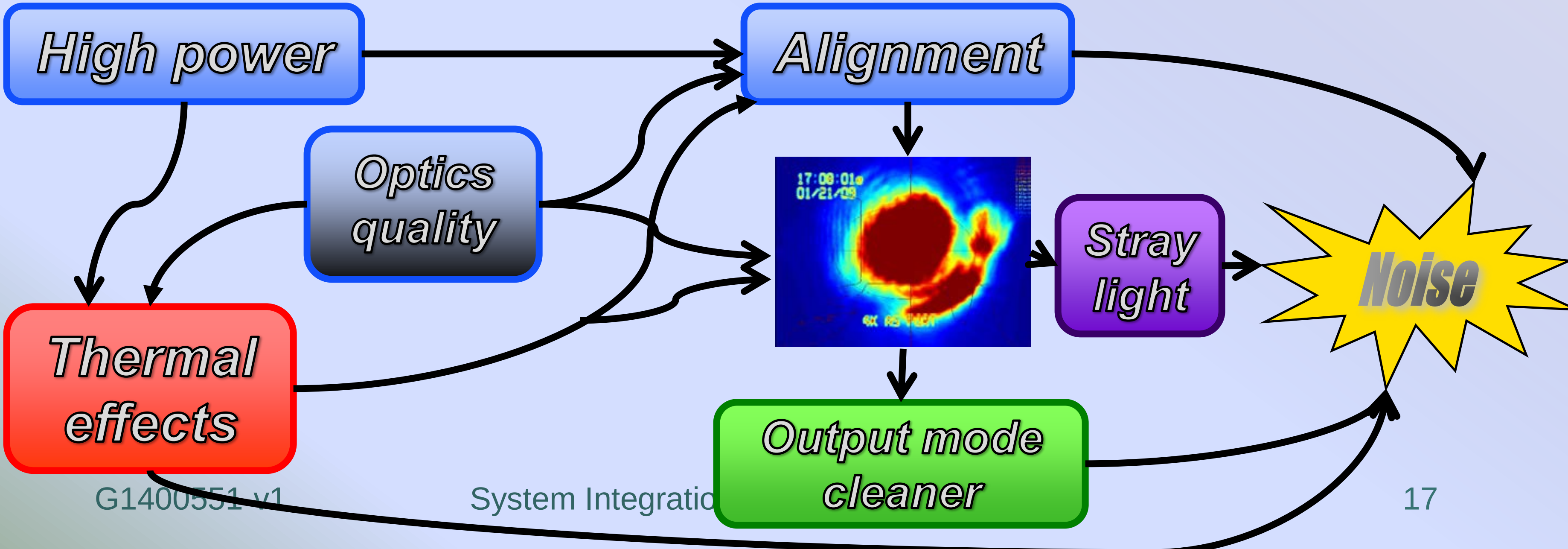
Post Project Plans for Commissioning

Post Project Plans for Commissioning

- Commissioning is the process of bringing each interferometer to its design sensitivity
  - Noise characterization & noise hunting
  - Achieving stable, low-noise operation
    - Tuning of controls systems
    - Gradual increase of injected laser power
    - Robust operation
- Implementation of new technologies and ideas to continually improve detector performance
- Commissioning is interleaved with engineering & science data collection runs

