Introduction: Advanced LIGO seismic isolation critical review, 13 Jan '05

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LIGO-G050007-00-R

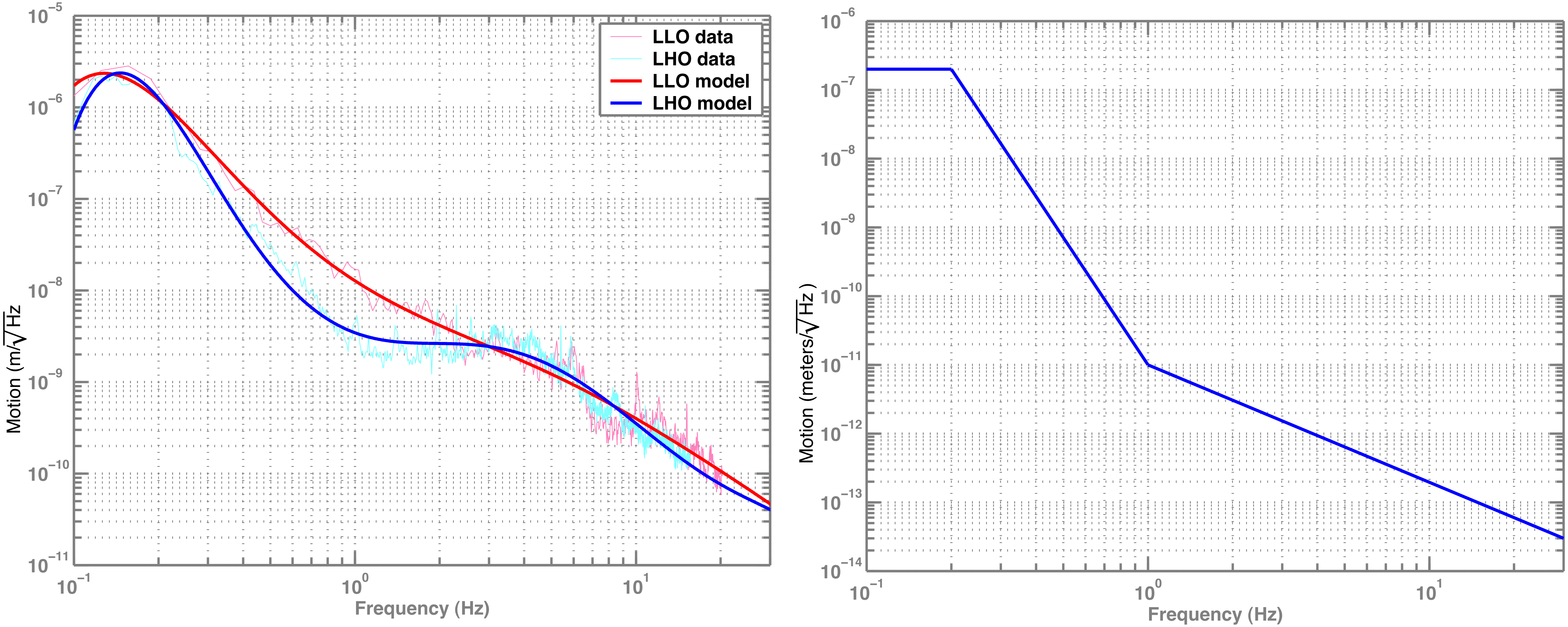
Summary & Conclusions

- It would be prudent to study the outcome of the present ETF tech demo commissioning process and compare it with noise models *before committing to purchase the ASI-design BSC structure*.
  - There is still risk of missing the 10 Hz noise requirement by a small factor if high-frequency plant features limit our loop gain: fixes may include rework of sensor layout or blade parameters.
  - *We believe that the design concept and mechanical design can meet the requirements, but that a wait of a couple or three months before placing orders will be fruitfully used to reduce performance risk.*
- It is likely that the total costs to implement Adv LIGO SEI may exceed the cost book amount.
  - *The current structure production estimate is now under the proposal cost.*
  - The excess is largely due to properly including installation and integrated test expenses.
  - The team will work to streamline installation and integrated testing procedures.

Required features of in-vacuum platform

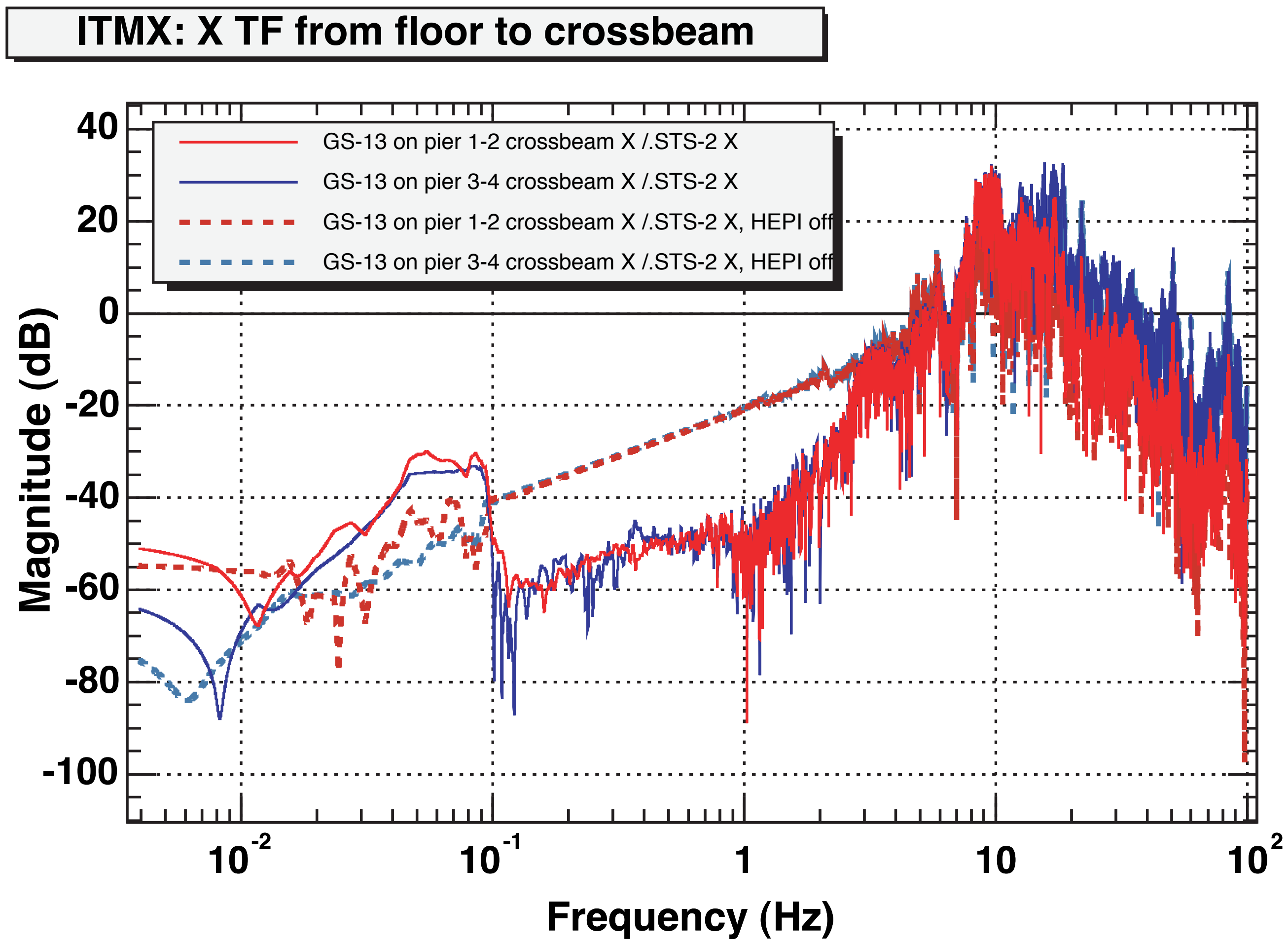
- Vibration Isolation
- Alignment/ coarse positioning (offloaded to HEPI)
- Mechanical interface (w/ chamber and suspension)
- Installation plan and fixtures
- Flexibility in payload positioning and size
- Power and signal routing to SUS
- Vacuum compatibility
- Operation and Ease of Use
- Thermal behavior
- E/M compatibility

