Paths to Improving Detector Performance

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NSF Review

Caltech, 30 April 2001

LIGO-G010206-00-M

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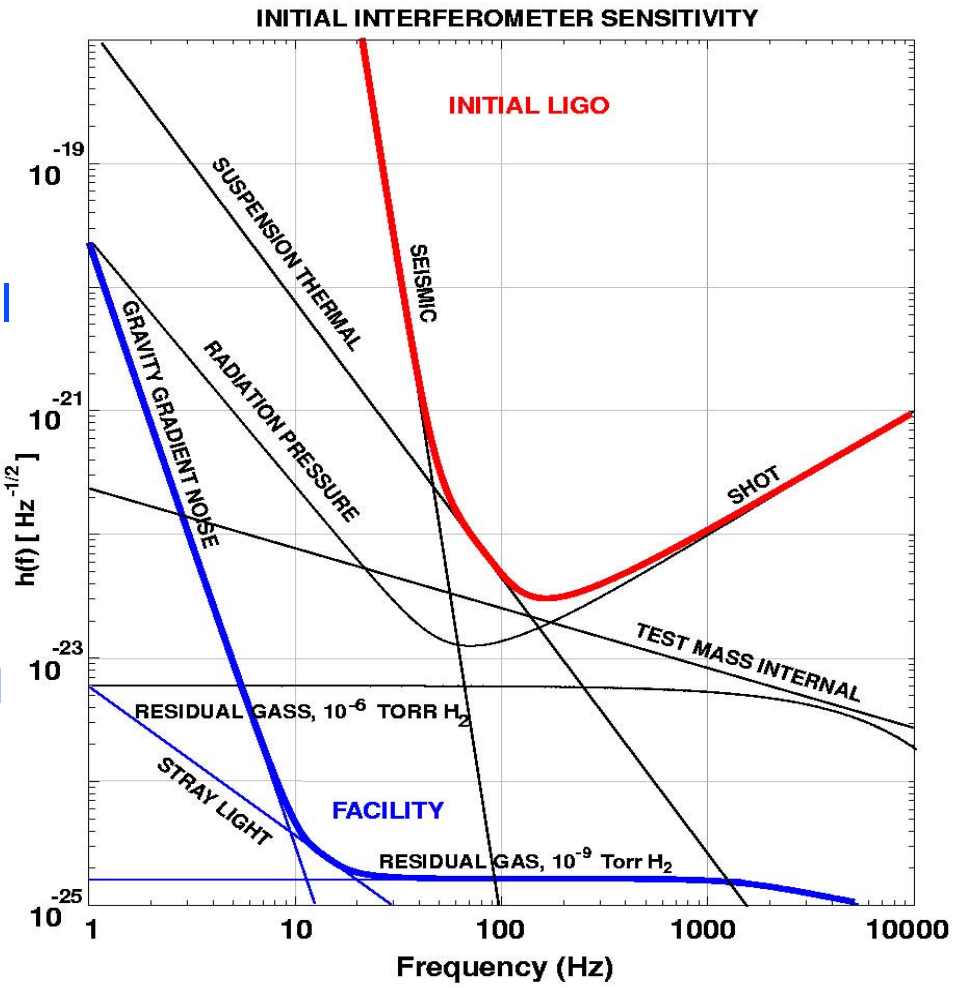
Objectives

- 'Availability' – operation at designed sensitivity level
  - » Individual detector designed for 90% uptime
  - » 3 detectors: 75% combined
  - » Maintenance ideally at 'down-times', not always possible
- Achievement of design sensitivity
  - » Measured via a spectral density over long times (many seconds)
- Stationarity of spectrum, near-gaussian statistics
  - » Measured via short-time spectra, 'burst' templates, etc.
- Detector Characterization → continued improvement
  - » Understanding of environmental input to detector performance

Noise budget

- "Fundamental" noise sources (seismic, thermal, shot) estimated by detail models
  - Models validated by prototype interferometers
- Non-fundamental noise sources all budgeted at 10% in amplitude of fundamental noise
  - Laser intensity noise
  - Electronics noise
  - Frequency noise
  - Thermal noise in non-fundamental degrees of freedom
  - Scattering
  - …