The challenge of commissioning

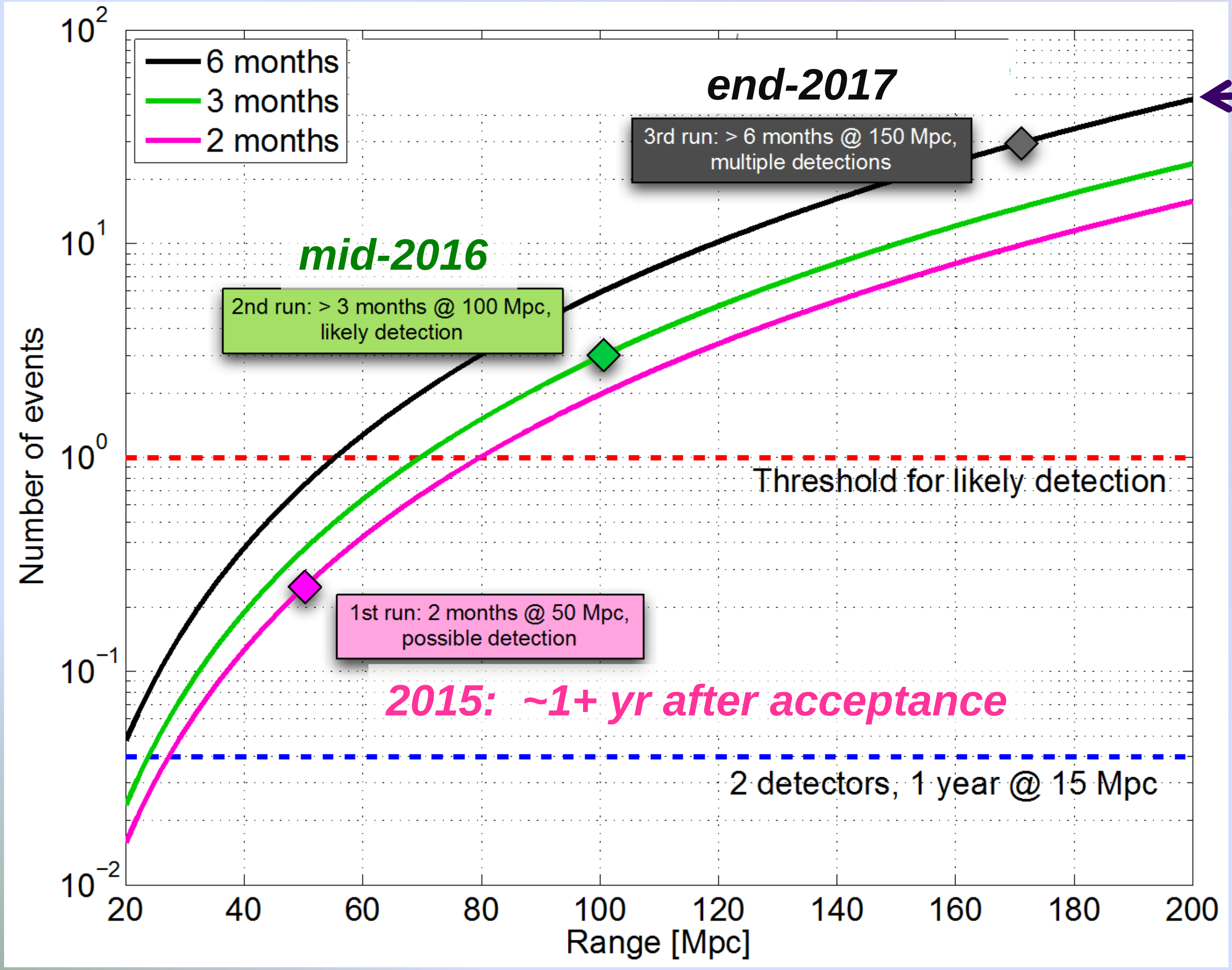
- Everything is operating near fundamental limits, and many effects cannot be tested on small scale setups
- Requirements are often set as a compromise between feasibility and design margin: some may turn out to be inadequate
- Many noise mechanisms arise from the interplay among several subsystems or interferometer characteristics



Starting Point: Advanced LIGO Project Acceptance

- Subsystems meet their acceptance criteria
  - Design documentation
  - Test results and requirements verification
  - User's manuals, procedures, parts lists, etc.
- Each interferometer locks for an extended time (2 hours)
  - Locking: acquire and maintain interferometer resonance under automated control
  - Functional prerequisite for sensitivity studies and improvements
  - Locking tests basic functional requirements; commissioning tests deeper performance requirements