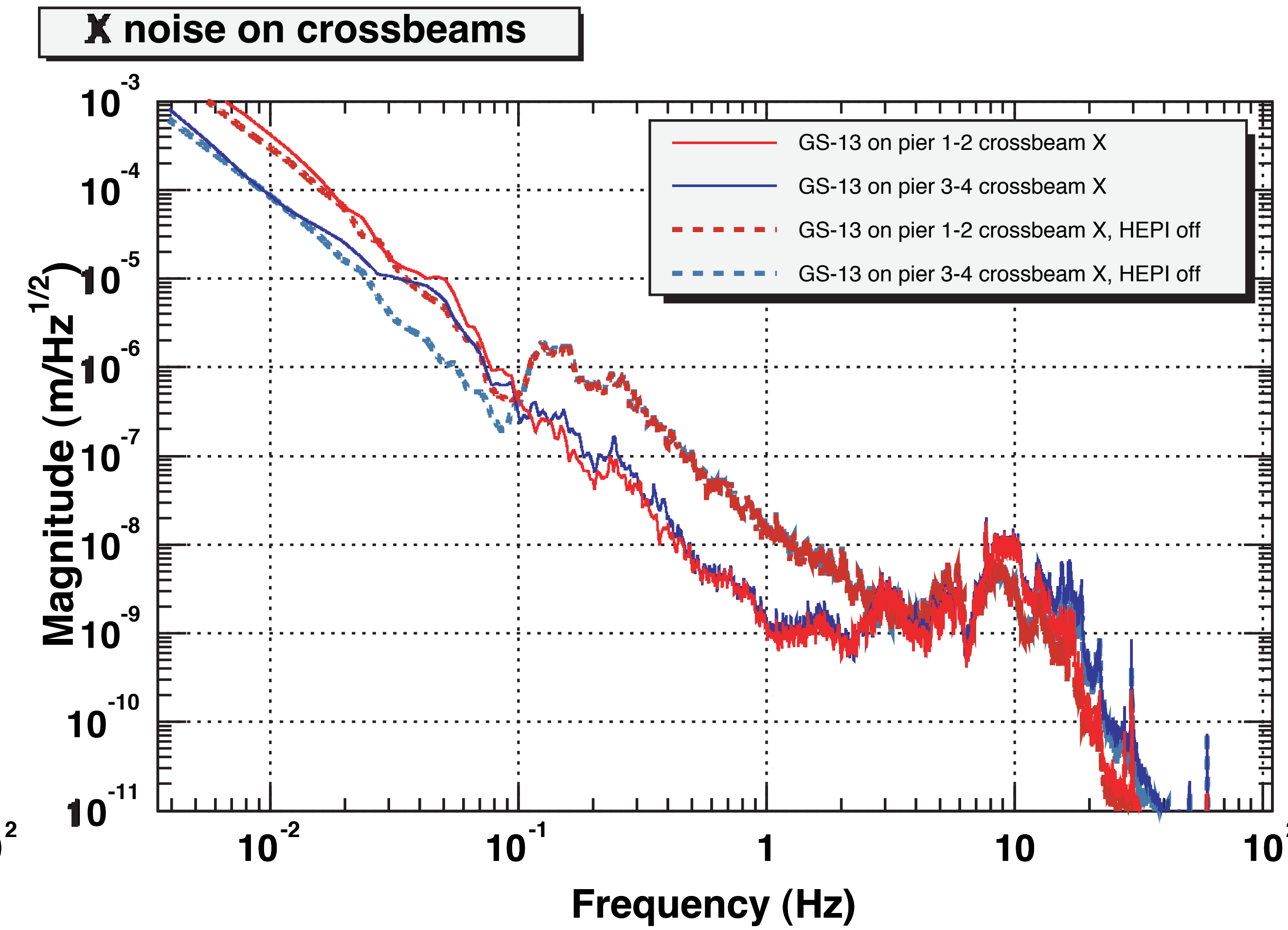
Seismic isolation requirements, approach



- Microseism (0.1–1 Hz) to be reduced by factor of 10 (via HEPI sensor correction).
- 1–10 Hz band quieted by two-stage internal platform, by factor of about 1000, using two-stage in-vacuum active isolation platform

