Enhancements to Initial LIGO

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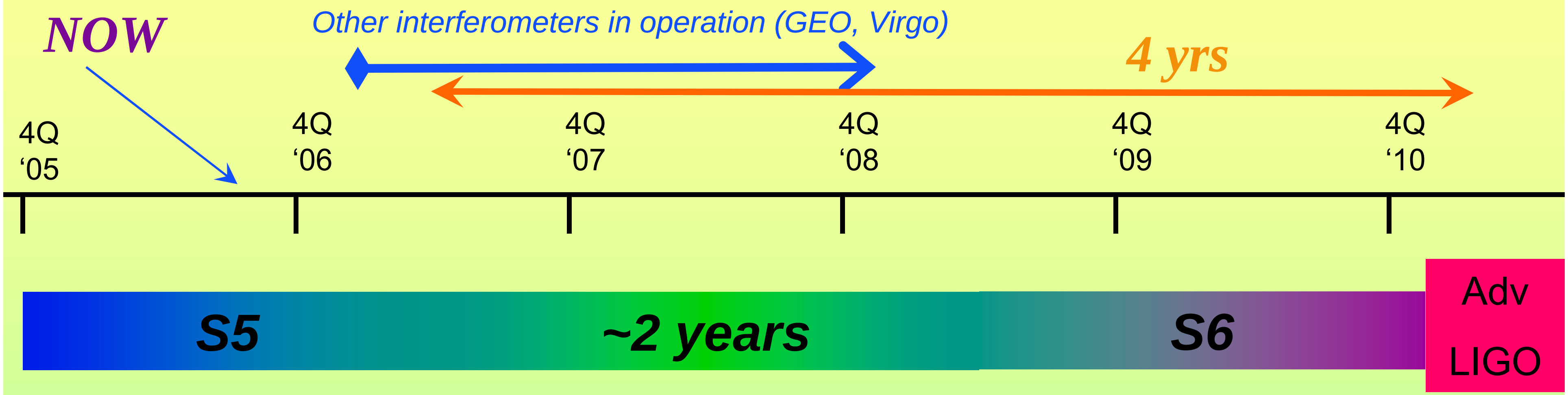
NSF Review, Hanford 2006

G060529-00-I

Before Advanced LIGO



- Between now and AdvLIGO, there is some time to improve…
  1) Sensitivity enhancement without drastic hardware changes.
  2) Factor of ~2 in noise, factor of ~10 in event rate.
  3) *Maximize likelihood of a detection before Advanced LIGO.*

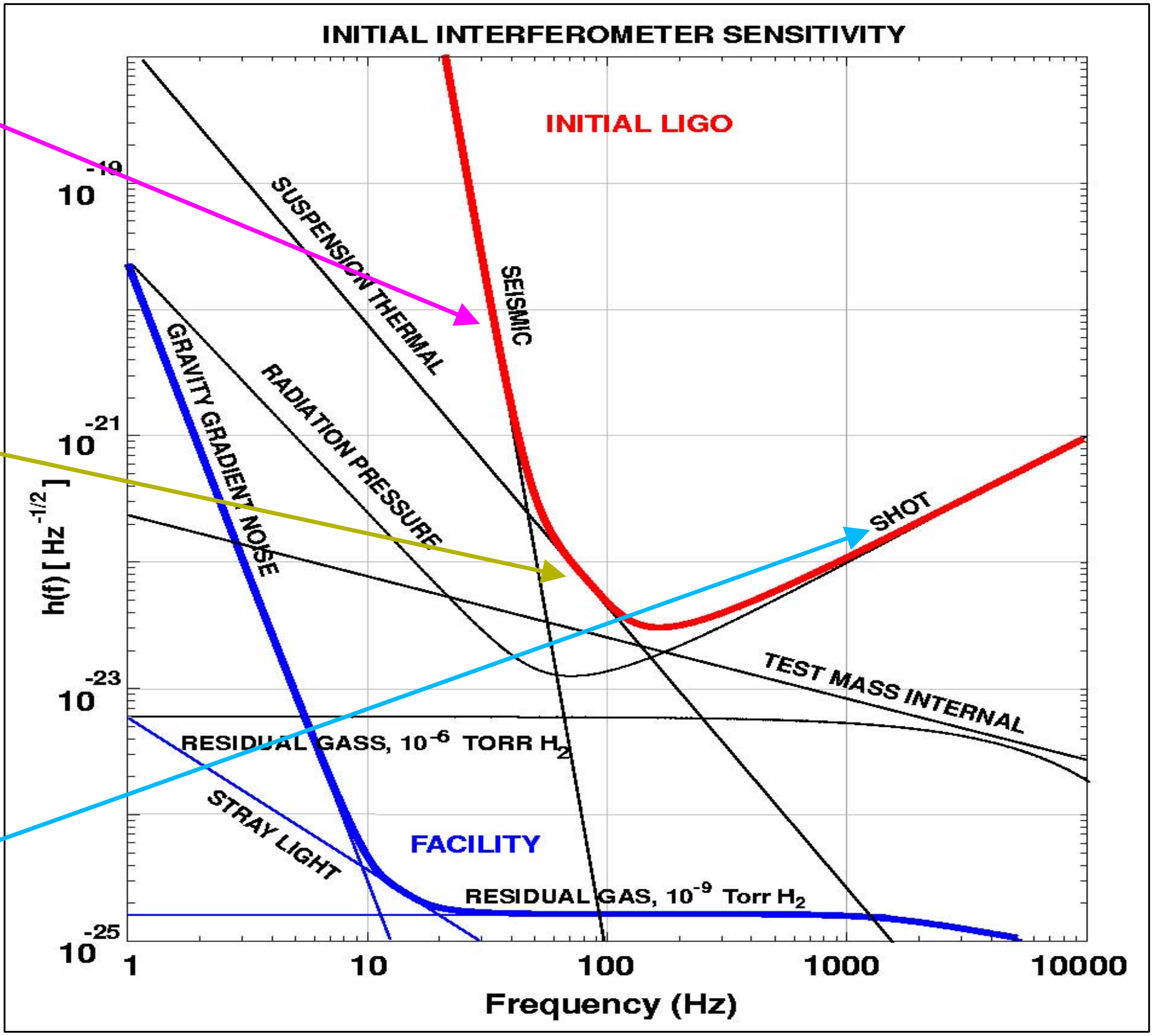
Science Requirements Doc: The LIGO-I Sensitivity Goal

Seismic:
Natural and anthropogenic ground motions, filtered by active/passive isolation systems. Depends strongly on in-vac seismic isolation.

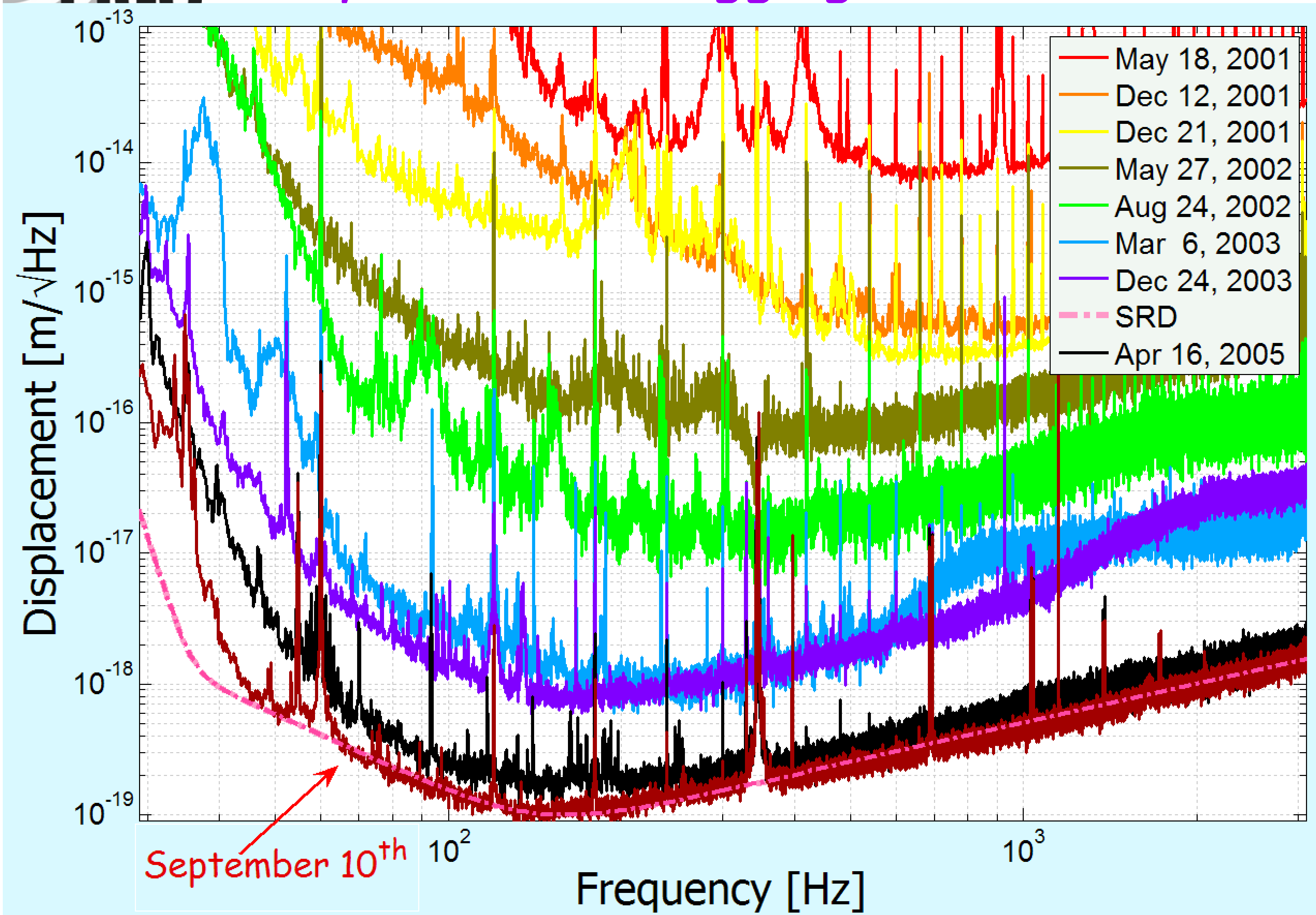
Thermal:
Brownian noise in the mirrors and in the mirrors' steel suspension wires.
Depends mostly on internal rubbing in the suspension wires.