Advanced LIGO: anticipated timeline



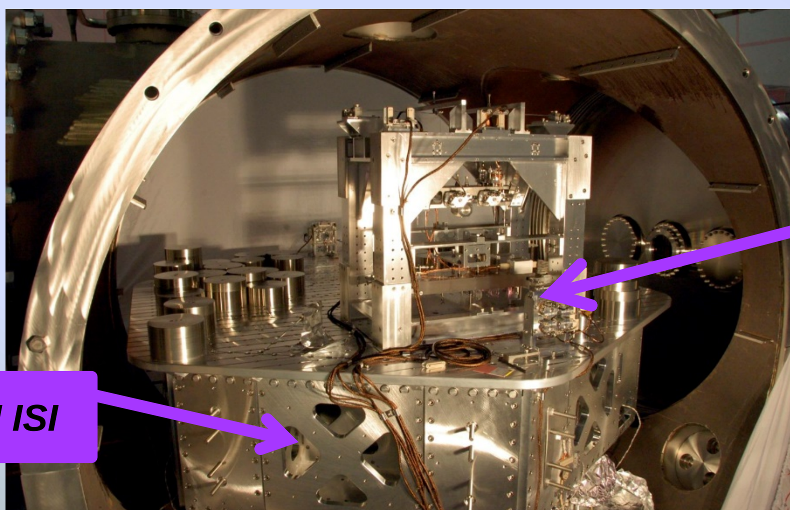
Full sensitivity (200 Mpc): end-2018

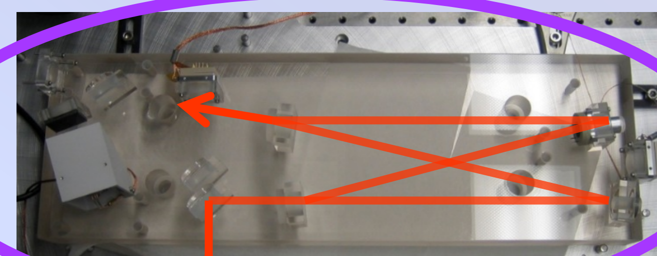
Initial LIGO: Overall, 4-5 years from locking to design sensitivity

How we expect to speed commissioning effort in aLIGO

- There is much more *upfront subsystem testing* in aLIGO, including …
- *Enhanced LIGO*, a full scale test bed for several aLIGO technologies.