Crossbeam versus ground noise

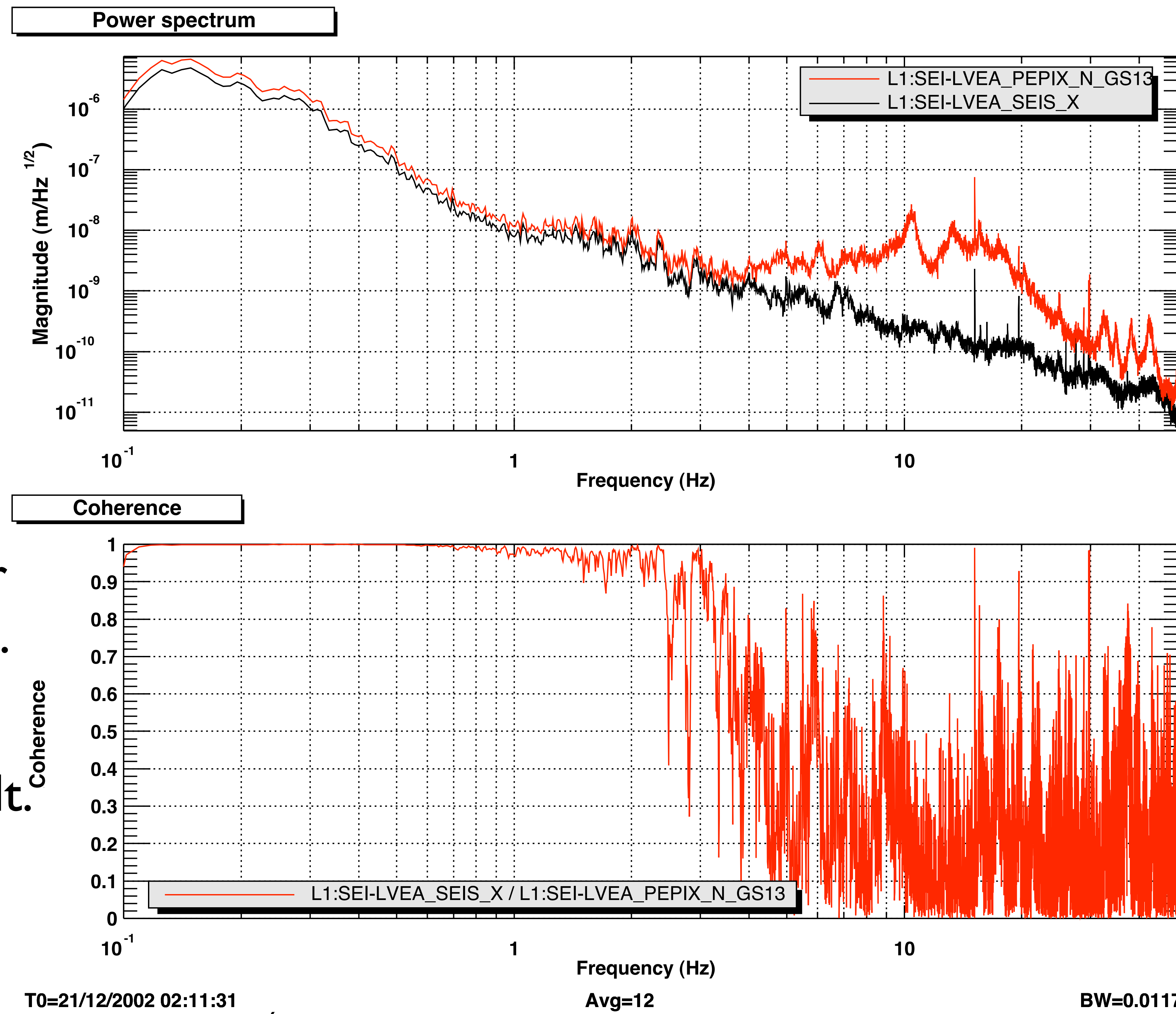




- Requirements based on floor-measured noise, but crossbeam noise is currently much higher around 10 Hz.
- This is thought to be an artifact of strong coupling of the external structure with the massive stack; such coupling should be absent in this band when the active platform is in use.

Effect from pre-HEPI install

- Ground noise, compared with crossbeam noise.
- above a few hertz, the coherence is low, indicating that the noise takes a phase-varying circuitous path (e. g., through other DOFs) , or is from a different source.
- It is not acoustic, and is not primarily from slab tilt.



Current R&D Status

- (HEPI - installed and working at LLO. Improvements being studied at MIT.)
- "Rapid" prototype at MIT and Stanford used to demonstrate robust control of 12 DOFs, and then used to develop new control strategy and accurate sensor correction used in HEPI.
- Two-stage in-vacuum platform technology demonstrator tests underway at Stanford. Some results can be discussed, but not yet all that are needed.
- Mechanical and system design in progress for LASTI BSC prototype. The mechanical system purchase is the main topic of today's meeting.
- Various dynamic models have been studied during the past few years, and used to make design requirements and predict noise levels.
- Plans and cost analysis from Adv LIGO cost book have been revisited and updated this month (DC talk).

Mechanical Design/ Fabrication Subcontract

- Technology demonstrator designed and built for Stanford vacuum system (ETF) by High Precision Devices (HPD), Boulder, CO., largely meeting requirements.
- LIGO sought bids in Spring '03 to design BSC and HAM versions of in-vacuum seismic structure
  - ETF structure met most Adv LIGO requirements, so design was to be based on it.
  - Main differences: payload capacity, UHV preparation, interface dimensions.
  - Three phases: 1. Value engineering of existing design, 2. design and manufacture of HAM & BSC prototypes for LASTI, 3. Adv. LIGO production.
  - Phase 1, $30,000 contract awarded to three competing firms. Product of phase 1 owned by LIGO, and also served as part of competition for later phases.
- Winning phase 2 proposal from Alliance Space Systems, Inc. (ASI)
  - Precision Engineering and manufacturing firm in Pasadena, CA.
  - JPL spin-off, aerospace mechanical engineering specialists. Supplier of robotic arms used on Mars robotic vehicles.
  - Expertise in complex design that involves both dynamic modeling and precise mechanical tolerances. Teamed with fabrication specialist shop, which would take lead in phase 3 during large-scale production.