Shot Noise:
Photon counting statistics --
  > 10 kW in the cavities
  ~ 200 mW detected power

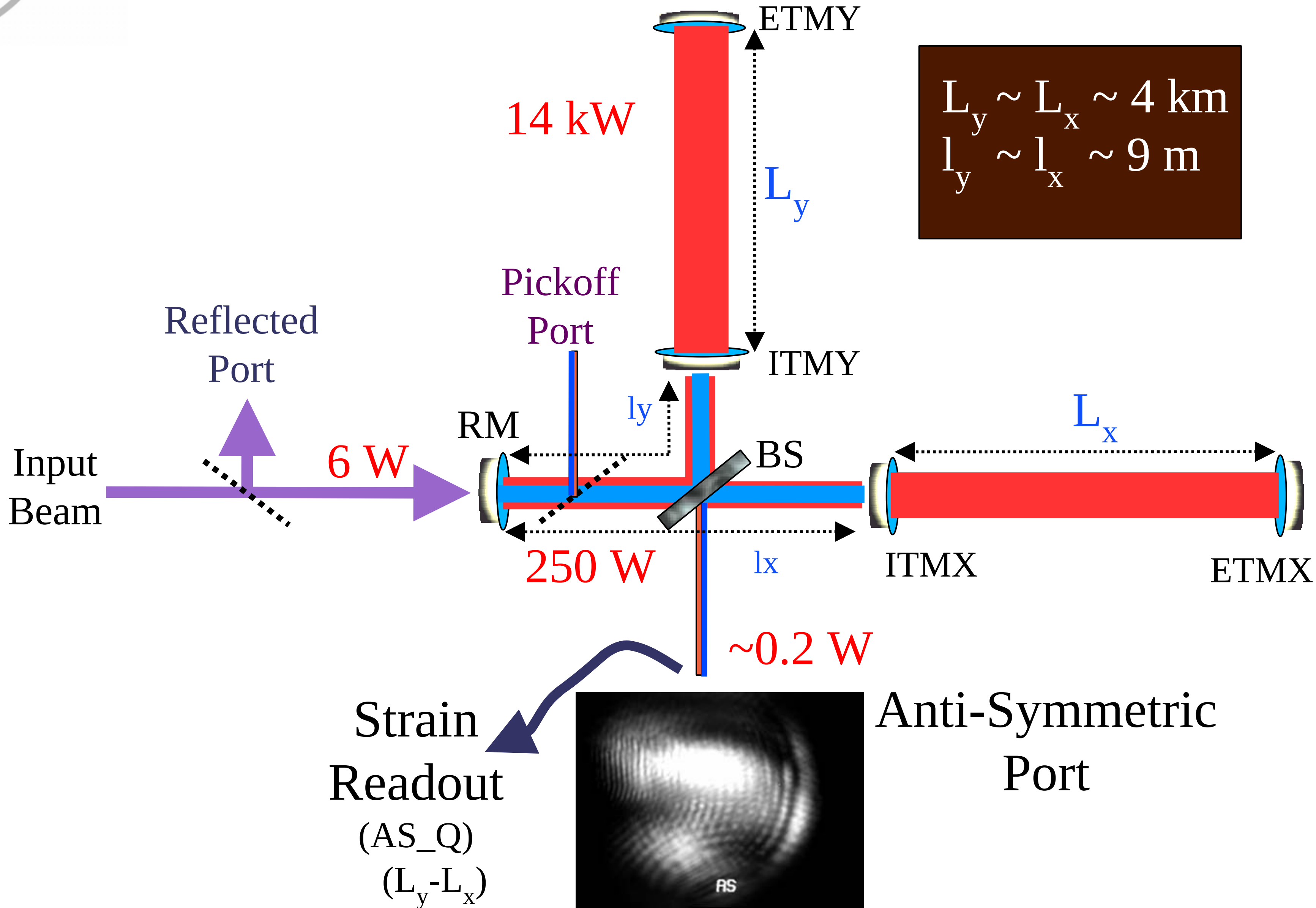
- Goes down with increased laser power and better fringe contrast

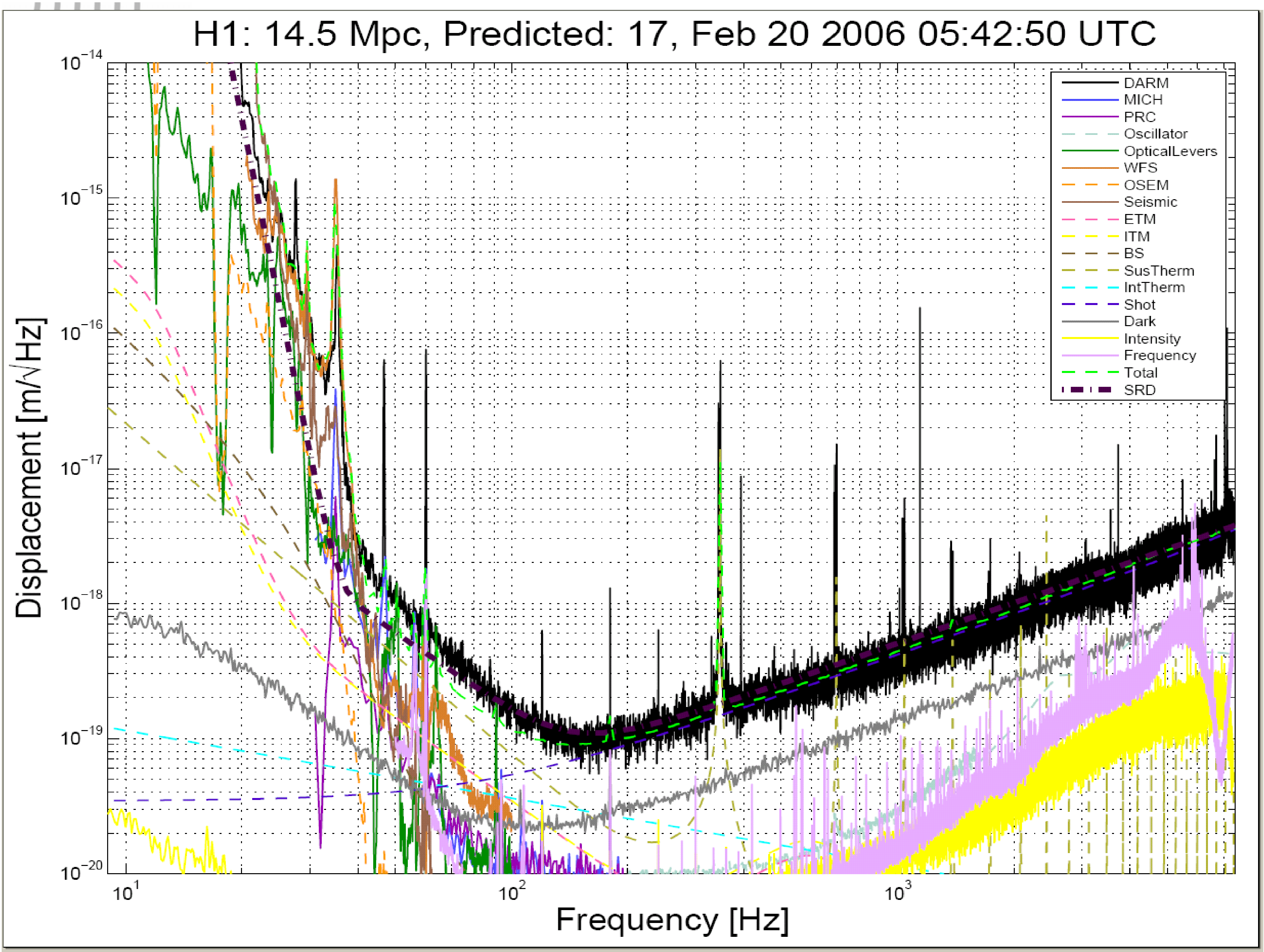


5 years of debugging in Louisiana…



The INTERFEROMETER





H1: 14.5 Mpc, Predicted: 17, Feb 20 2006 05:42:50 UTC
Displacement [m/√Hz]
Frequency [Hz]
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD

What to Improve?