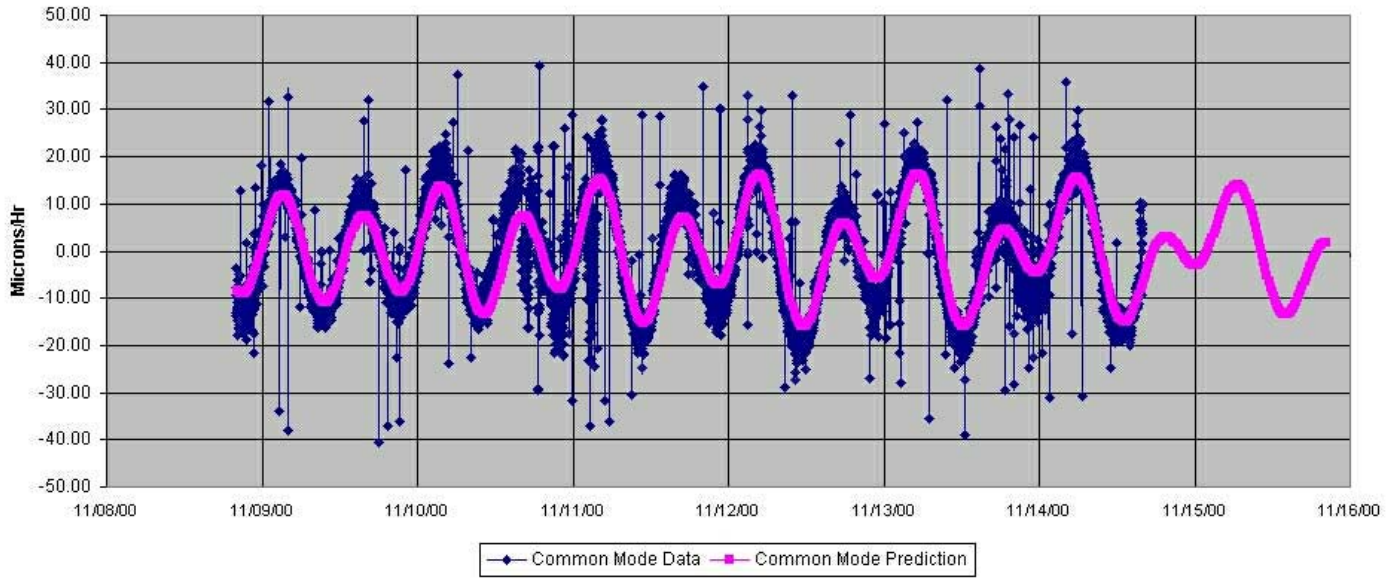


Approaches…

- Subsystem testing
  - » Explicit starting point for simplification by reduction of scope
  - » All nominally testable stand-alone and cumulatively
  - » Models exist for performance of all subsystems; measurements in process
    - – Seismic noise
      - In-vacuum seismic measurements match design model
      - 1e6 attenuation at ~40 Hz
    - – Test mass thermal noise
      - Suspension mode Q
        - » Design value 500,000, excluding reaction loss
        - » Measured 100,000, including reaction loss
      - Internal Q
        - » Design value 2e6
        - » Measured values 1.5 – 8e6 (one mode at 2e5)
    - – Sensing noise
      - Bench testing of photodiodes at full power
      - Electronics noise meet requirements

….Approaches

- Variation of parameters
  - » Exploration around design point
- Environmental characterization
  - » Much of system performance strongly linked to mechanical disturbances, as-built resonances