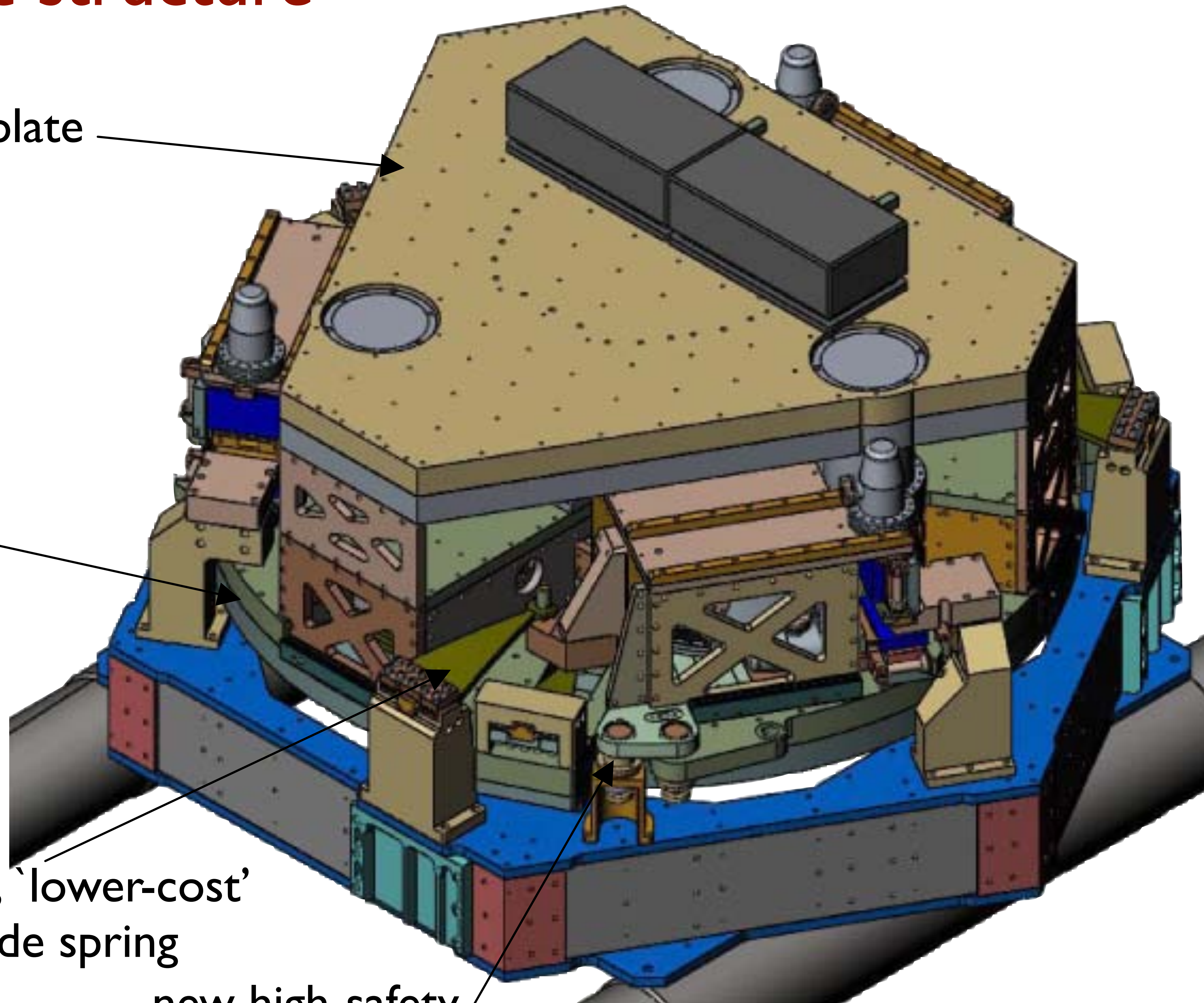
Summary of SEI mechanical requirements

- Stiffness: resonant frequencies above 150 Hz, phase delay specs in actuator-to-sensor transfer functions.
- Kinematics: Since active seismic isolation servo-control design is quite sensitive to cross terms between angular motion and horizontal displacement, the blade springs and vertical flexure rods that suspend the stages need to be designed to minimize these cross terms. Also, less stringent constraints on CG locations.
- Dimensional precision: Due to the necessary small dynamic range of the displacement sensors, <0.05 mm, 0.1 mrad overall dimension requirements are required, under load.
- Vacuum compatibility: Materials, design, preparation, and cleaning must meet LIGO's rather strict UHV specifications. (LASTI vacuum is to be similar to Adv LIGO's.)
- Interfaces: Flexible-use optics table to support large, heavy quad pendulums and other optical assemblies as payload. New 'stage 0' structures mate with existing seismic support tubes at threaded bosses.

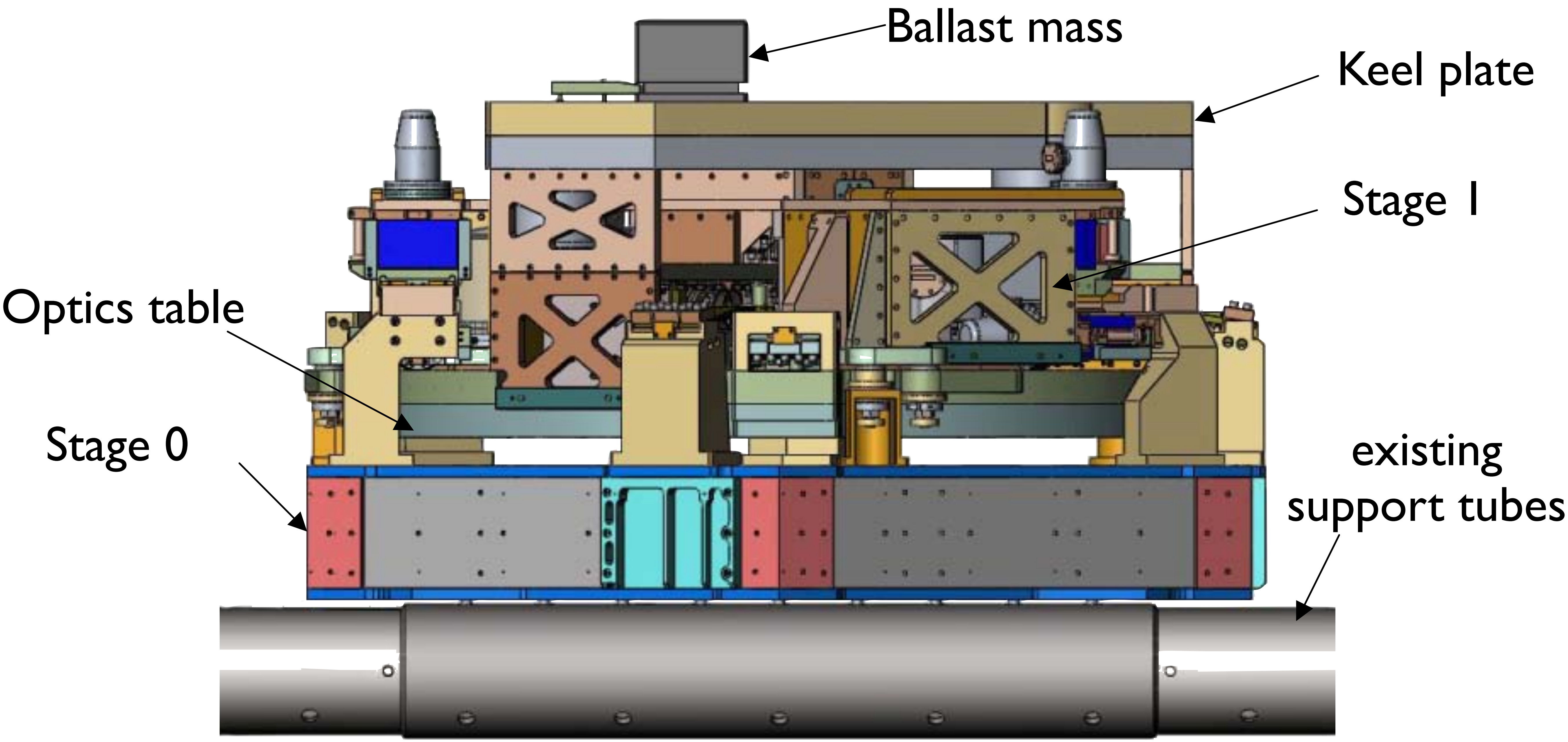
ASI technical approach

- Based in part on their phase 1 study conclusions, ASI worked to *replace complex parts* in the ETF design, which require high machining expertise and special shop capabilities, with a somewhat larger number of plate-like parts, which can largely be made on 2½ axis CNC milling machines.
- The ETF blade springs were wire-EDM machined from fairly large blocks of expensive maraging stainless steel, in order that the spring's shape would be curved when unloaded and perfectly flat when under its design load. ASI *redesigned the blade and flexure geometry* so that the blades could be cut from flat plate, potentially saving $1 million during phase 3.