Output Mode Cleaner





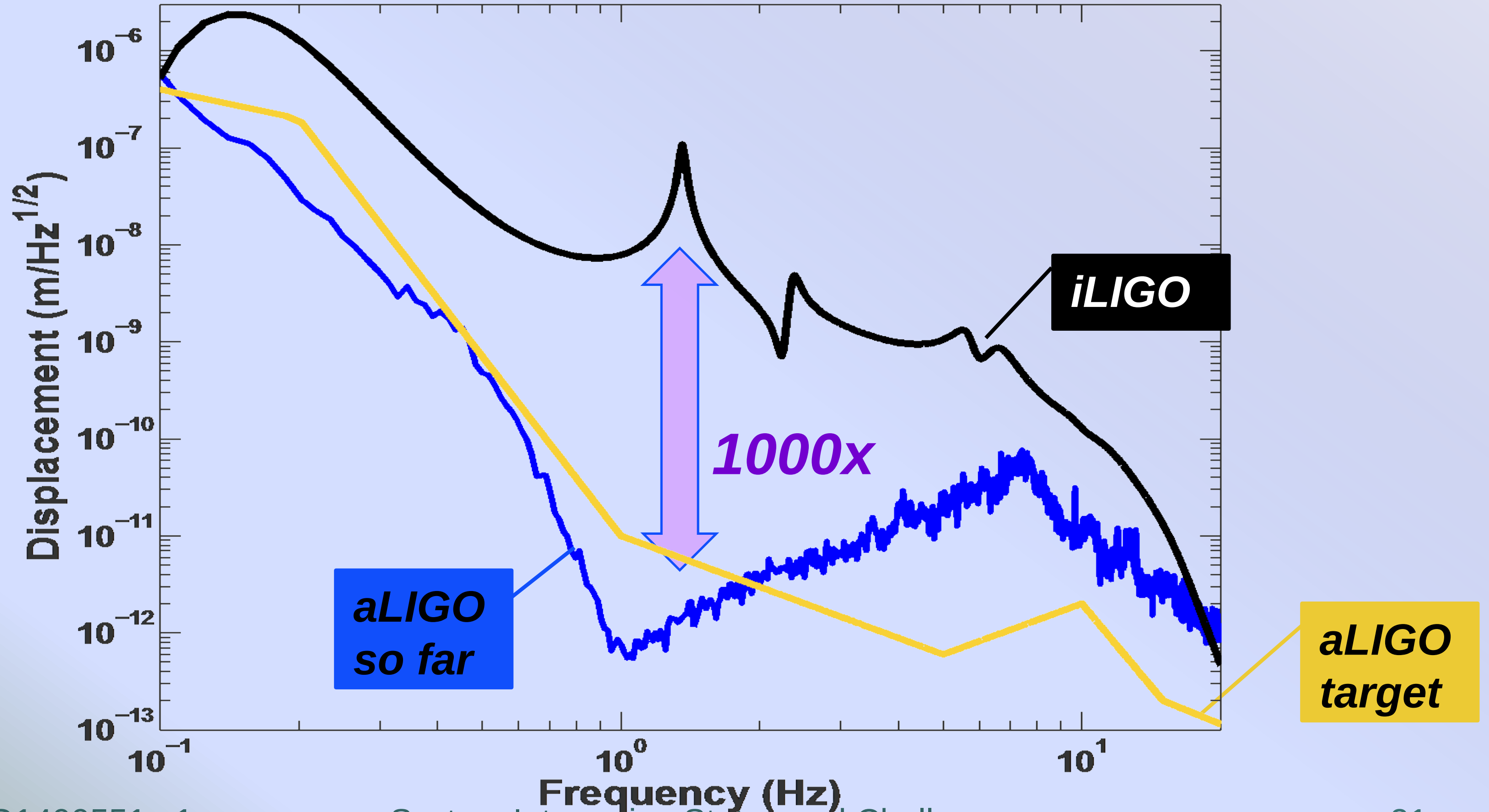
HAM ISI

Commissioning advances:

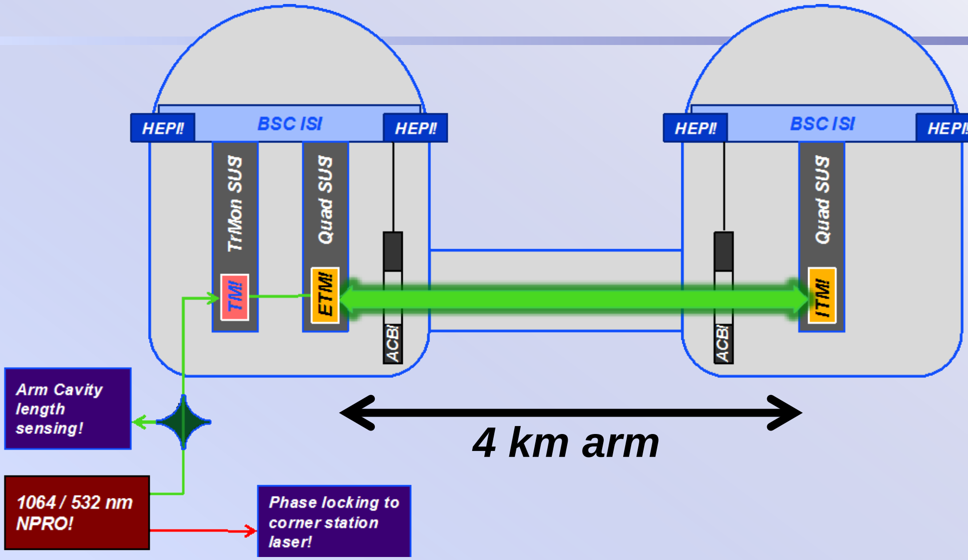
Alignment of the output mode cleaner
Diagnosis and mitigation of beam jitter noise

Much greater *seismic isolation* in the control band

Motion input to the test mass suspensions



Speedier commissioning



- *Lock acquisition strategy* designed in from the start, including a new Arm Length Stabilization system
  - Long arm cavities are controlled independently using a different wavelength laser
- *Better teams* on hand
  - More people and with more experience
  - Observatory staff, including operators, involved from the beginning
- *Better support structure* in place
  - Software tools in place
  - Online web tools in place
- Having been there before helps a lot!