Experience

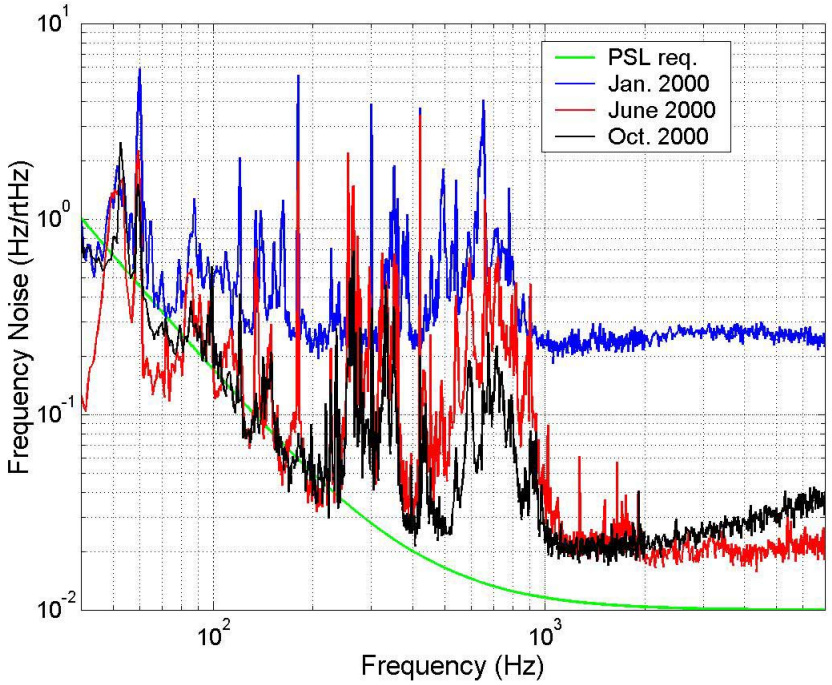
- 40m (displacement noise testbed) interferometer
  - » Demonstration of mechanical noise sources, recycled configuration
- PNI (phase noise testbed) interferometer
  - » Demonstration of fringe-splitting, digital servoloops
- Other prototype efforts
  - » Garching and Glasgow suspended interferometers
  - » Tabletop systems for proof-of-principle
- Development of methodical approaches to hunting and solving problems
- Training of critical workforce - ~125 person-years
  - » Circulation of skilled experimentalists to Observatories

Tools

- Qualitative change from earlier experience
- All signals available in real time or after the fact
  - » Thousands!
- Traditional signal analysis functions with friendly GUI
- Stimulus via digital or waveform synthesizer sources
- Porting to Data Monitoring Tool (DMT) or Matlab or…
- End-to-End (e2e) modeling

Anecdotes

- Achieving required servo control gains
  - » Coupling of 14 Hz vertical ‘bounce’ mode to optical path via wedges – surprise!
  - » Trial of resonant gain stages had taken place in prototypes
  - » Application, tuning, trial, failures, successes
- Studies, improvement in the frequency noise of Laser system
  - » Multiple sensors: reference cavity, mode cleaner, common mode interferometer
  - » Trades on servo gains
  - » Identification of mechanical resonances in optic mounts (plunking, headphones)
  - » Excitation of table by acoustic noise (loudspeakers, ratios of power spectra)
  - » Rebuild mounts; isolate table acoustically



Anecdotes

- Coupling of interferometer sensing light to local mass control sensors
  - » Observation of sudden alignment changes with resonance in cavities
  - » Track down coincidence of (false) local sensor signals with laser light fluctuations – eased by access to all channels all the time
  - » Modulation of light intensity, confirmation and quantification of coupling
  - » Two solutions pursued: dichroic filters, mod/demod systems
    - – Retrofit at targets of opportunity (earthquakes…) underway
  - » Also, use of optical levers in flexible DAQ/control system as external references

