Advanced LIGO Technical Description
Part I

NSF Review of Advanced LIGO Project
25-27 April 2011

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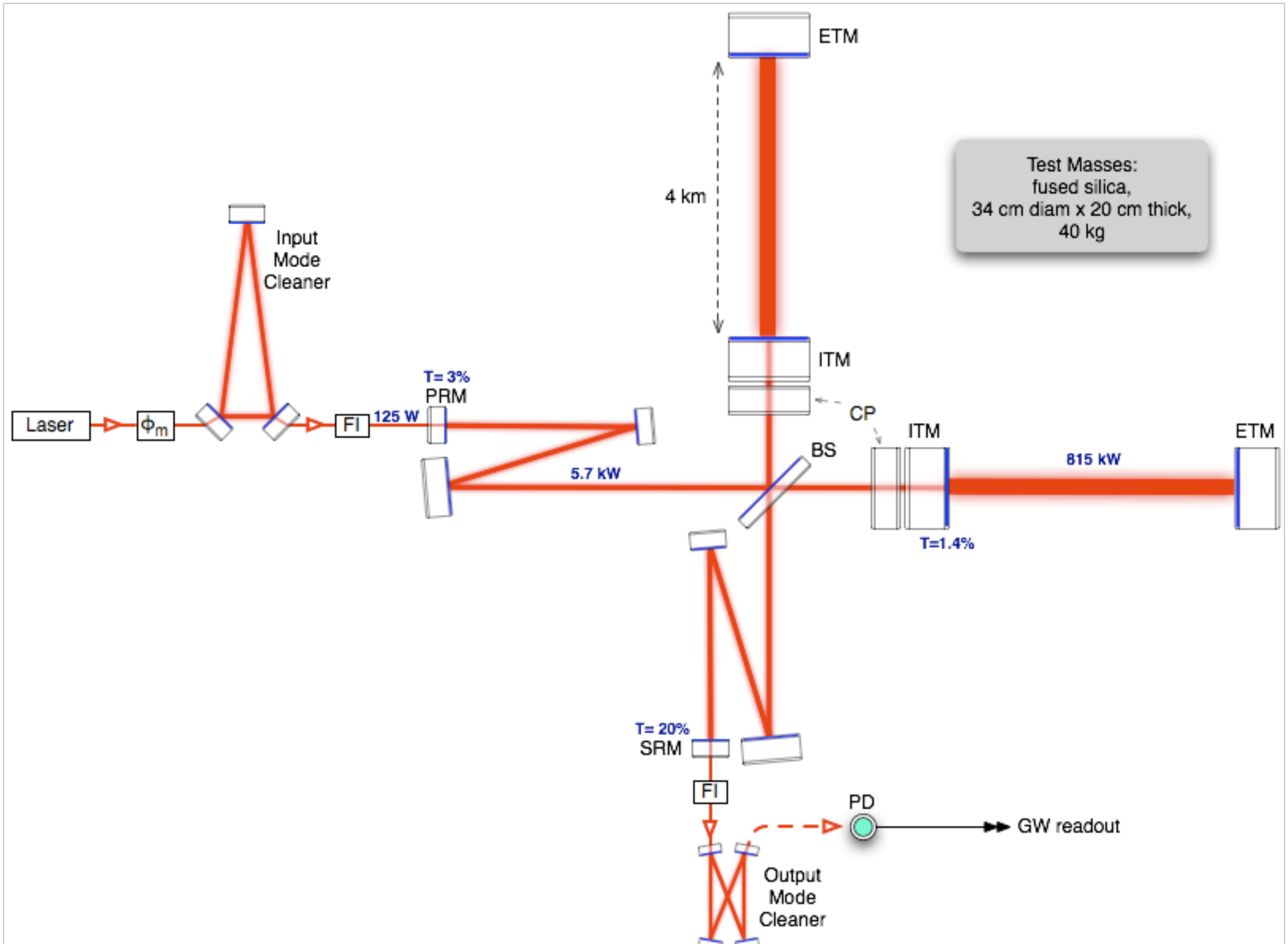
LIGO-G1100505-v2