- ~2 years for installation and commissioning
- ~1 ½ years for data taking

Not These:

- Core Optics: Very good contrast, good power recycling gain. High cost, high risk, low payoff.
- Vacuum: No serious problems. Nothing to fix.
- Facility: HVAC turbulence and wind susceptibility are being studied.
- Beam Path: Lot of work for not so much payoff (e.g. Signal Recycling)
- Isolation Stacks: Good attenuation above ~30 Hz. Some low frequency isolation with PEPI/HEPI solutions.

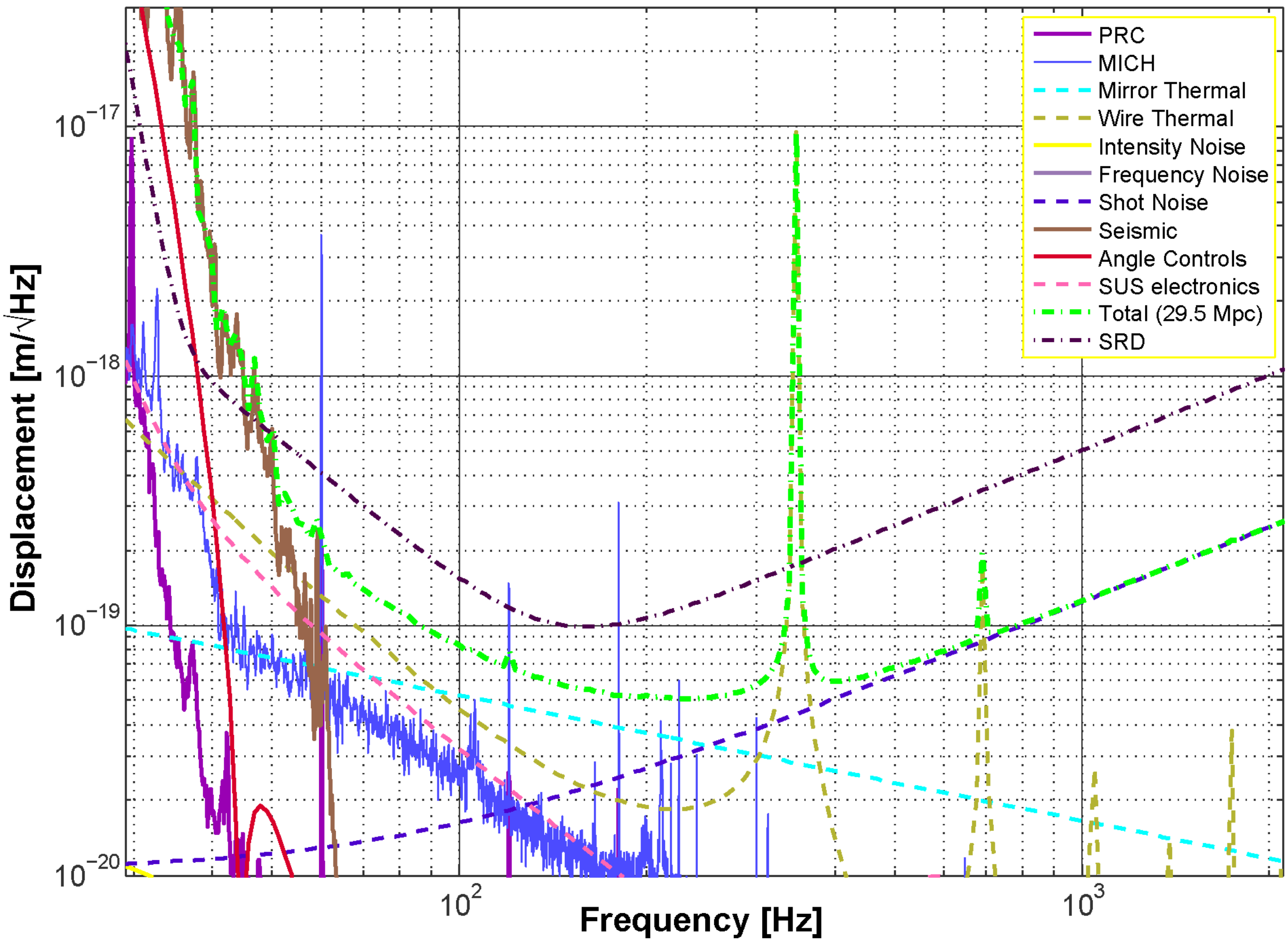
Resource Considerations

- Hardware Budget
  - ~ $1.5M, over a couple of years, available for Detector upgrades
- Schedule
  - Plan should ease (not delay) Advanced LIGO implementation
  - Feasible, debuggable upgrades
- People
  - Limited number of available people
  - Plan to leverage the accumulated experience of the site staff
  - R&D expertise utilized adds to experience for AdLIGO
  - Strong commissioning support from campus staff and grad students

Baseline

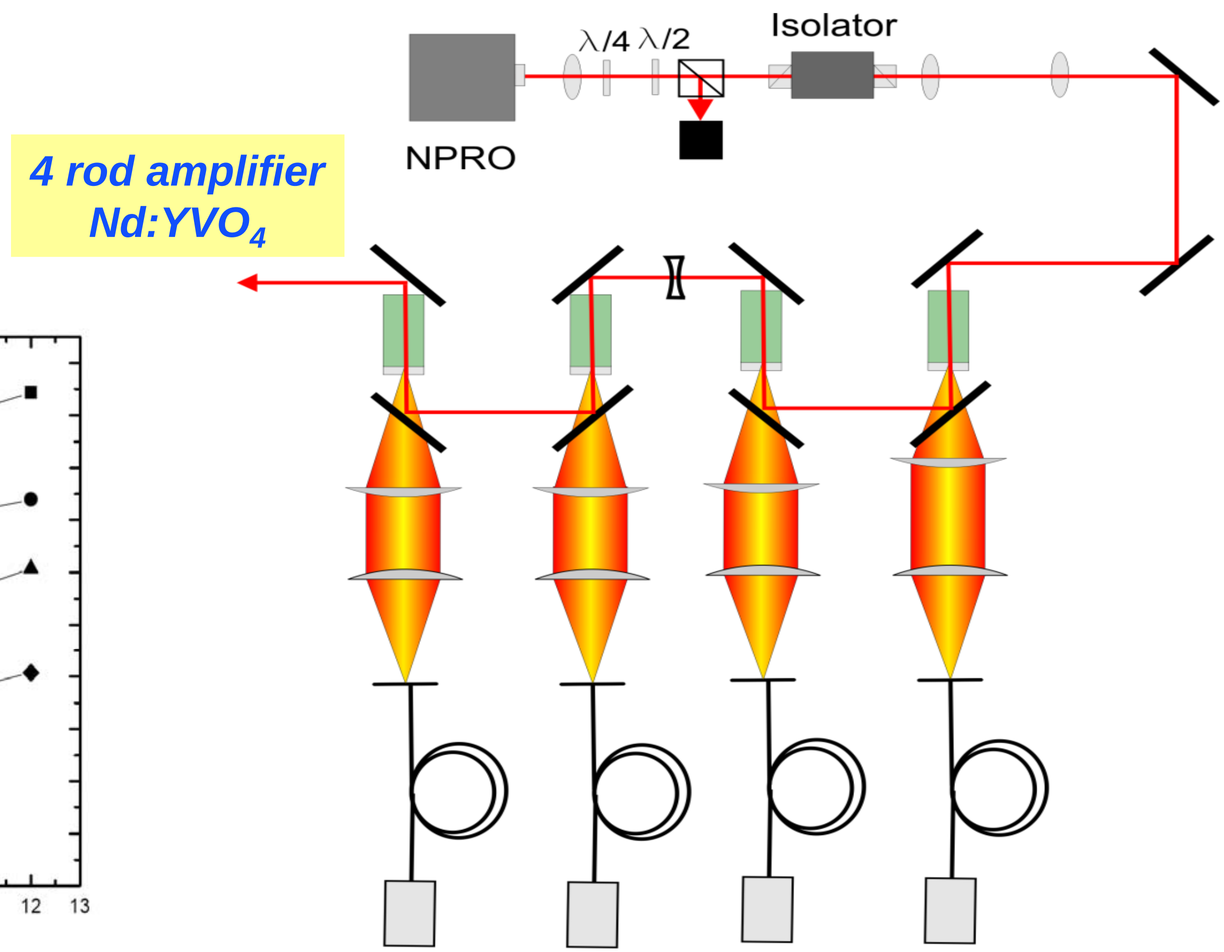
1. DC Readout of GW Strain
   1. AdvLIGO Readout Scheme (DC instead of RF)
   2. Output Mode Cleaner cavity
   3. All in-vac hardware (cavity, isolation, photodetectors)
2. 35 W Laser
   1. 3.5x increase in power
   2. Using the front-end of the AdvLIGO laser
   3. Supplied by AEI for free!
3. High Power Input Optics (Modulators / Isolators)
4. Thermal Compensation
5. Miscellaneous …