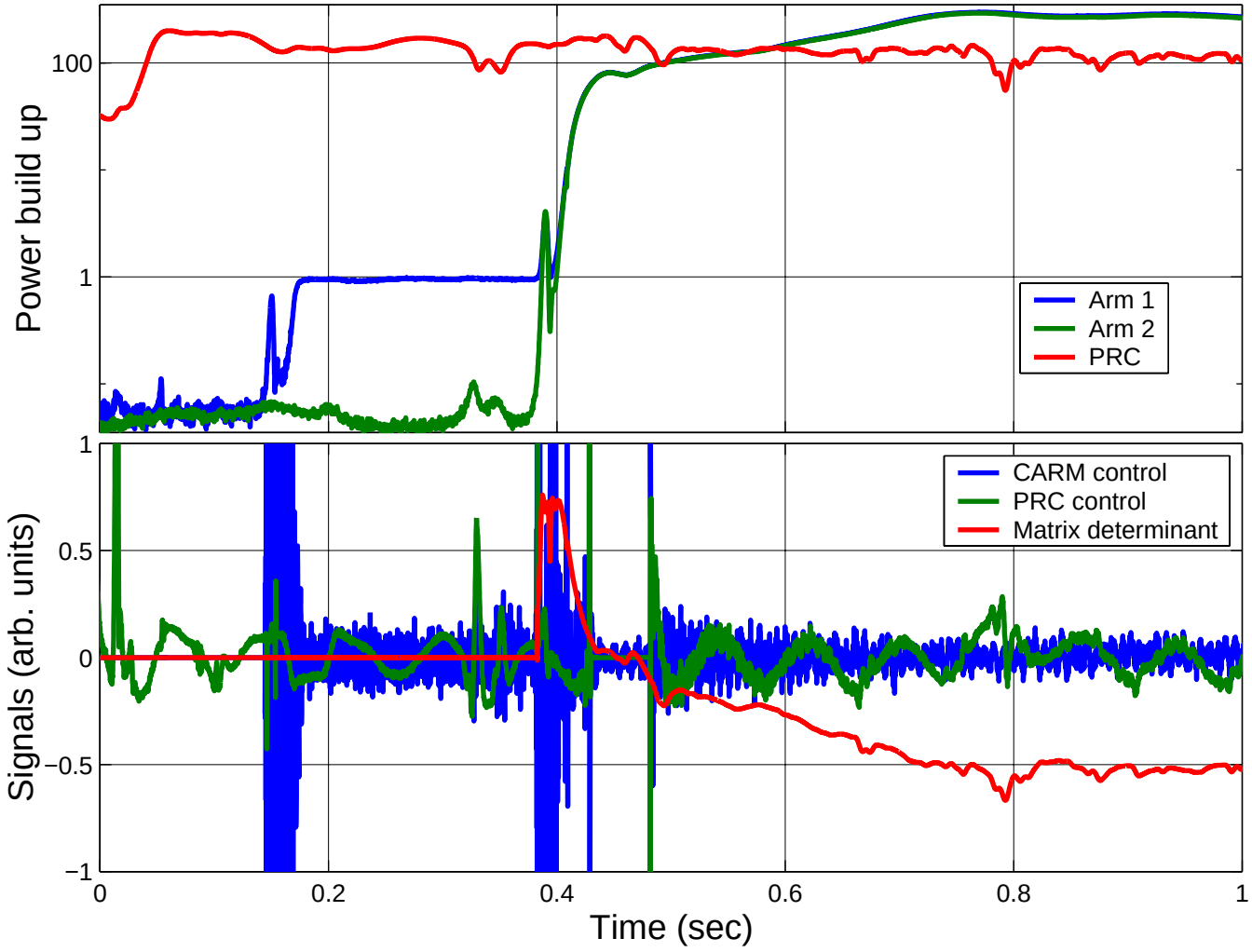
Anecdotes

- Noise limitations of A-D converters
  - » High noise level observed for critical interferometer lengths
  - » Classic troubleshooting leading to source: A-D converters; most noisy, some not
  - » Re-order units for best near-term performance, work with vendor for best results
  - » Design/fab/install whitening filters to best use available technology