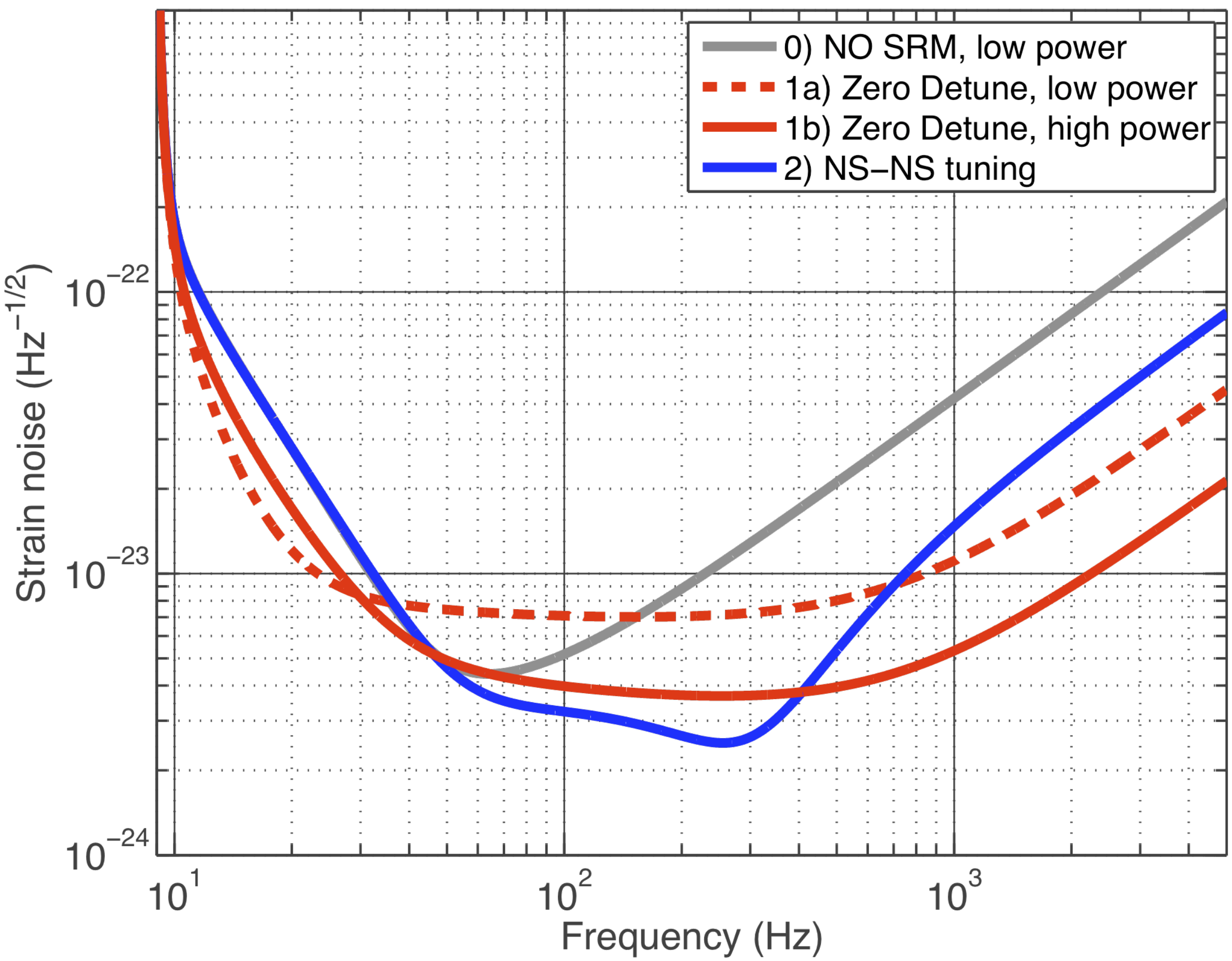
Agenda

- Systems Engineering (SYS) I: Interferometer design
- Pre-stabilized Laser (PSL)
- Input Optics (IO)
- Core Optics Components (COC)
- Interferometer Sensing & Control (ISC)
- Systems Engineering (SYS) II: High Power & gas damping
- Auxiliary Optics Subsystem (AOS)
- Seismic Isolation (SEI)
- Suspensions (SUS)
- Data Acquisition, Diagnostics, Networking & Supervisory Control (DAQ)
- Data Computing System (DCS)
- Facility Modifications & Preparation (FMP)
- Systems Engineering (SYS) III: layout, interfaces, etc
- Summary