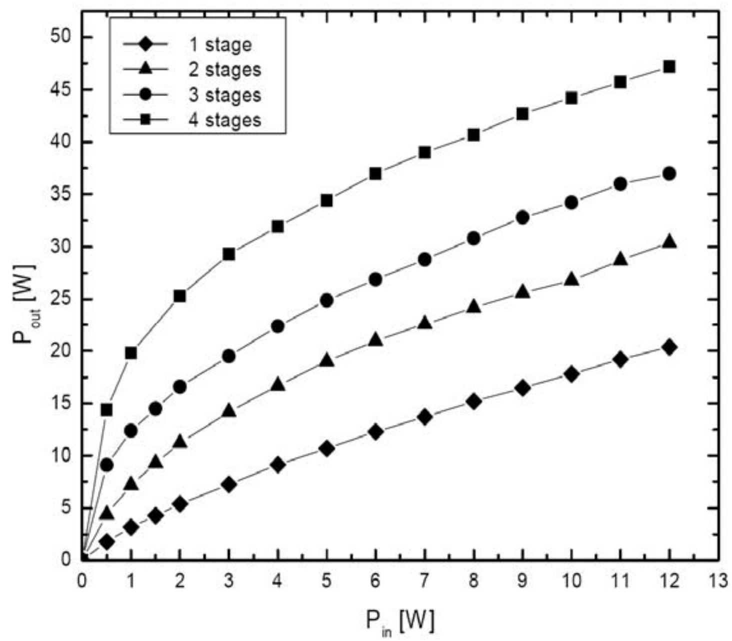
Noise sources for an enhanced detector



Higher Power Laser

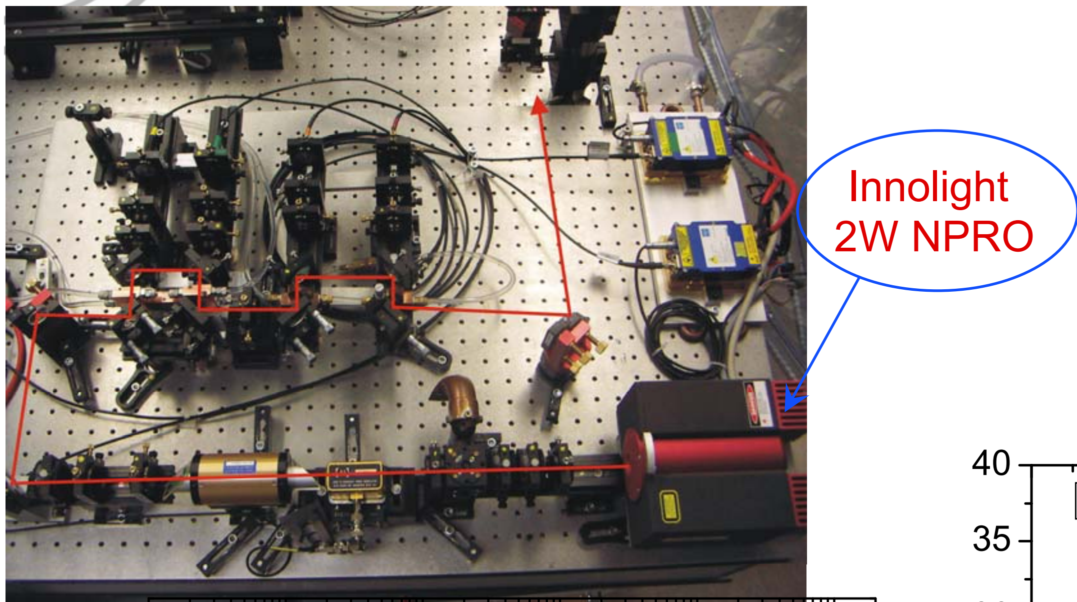
- 35W MOPA:
  - 2W Innolight Mephisto (NPRO) [http://www.innolight.de/]
  - 4-rod amplifier from LZH (front-end of the AdvLIGO laser)