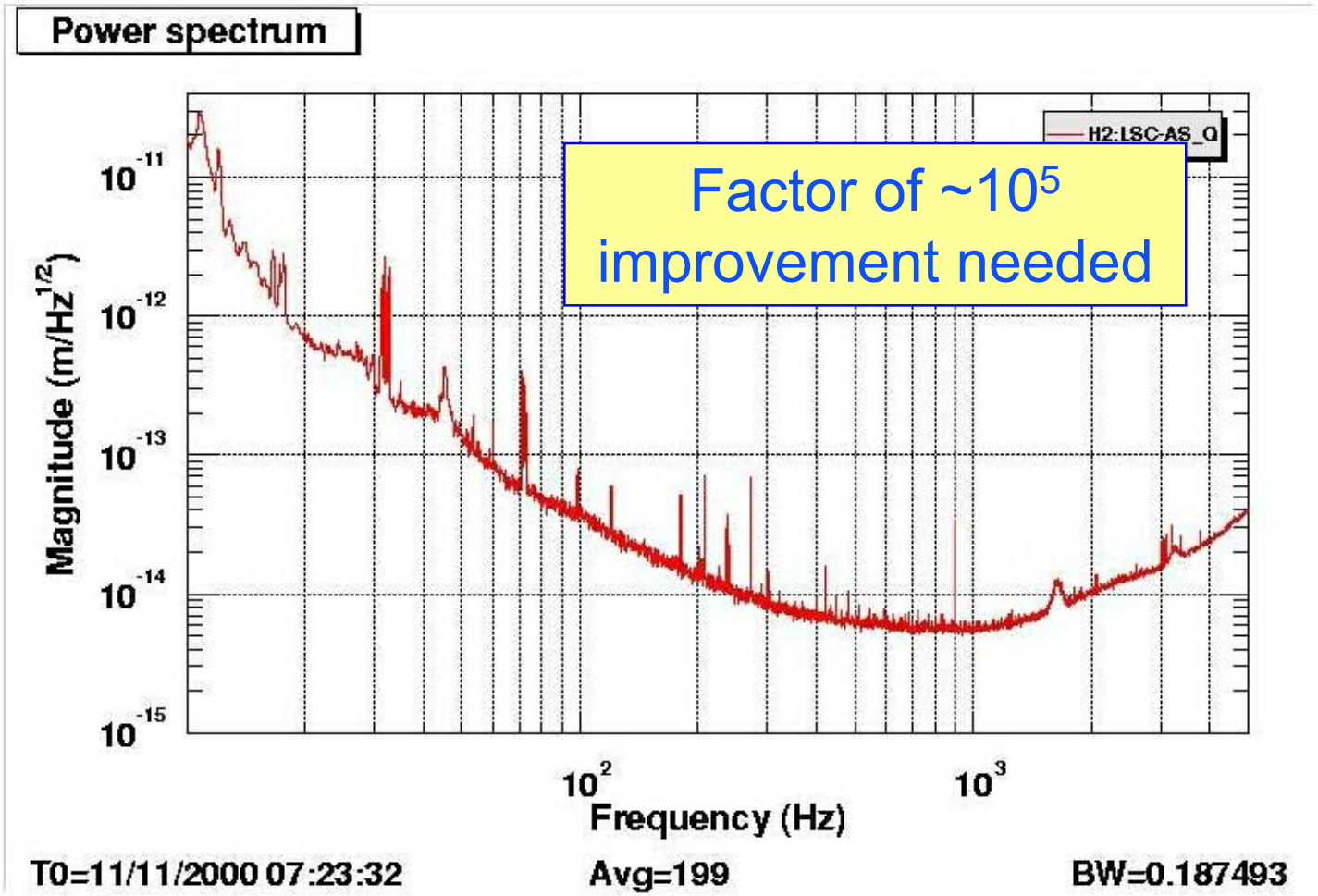
Anecdotes

- Bringing servo systems to operational condition (‘locking’)
  - » Baseline scenario, tests with End-to-End (e2e) modeling
  - » Little success at first application
  - » Measurements of seismic noise, observation of passing fringes in both error-signal-sensing detectors, and diagnostic power level sensors
  - » Integration of environmental data with e2e models
  - » Combine data with very good graduate student
  - » Decision to employ fully parametric solution – measured intensities scale gains, set signs of servo systems
  - » …and it works