BSC seismic structure

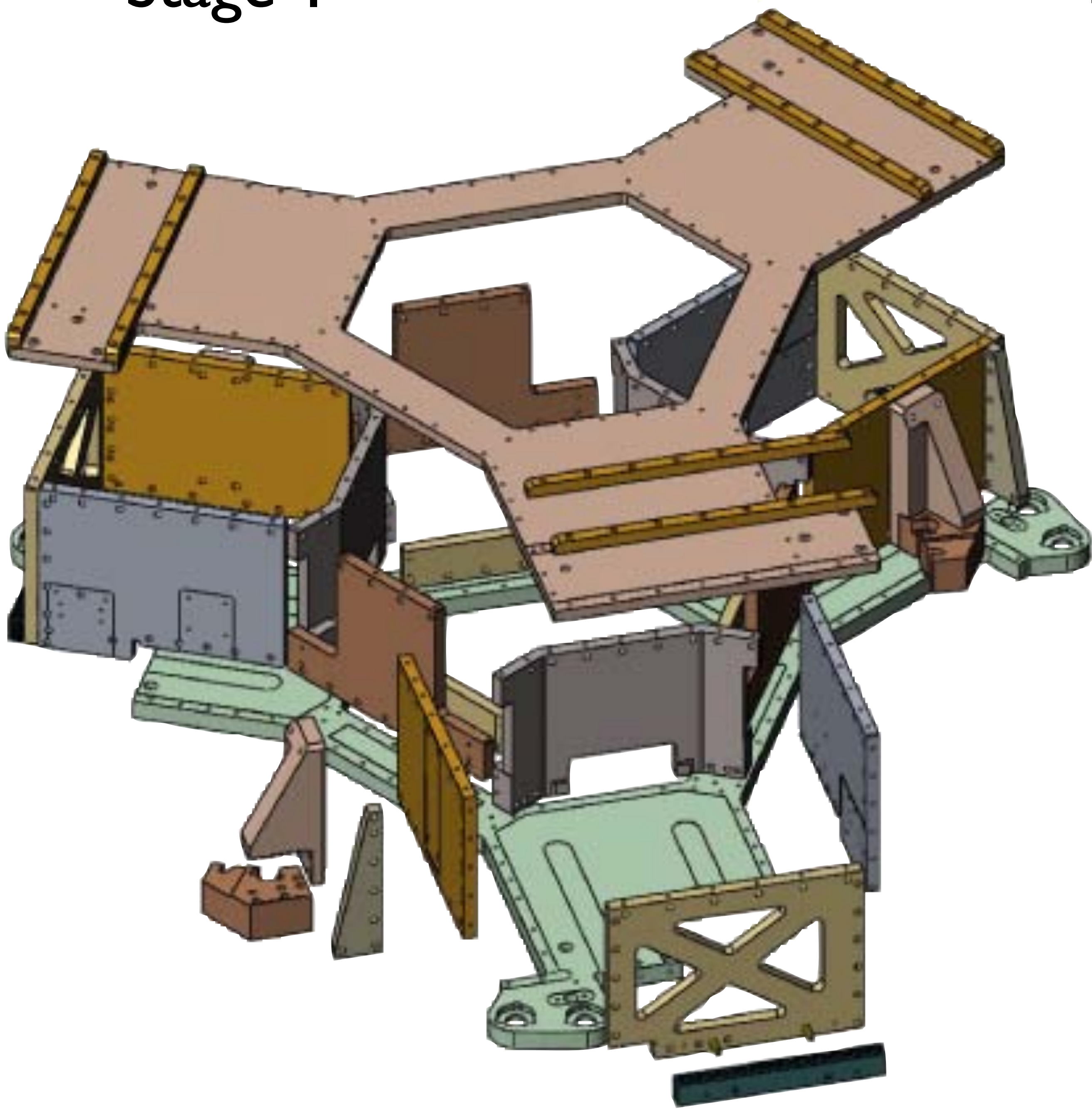


BSC structure (elevation)