On the other hand: Principal Technical Risks

- High power operations
  - Absorption & thermal compensation; parametric instability potential
- Required displacement noise levels not verified directly
  - Essentially impossible to test in subscale setups
  - Thermal noises (suspension and mirror coating): rely on design calculations; material parameter measurements; scaled noise tests
  - Technical noises (magnetic field coupling, e.g.!): design calculations & best practices
- Increased complexity
  - Number of control loops an order of magnitude larger than in iLIGO
  - Mechanical systems have many more degrees-of-freedom; e.g., Test Mass Quad suspension has 48 DOF, vs. 6 in iLIGO
  - Reliable and robust controls of interferometer

Challenges

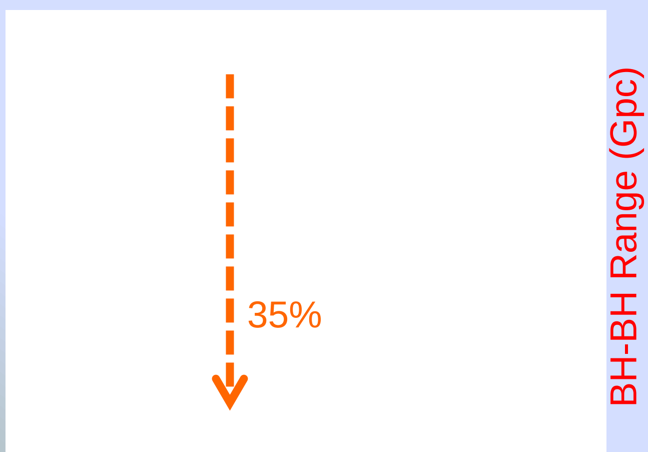
- Operational and logistical aspects must be addressed from the beginning; greater complexity of aLIGO demands more investment in:
  - Configuration control
  - Operator training
  - Maintainability
  - Simplification of operations
- Must anticipate that some components may need to be re-designed or upgraded with new features
  - Nature of a new and complex scientific instrument that not all requirements are adequately known beforehand
  - A number of such examples from initial LIGO enforce the lessons:
    - Initiate & maintain R&D in supporting technologies
    - Identify deficiencies early and commit resources to dealing with them

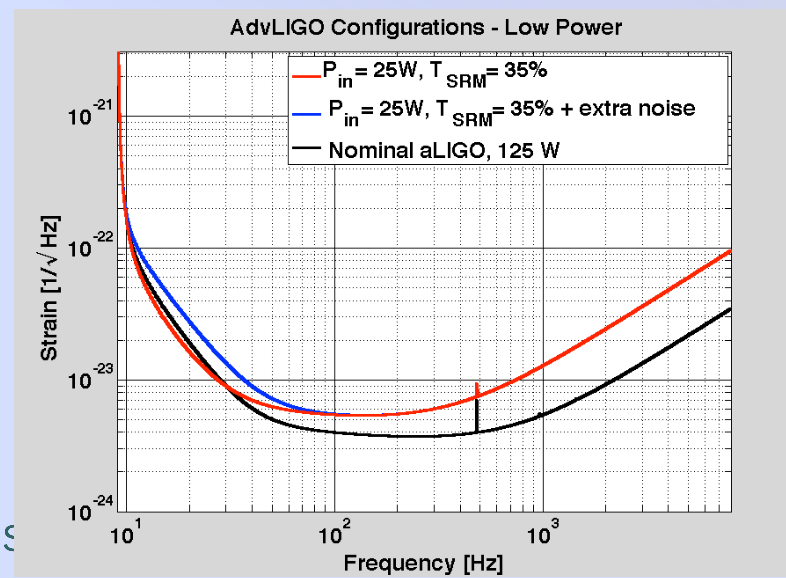
Commissioning strategy for early discovery