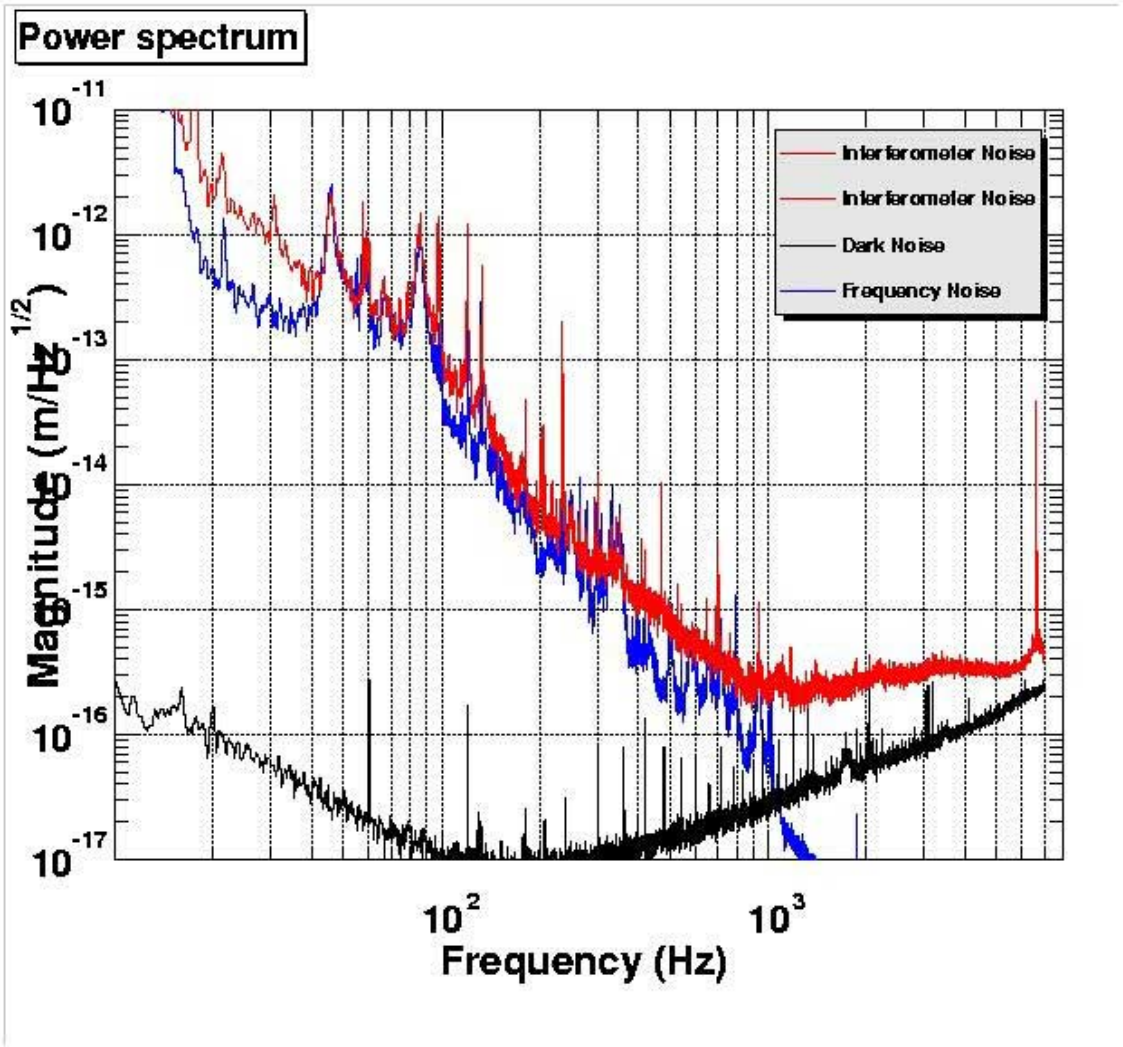
Lock Acquisition



First differential arm spectrum, Nov 2000



Known Contributors to Noise



Feb 2001 limiting noise:

- Dark noise scales as P^{-1} at current level
- Frequency noise reduction underway
  - Laser vibration isolation
  - Tailoring of M/C servo
  - Feedback from arm common mode
- Possible suspension controller noise?
  - Engage low pass filters

Challenges

- 1) Straightforward engineering tuning
  - » All effort to date on LIGO to date
  - » Opinion: this gets us to ~10x desired performance, fairly expeditiously …barring earthquakes
- 2) Learning new things, solving unexpected problems, like….
  - » Cross-couplings
    - – Gain trades, servo offsets, sweet spots
  - » Excess seismic noise
    - – External additional attenuation (early Adv LIGO technology?)
    - – More tuned sections in servo loops
  - » Excess scattered light from optics
    - – One optic: use spare
    - – Many optics: co-add lasers
  - » Thermal noise
    - – In auxiliary systems, DOF → fixes
    - – In core optics → re-assembly of system
- System is flexible, trades possible for many scenarios

Initial Detector Milestones