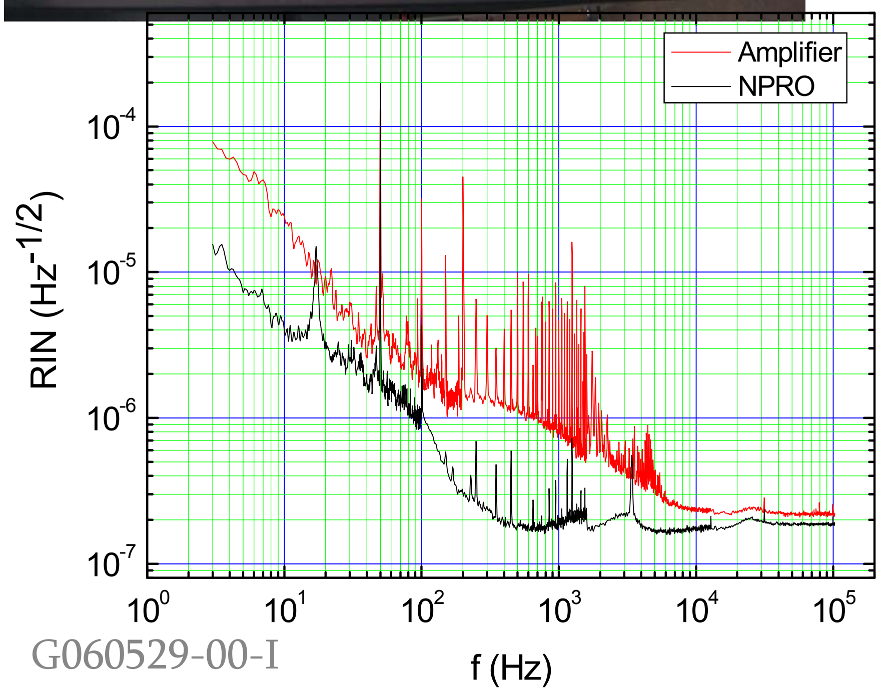


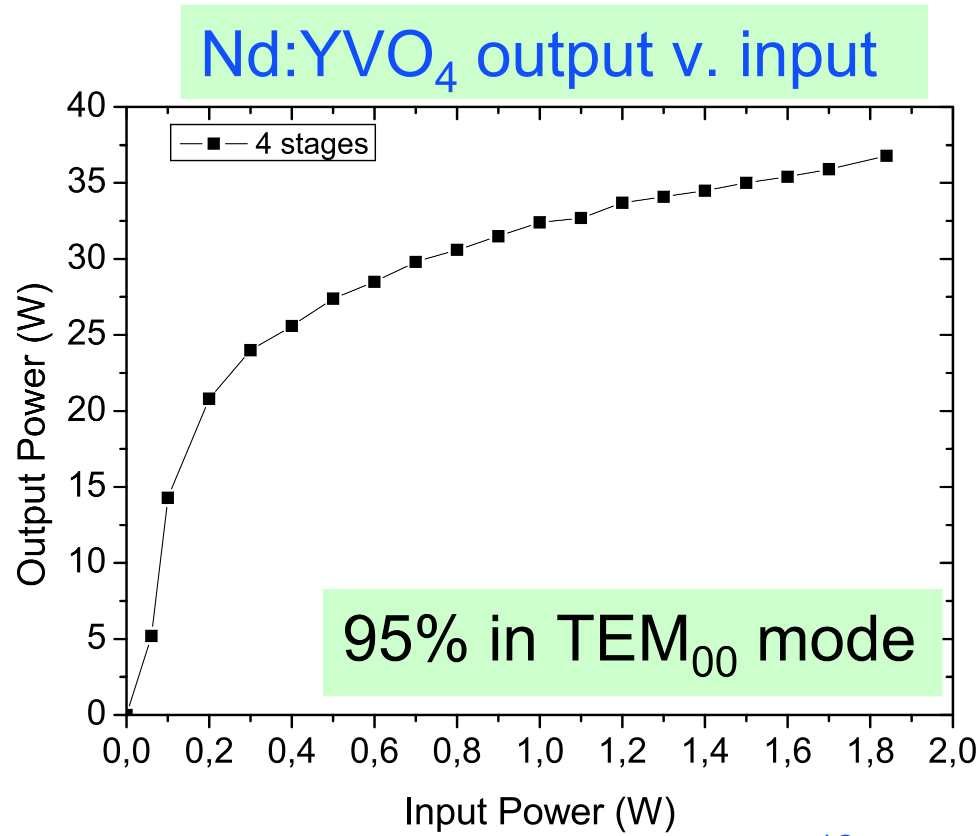
35W LZH Laser

No LWE/JDSU products included



Lasers for H1 & L1
+ 1 spare offered by AEI
as their eLIGO contribution
(for free)





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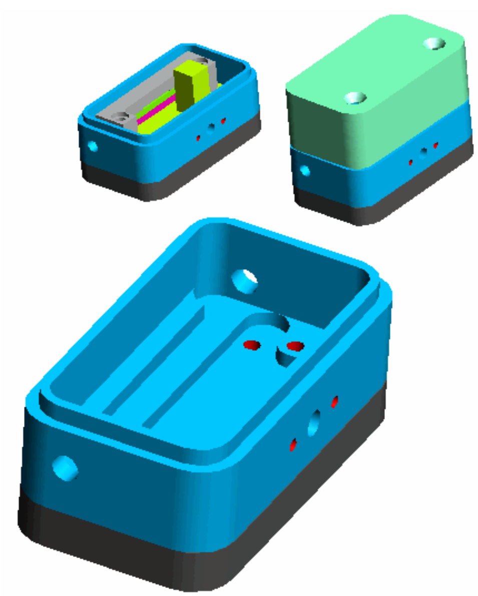
from Bastian Schulz (LZH)

High Power Input Optics:
Phase Modulators

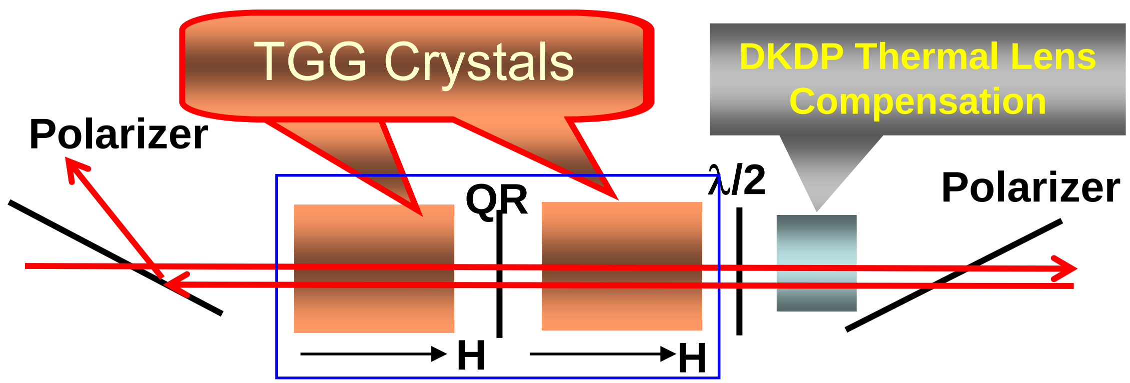
- RTP modulators developed by UFlorida for AdLIGO
- Thermal lensing is 30-50x smaller than in LiNbO3
- Crystals available from 2 vendors
- Packaged by UFI in a housing similar to New Focus



- Packaging details:
  - Electrodes: 2 independent electrodes on 1 crystal to apply multiple frequencies
  - Multi-freq RF matching Network

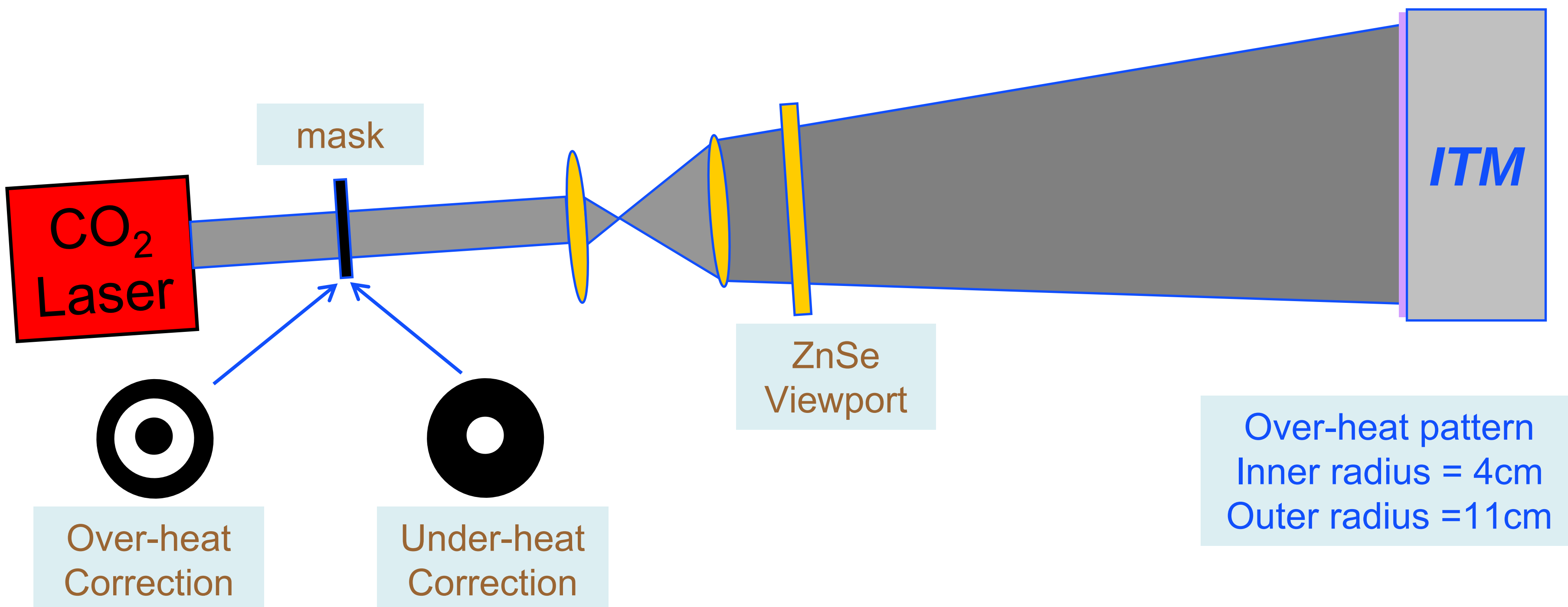
New in-vacuum Faraday Isolator

- Design developed by UFI for AdLIGO
  - Two 22.5° TGG-based rotators with a reciprocal 67.5° quartz rotator between
  - Polarization distortions from the first rotator compensated in the second.
  - Thermal lens compensation *via* negative *dn/dT* material: deuterated potassium dihydrogen phosphate, KD_2PO_4, or 'DKDP').
- Polarizers:
  - Thin film polarizers: smaller thermal beam deflection than calcite
  - TFPs possibly complemented with calcite pols for better isolation
- Mounted on breadboard as single component