- Frequency range of 25-250 Hz is the most important for NS-NS inspiral range
- Laser power
  - Operation at full laser power will take significant commissioning time, but is not necessary to achieve very good inspiral range
  - We've targeted 25 W as the input power level for the first stages of operation (approximately the level achieved in Enhanced LIGO)
- Technical noise sources
  - For many noise contributors, ultimate performance at 10 Hz can be deferred, with ~20 Hz as an intermediate goal, with no effect on NS-NS inspiral range

Design for performance at lower power

- Recycling cavities designed so that little or no compensation of thermal lensing will be needed
  - Implementation/optimization of thermal compensation was a big time sink in iLIGO/eLIGO
- Signal recycling optimized for lower power





Steps to get to Low-Noise Operation

There are many steps in getting to a functional GW detector – these are split into 3 phases

- Acquisition
  - All steps to bring an uncontrolled interferometer to its operating point
  - All cavities on resonance; alignment close to optimal
- Locked
  - All steps between acquisition mode and low-noise mode
- Low-noise or Science mode
  - Science data is collected

Locked Phase Steps

- Transition to low-noise sensors for global control
  - Initial locking achieved with more robust, but lower SNR sensors
  - aLIGO innovation: all low-noise sensors are located in vacuum, on isolated platforms
- Increase laser power
  - Initial locking done at low power, one-to-several Watts
  - Typically increased in multiple steps
- Full implementation of alignment control system
  - Initial acquisition mode, with a simple sensing matrix but relatively poor performance
  - Science mode, with more complex sensing, tuned control bandwidths and noise cut-off filters

Locked phase steps, cont'd

- Global length controls optimization
  - Tuning of the GW channel loop for stable, low-noise performance
  - Reducing noise contribution from auxiliary loops via bandwidth tuning; filter design; on-line correction paths
- Low-noise mode for suspension and seismic systems
  - Optimization of suspension local damping filters
  - Engagement of low-noise mode for suspension actuator drivers
- Thermal compensation activation
  - First level of compensation achieved with the ITM ring heaters
  - Greater levels of compensation using the CO_2 laser projector beams
- Preceding steps aren't entirely sequential

Establishing and optimizing the Locked Phase sequence is one of the two main tasks of commissioning

Potential Component Upgrades

Why are we talking about upgrades at this stage?

- Non-essential design element may not have been ready for baseline
  - Example: input beam mode-matching control
- New analysis may indicate less margin in the design, or uncertainty in the original design margin
  - Example: squeezed-film damping in the End Reaction Masses
  - Example: improved suspensions for output beam steering optics
- New developments since the design was frozen
  - Example: output beam mode-matching control

Paper design might not cut it, and we need to be prepared to rectify it

Resources

Increased observing

- Commissioning teams comprised of observatory-based personnel, plus students, post-docs, scientists and engineers from the MIT and Caltech groups
- Equipment budget of $8M over five years
  - Covers modifications required to the basic aLIGO design
  - Engineering estimate using aLIGO design/procurement data, and comparison with analogous iLIGO activities

Requested budgeted is at the low end of this range

Summary

- Commissioning Advanced LIGO is the biggest challenge for the Lab
- We have a well defined plan for where we want to be and how to get there
- Improvements in technology, test plans, and overall experience and personnel should result in faster commissioning
- Faster to get close to design sensitivity: ***Within a factor of 2 of the design goal in 2 years of commissioning***

Squeezer Effort

- First upgrade to aLIGO
  - Goal 10dB, minimum 6dB
  - Proposal: TBD
- R&D effort at MIT/ANU
  - Filter cavity experiment (with H1 squeezer)
  - In-vacuum OPO: Prototype at ANU
  - Fiber-coupling: UHV feedthroughs, drift, noise, etc.
- Other efforts
  - Syracuse: adaptive mode matching at AS port
  - Florida: Low loss Faraday