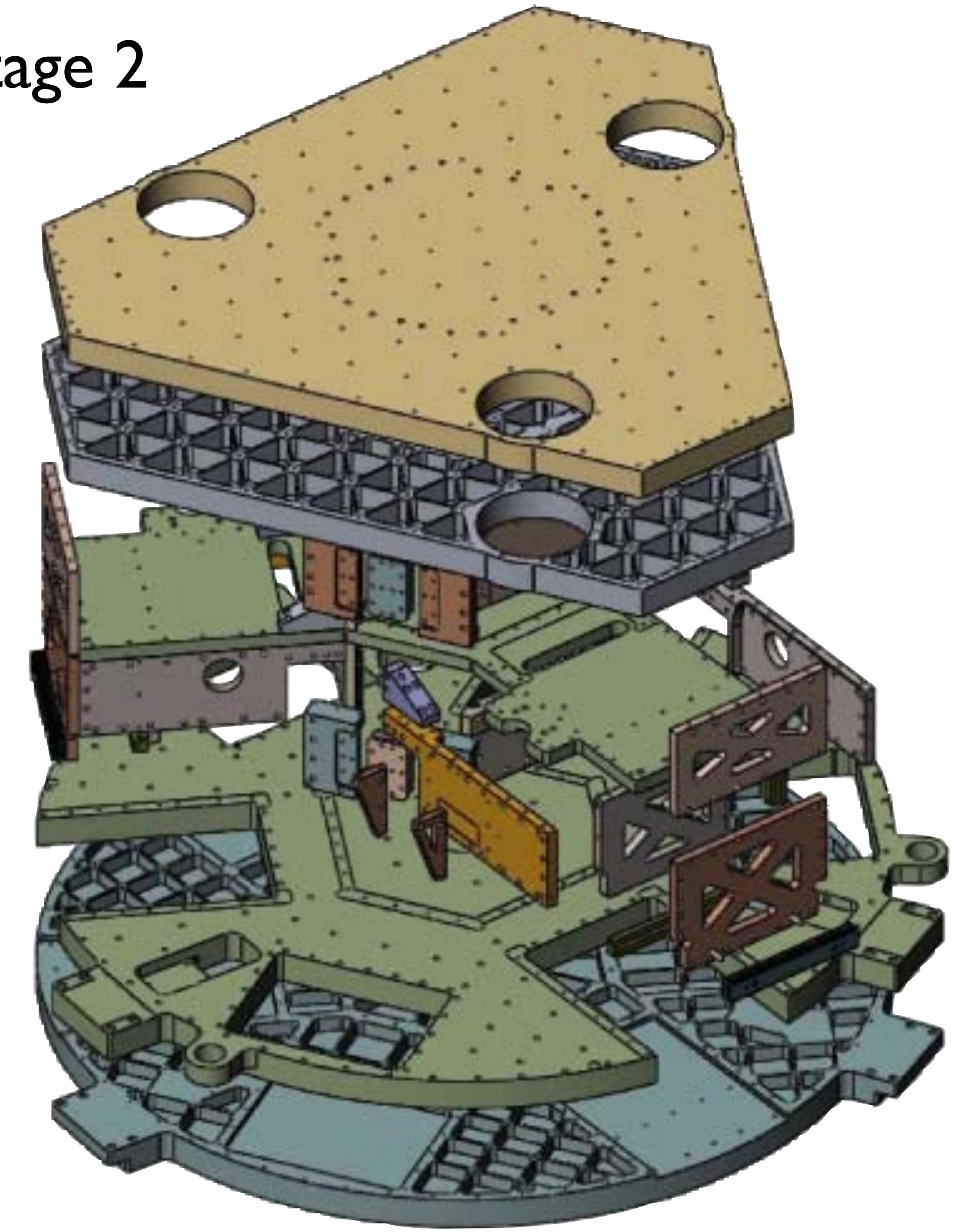


Stiff, plate-based structures

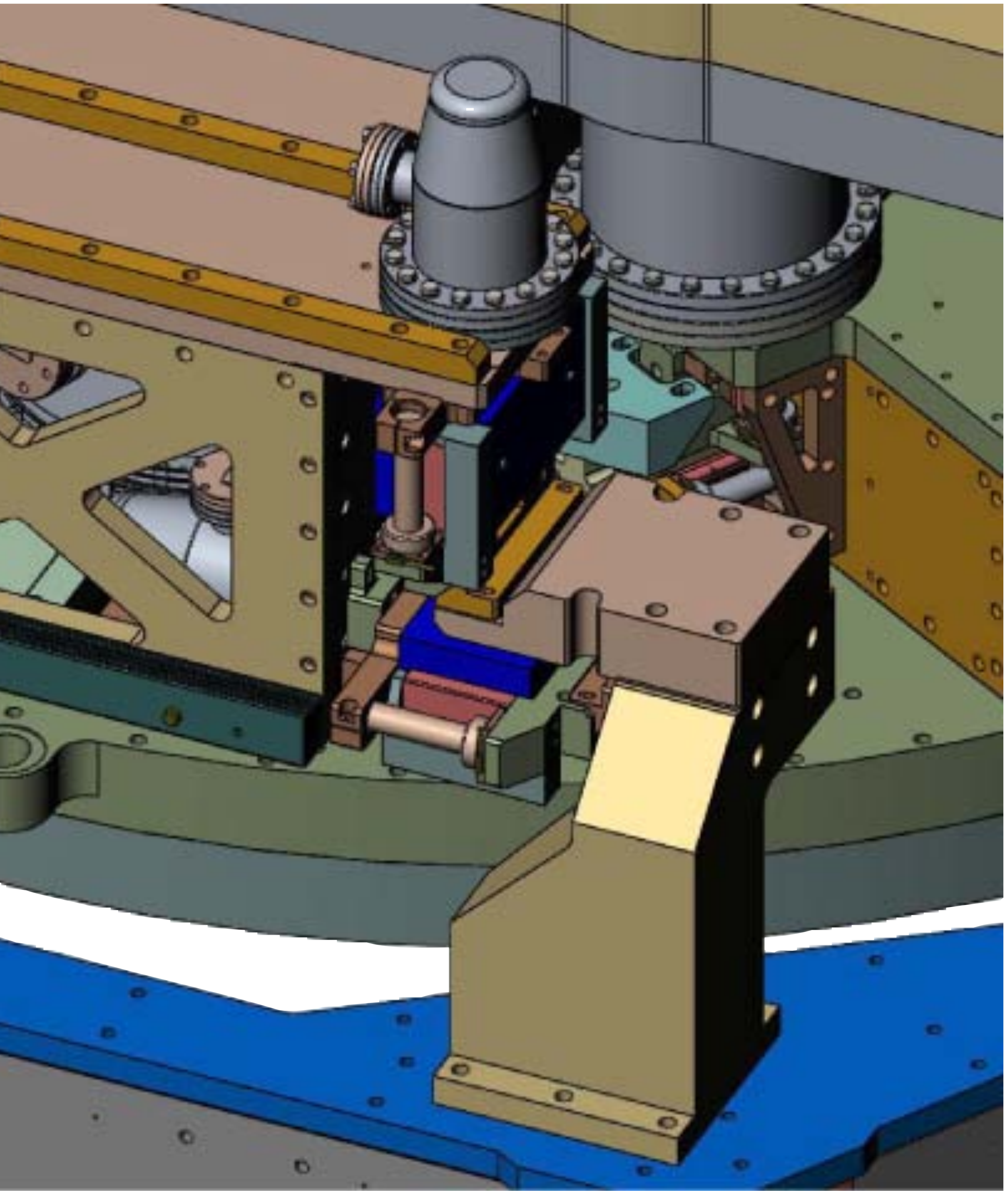
Stage 1



Stage 2

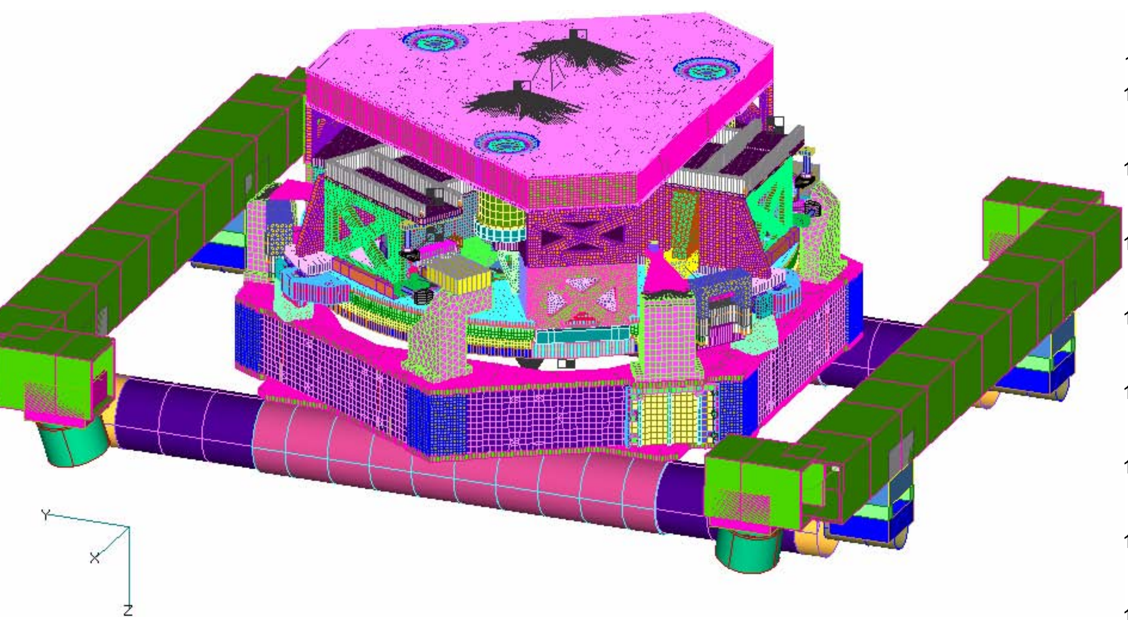


Sensor-actuator collocation



- To minimize phase delay in feedback loops, we minimize mechanical load line and compliance between actuator and adjacent inertial sensor.
- It is not trivial to do this for all 12 collocated sensor pairs and still have everything ‘fit’ and maintain overall stage stiffness.