Thermal Compensation System

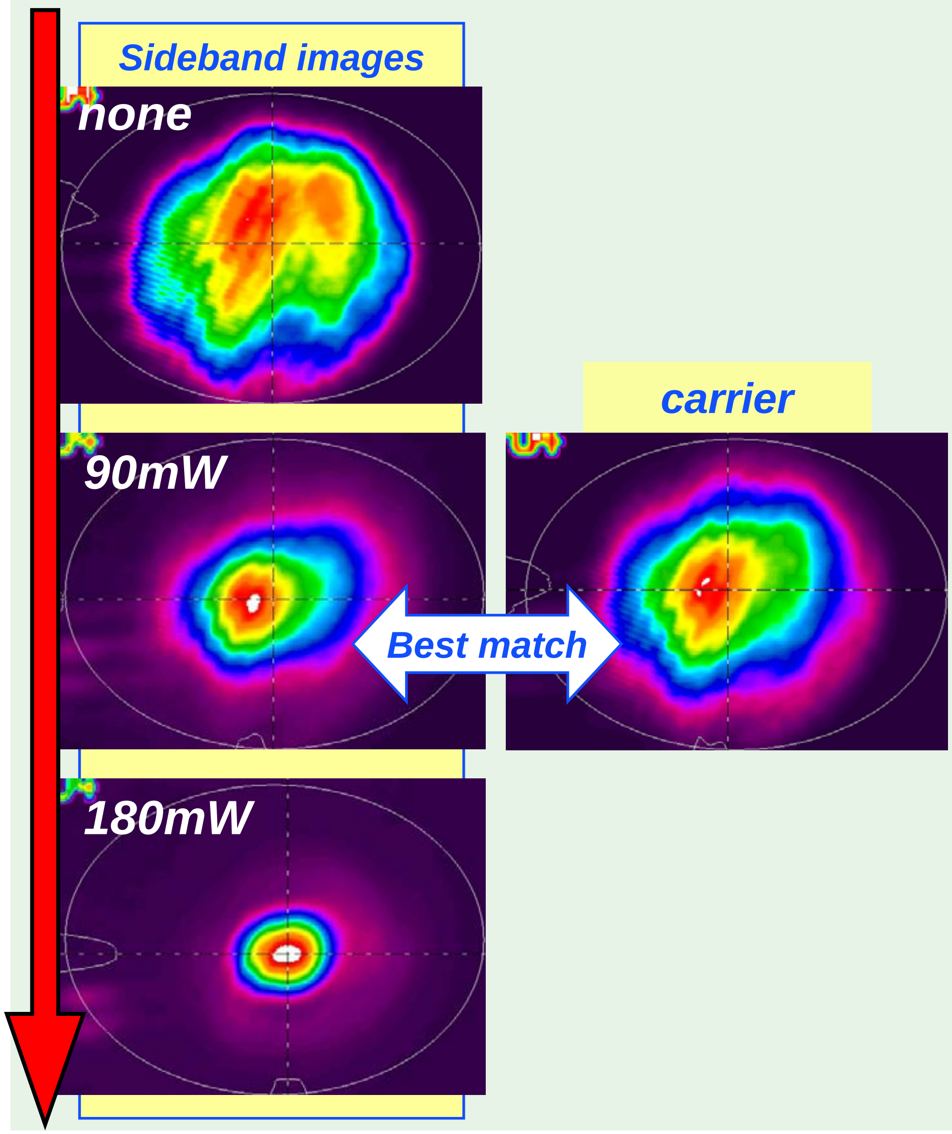
- Cold power recycling cavity is unstable: poor buildup and mode shape for the RF sidebands
- Require 10's of mW absorbed by 1µm beam for optimal thermal lensing
- Can't count on a specific level of 1µm beam absorption, so we provide our own:



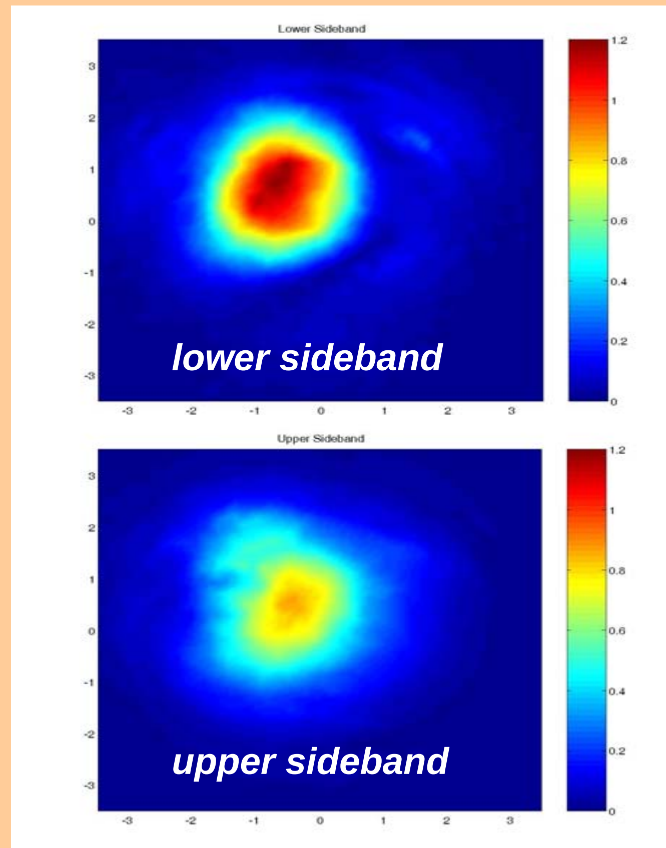
2 functions of the TCS

Matching SB & carrier modes

CO_2 heating



Symmetrizing the SBs to minimize the orthogonal-phase signal: controlling RF saturation



Thermal Compensation System

optic	calculated induced central heat	Req'd annulus TCS heating	Req'd CO2 power	Calc. thermolastic noise
H1 ITMX	-225 mW	2.5 W	5.8 W	3.8×10^{-19} m / $Hz^{1/2}$
H1 ITMY	-356 mW	3.9 W	9.1 W	5.9×10^{-19} m / $Hz^{1/2}$

assumptions:

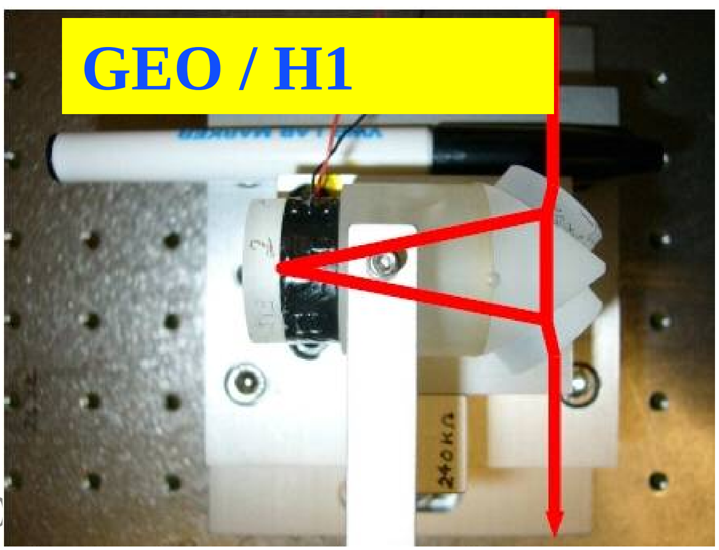
- 30 W YAG power
- Induced central heat is the equivalent TCS power
- 11 annulus W is equivalent to 1 central W induced ROC
- Thermoelastic noise at 100 Hz with 1e-5 / rtHz RIN.

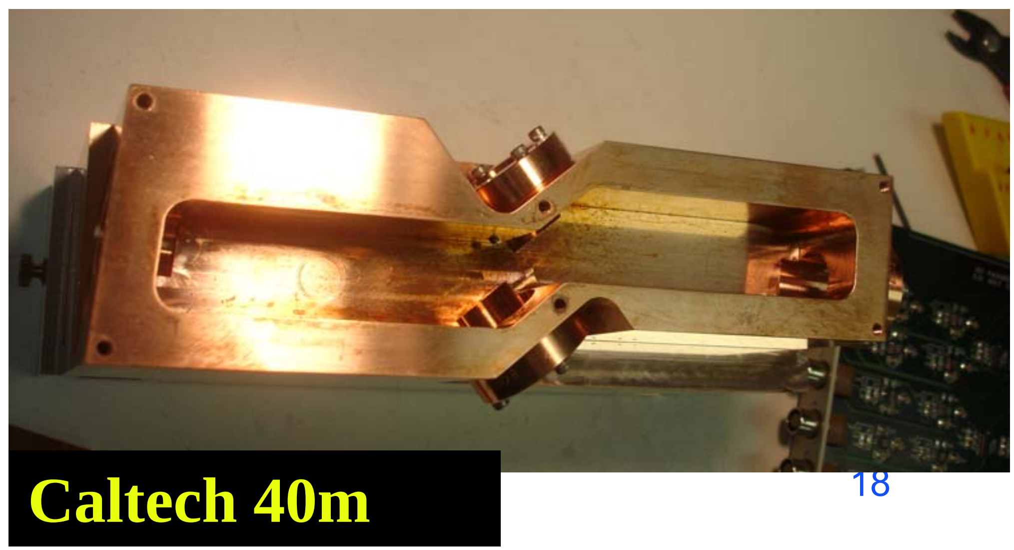
WIKI: http://ilog.ligo-wa.caltech.edu:7285/advligo/Thermal_Compensation_for_mLIGO

Better Signal Detection:
Output Mode Cleaner

Basic Motivations

- Limited by photodetector saturations; OMC removes most of the junk light
- Removing the junk light reduces shot noise
- DC Readout (AdvLIGO baseline) has technical noise benefits:
  - Optical gain increase (field overlap)
  - RF Oscillator phase noise (significant at ~few kHz)
  - Laser frequency noise (close to limiting)
- Past OMC testing on H1 showed benefits, but was ~300x too noisy
- Critical for any high power operations (H2 only uses 2.5 W of laser power)



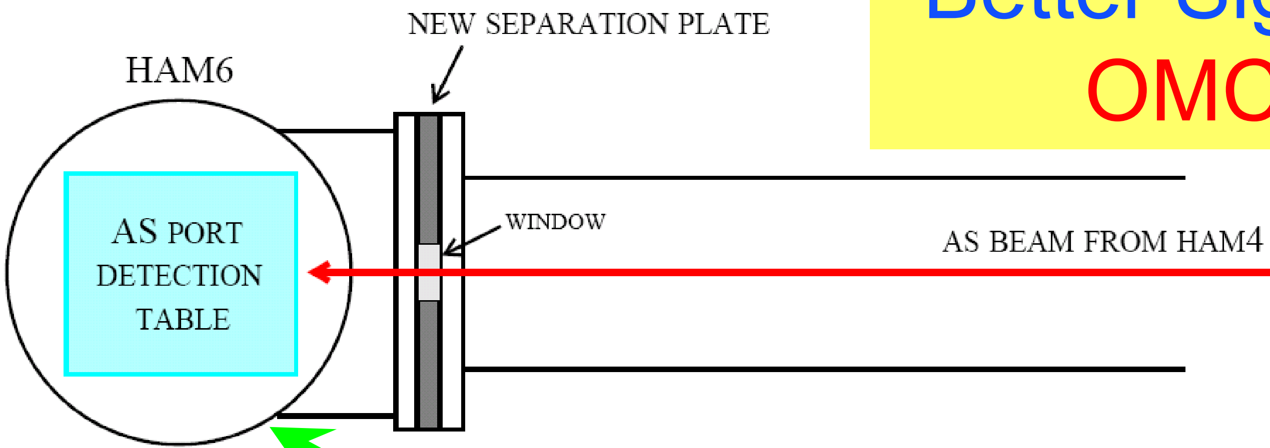


Better Signal Detection: Output Mode Cleaner

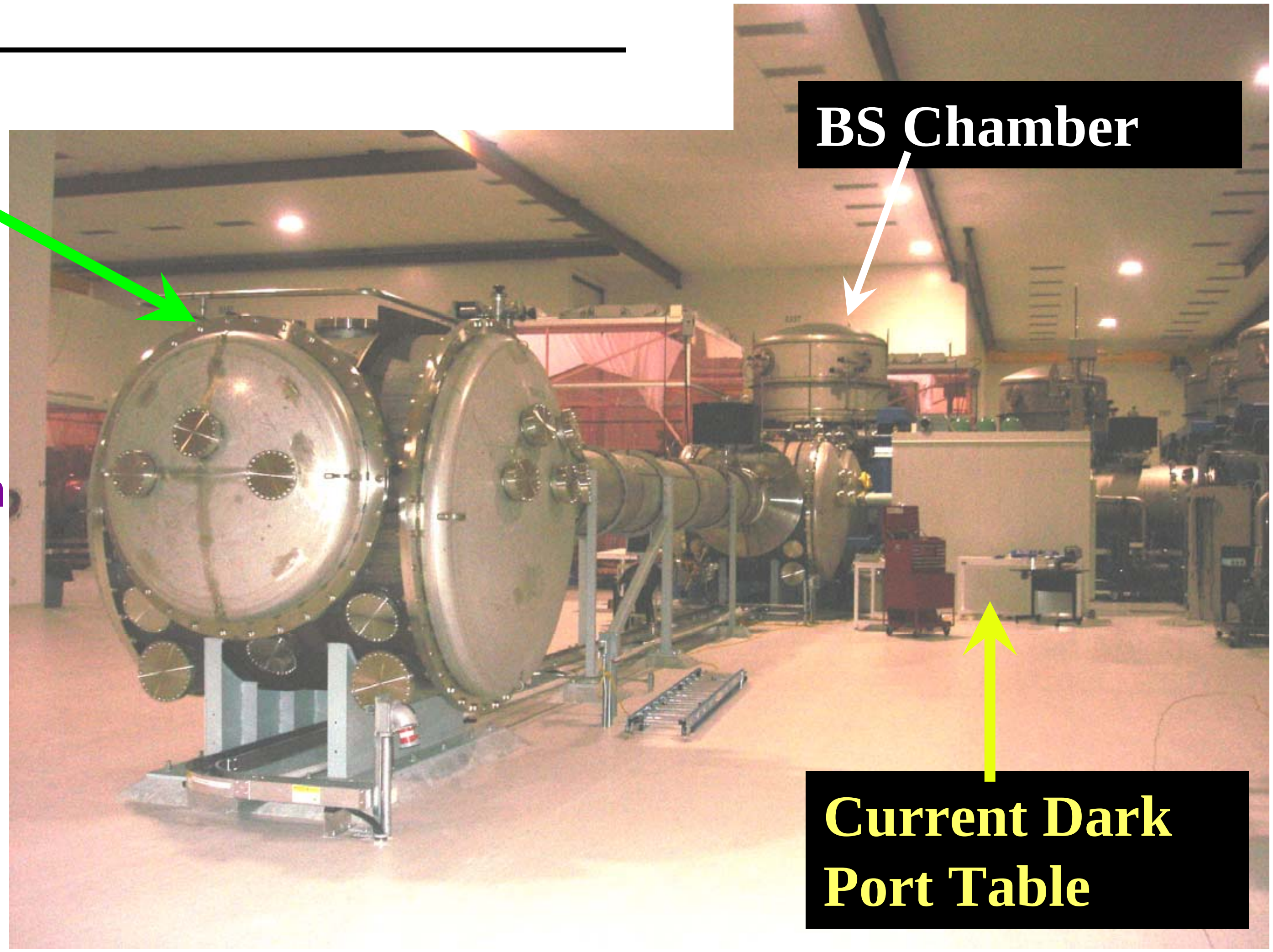
1. In-vacuum Cavity and Photodetectors*
   1. Hanford 4K experience: too much seismic/acoustic noise
   2. In an unused HAM chamber (HAM6)
   3. Baseline for AdvLIGO
2. Seismic Isolation (AdvLIGO Stack)
   1. Baseline HAM: 1 stiff internal stage + HEPI
   2. Alternative HAM: HAM-SAS (low resonant frequency)
3. **In-Vac Photodetectors**
   1. Being developed at the 40m for the DC readout experiments
   2. Pair of 2 mm InGaAs diodes with load resistors and LT1128's
4. In-Vac Auto-alignment system
   1. Vacuum compatible tip-tilt mirrors (~few mrad range)
   2. In-vac mode matching telescope w/ pico motors

* Items in blue being tested at the 40m this summer

Better Signal Detection: OMC Chamber



- Separate vacuum system
- Design for easy access
- In-air commissioning in the beginning