Detailed dynamic modeling



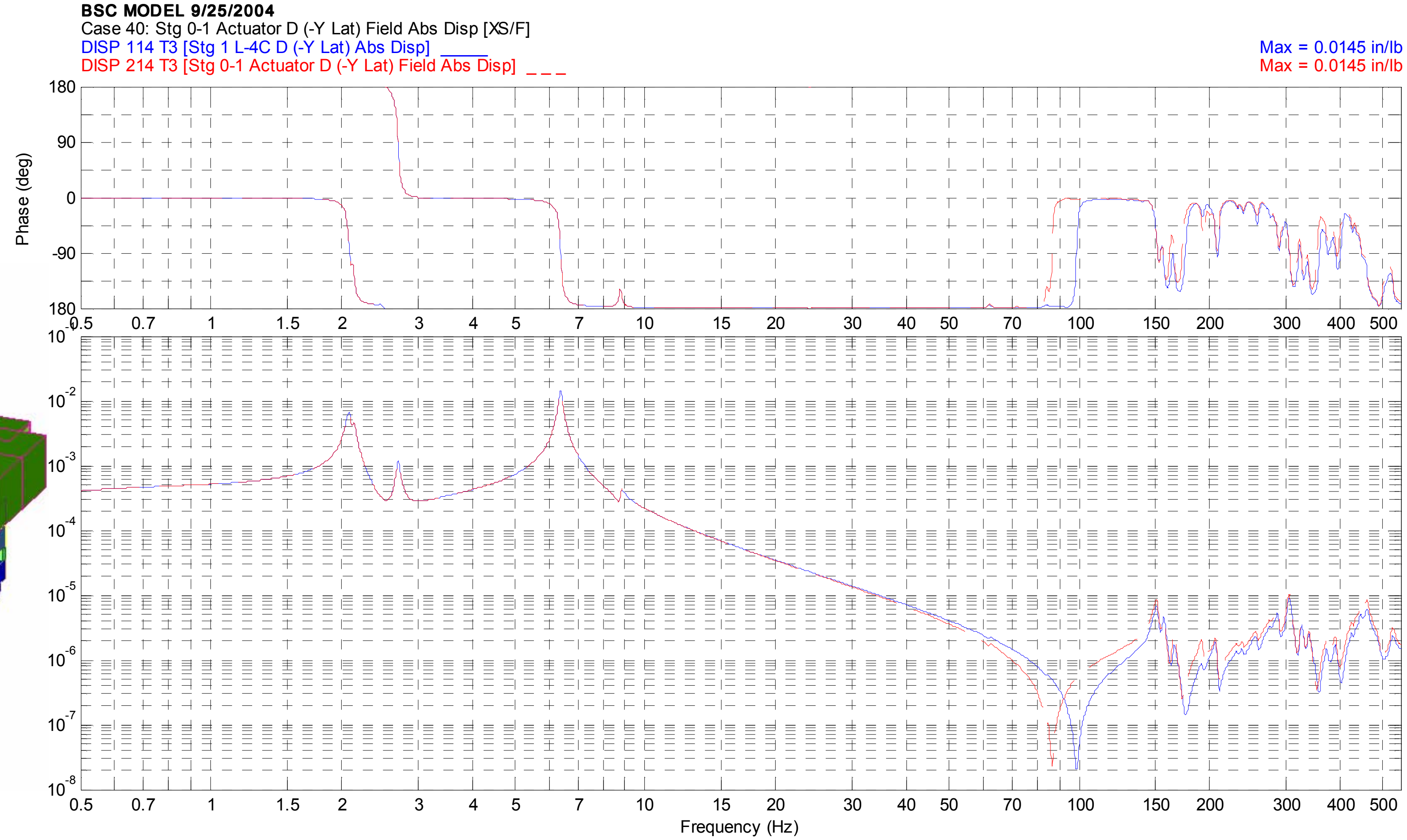
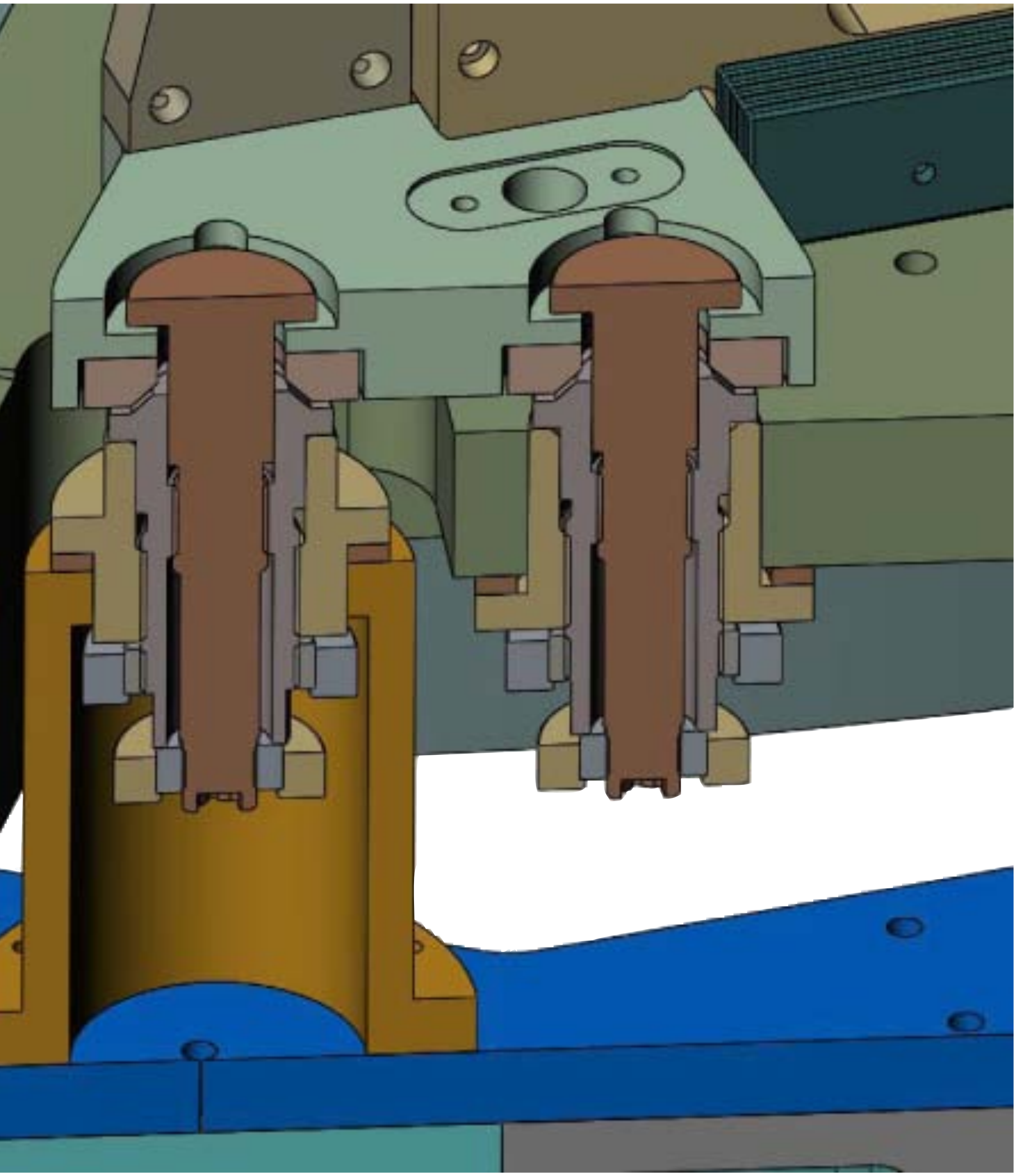