Seismic Isolation for OMC

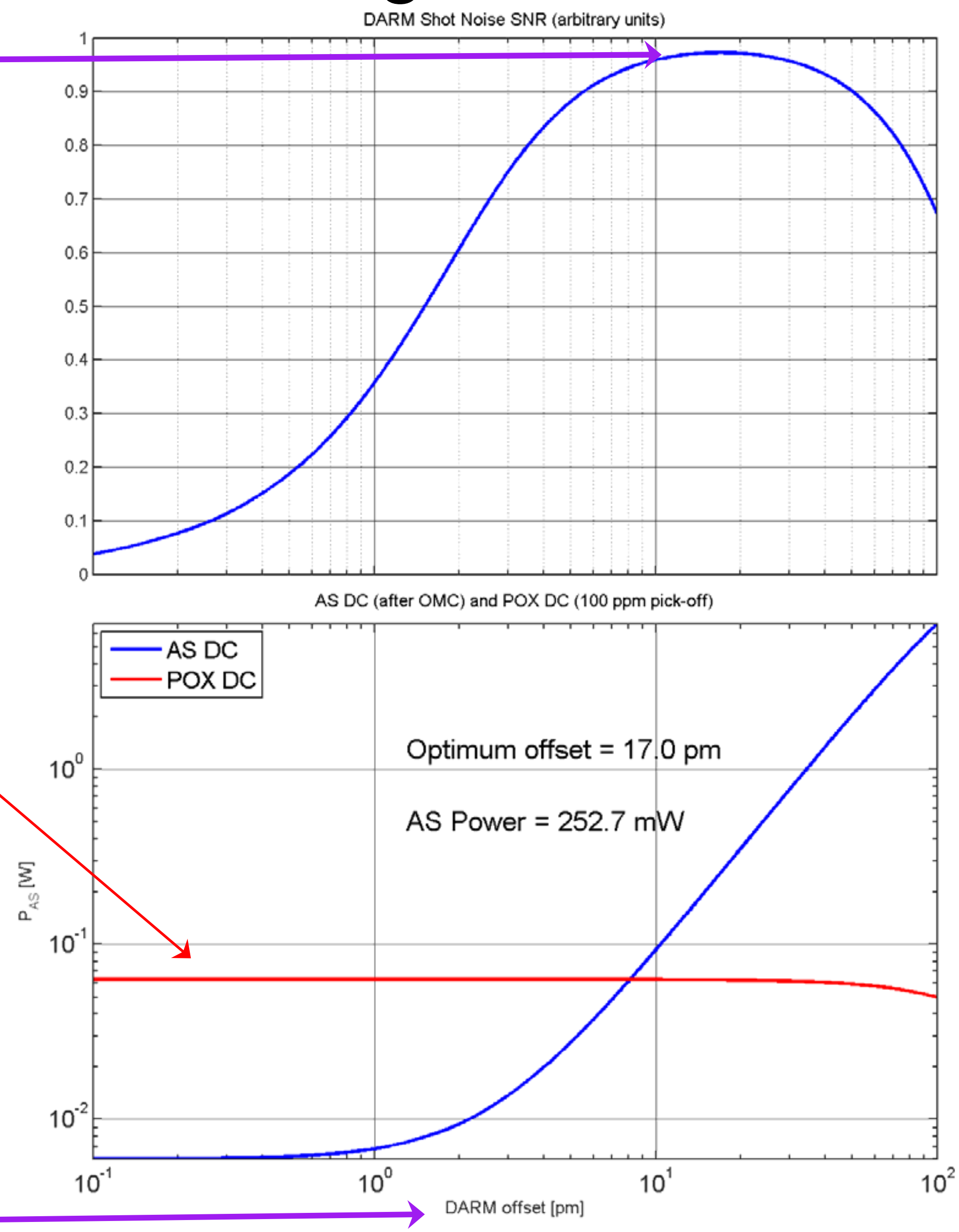
- Requirements are ‘easy’ to meet. Only need ~2 passive stages (1 double pend or a decent stack).
- Plan for the minimal suspension that might also work for AdvLIGO.

- OMC Suspension Requirements
  - Beam jitter into OMC dominated by test mass motions
  - Need a ~50 Hz BW auto-alignment servo to preserve strain noise
  - Future work: length noise requirements, design of a fast thermal actuator, HOM scattering noise modeling (need beam profiles of the real AS port beams)

DC Readout Modeling

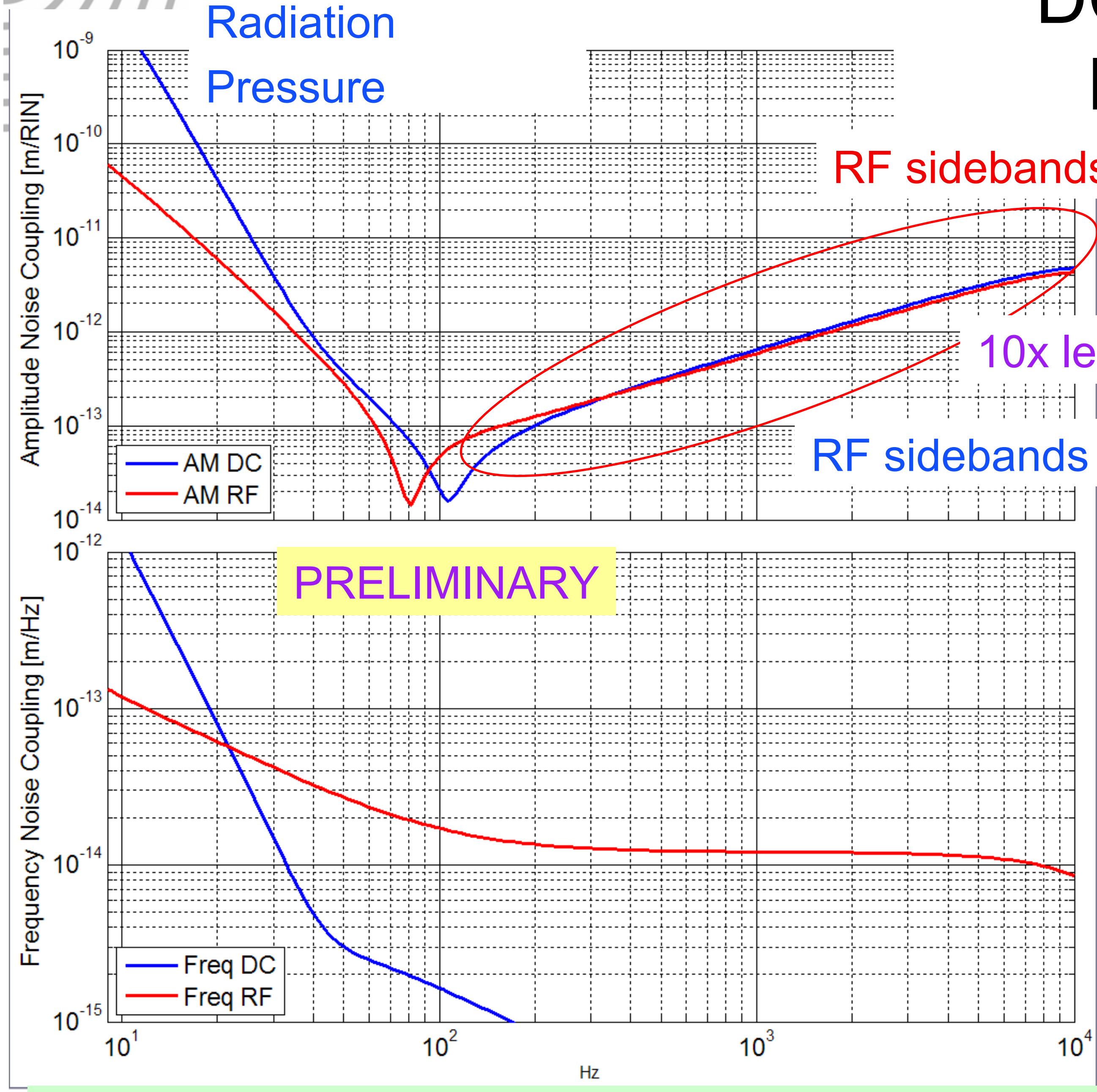
Optimum operating point

- Offset set by SNR
- Larger offset results in less stored power



Differential Arm Length

DC Readout Modeling



RF sidebands modulating L- offset

10x less coupling than in S5

RF sidebands leaking through OMC

L- = 10 pm

OMC F = 500

$\Gamma_{25} = 0.3$

Frequency domain tool, including radiation pressure

DC v. RF: Phase Sensitivity Budget

- RF readout originally developed to reduce get around the 1/f noises and the low frequency laser noises
- Long storage time of the LIGO IFO filters out laser noise above ~1 Hz, reducing the noise at 100 Hz to the shot noise level.

- 3.5x in raw laser power
- 1.3x increase in throughput to the Interferometer
- RF Sideband transmission to Dark port ~75%
- Field overlap between carrier & SB ~70%

- Overall high frequency sensitivity increase is ~3.5x

Outlook

- **Lots of design, development, procurement (now ->7/07)**
- 2 years of installation and commissioning (until Fall of 2009)
- 18 months for S6 (Fall 09 -> early 2011) @ LLO
- Hardware Cost: ~1.5 M$
- Enhancement: ~2X in NS range for H1/L1

Risk Retirements

- Use of the AdvLIGO Laser front-end as the source
- DC Readout for gravitational wave detection
- Suspended, in-vacuum Output Mode Cleaner
- AdvLIGO active seismic isolation platform
- High power Electro-optic modulators with long-term, high power exposure
- Faraday Isolator under high power for the long term.
- AdvLIGO Controls infrastructure (ADC, DAC, CPU)
- Observatory staff become experience AdvLIGO commissioning staff !