Figure 1.3a. Transfer function [Displacement/Force] with force input at Stage 0-1 Actuator D (-Y Lateral), and displacement response at the collocated L-4C seismometer (in blue), and the actuator drive point (in red). The two plots remain in phase except between 86 and 99 Hz.

- FEM-based dynamic simulations run by ASI engineer to verify our specific dynamic requirements.
- The Adv LIGO test mass suspension and cage is very massive, and the seismic stage 2 must be very stiff to avoid low frequency resonances.

Lock and Limit assemblies



- Locks secure device during shipment and assembly.
- Limit stops prevent stages from moving in directions and distances that would damage the sensors and actuators.
- The seismic isolation system and payload is planned to be about 5 tons, so these assemblies have to hold back a large moving object against a motion constraint at the tenth mm level.

Modeling Efforts

- FE model of tech demo structure, as part of HPD contract, predicting modal frequencies of structures. Verified experimentally.
- Calculation of flexure geometry and blade design, leading to highly diagonal stiffness matrix. Verified experimentally.
- FE models of LASTI BSC structure, as part of ASI contract work, used to qualify design stiffness and other parameters.
- Joined BSC stage 2 and quad SUS cage model, by Coyne, using IDEAS, used to estimate the effects on SEI's mechanical plant from the heavy cage.
- Various Matlab dynamic models (Lantz):
  - 2-stage dynamic plant model used in conceptual SEI design (ca. 2001)
  - old-strategy (collocated) controller model.
  - 2-stage plus mass-spring payload plant model.
  - Updated dynamic plant model, using masses, moments and stiffness matrices from near-current ASI design. Used to justify relaxation of CG placement requirements for ASI

Risks in LASTI prototype and beyond

Result of 'bad outcome'

- Risks due to changes in design from ETF Tech Demo:
  - Vertical centering: vertical spring rates carefully controlled in manufacturing, requiring less trim mass.
  - New stage lock and center-of-range position system.
  - First use of steel pod enclosures.

  Mechanical re-work

- Thermal behavior in vacuum not yet measured, including effects of gradients and thermal transients.

  Mechanical re-work, employing heat conducting straps, possible controller logic adjustments. Worst cases: servo 'hunting,' dimensional tolerance problems, and outgassing.

- Seismometer sensors: noise floor not yet proven.

  Purchase or development of better sensors (very hard), or servo redesign (hard). Perhaps failure to reach noise requirement.

- Structural modes between tens and hundreds of hertz can make control design tedious.

  Stanford plans to study this problem in detail, and provide methods and procedures. Worst case is that some plant variations can't be controlled with high enough gain, and failure to reach requirement.

- STS-2 is to be phased out by manufacturer after STS-3 is in stable production; we need to watch this.

  Mid-stream design change.

Risk from complexity

- LIGO-wide, internal SEI uses ~450 sensors and ~180 actuators and control loops (i.e., the same order as SUS). All of these channels, including electronics, wiring, timing, and processes have to work with considerably higher reliability than the LIGO detector itself.
- Proposed Approach:
  - Extension of M. Evans's diagnostic suite, to be used before, during and after commissioning.
  - Staged qualification of all signal channels, end-to-end. This will require earlier definition of the signal topology and front-end processing requirements than in LIGO-1 or other work, so that data systems are up and running before hardware commissioning.
  - Huddle qualification of sensor pods on isolated granite table near LASTI or in staging building at LxO (tests of gain, noise level, alignment of internal components.)
  - Complete system function test (probably in damping mode) on top of staging stand, requiring extra cables and pre-qualified control/data systems.
  - 'Dummy' sensor and actuator stand-ins, used to qualify data systems and upstream electronics.
  - Sys-id and diagnostics should be automated and easy to use, to save 'brain-power' for controller design and performance studies.

Complexity, continued.

- Stanford (Lantz & Co.) have agreed to study the controller design process, using varying plants, to develop a procedure.
  - Separate out the routine steps, which are amenable to automation.
  - Develop well-oiled tools used to help commissioning team carry out the tricky design steps, and evaluate performance.
- In addition to fit/functional/installation tests already planned, LASTI team needs to use and evaluate the complexity-reducing techniques, *even if this isn't the fastest path to LASTI operation. Success at LASTI is defined by how well Advanced LIGO installation & commissioning goes at the Observatories.*

Planned (related) ETF R&D

- Completion of ETF controller design, and performance comparison against model. (Hua)
- Use of ETF payload witness seismometers to measure true noise floor of seismometers in our environment.
- Thermal tests in vacuum, and comparison against simple heat transfer models.
- Dynamic tests with Adv LIGO suspension cage bolted to stage 2.
- Development of systematic servo controller methods appropriate for LIGO commissioning.
- Control reallocation tests with triple.

Planned LASTI R&D

- Prototype tests of LIGO-type instrumentation.
- SEI-only performance test.
- SEI & SUS tests.
- Development of commissioning methods to be used in LIGO.
    - Staged noise, gain and functionality qualification of instruments and electronics.
    - Automated end-to-end diagnostics and sys-id.
    - Functional tests of assembled system on its stand.

Summary & Conclusions (reprise)

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