Systems: Interferometer Design



Interferometer Performance

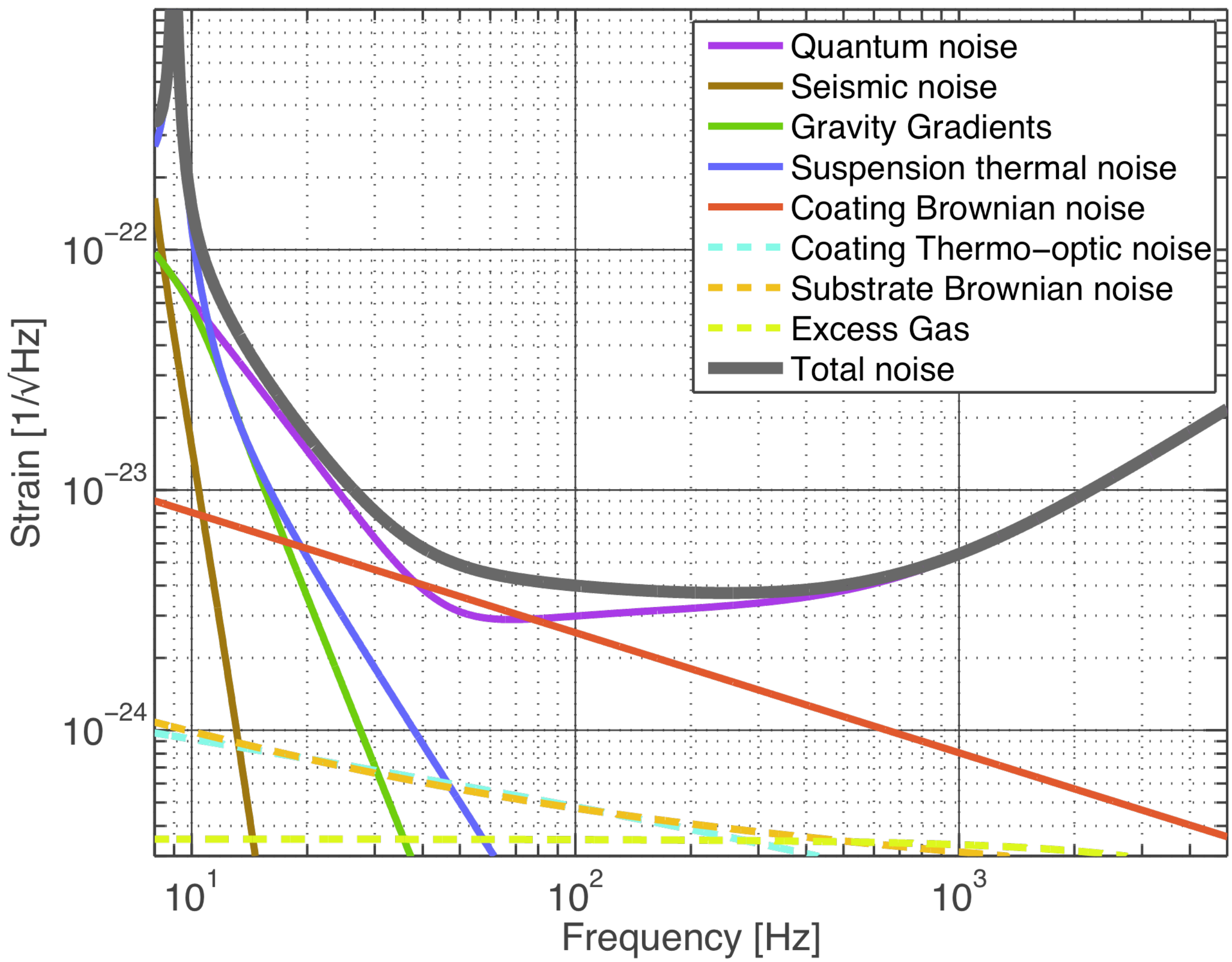


Detection range for binary inspirals

case	NS-NS	BH-BH (30 $M_\odot$)
0	150 Mpc	1.60 Gpc
1a	145 Mpc	1.65 Gpc
1b	190 Mpc	1.85 Gpc
2	200 Mpc	1.65 Gpc

Limiting Noise Sources

Broadband tuning, full input power (125 W)

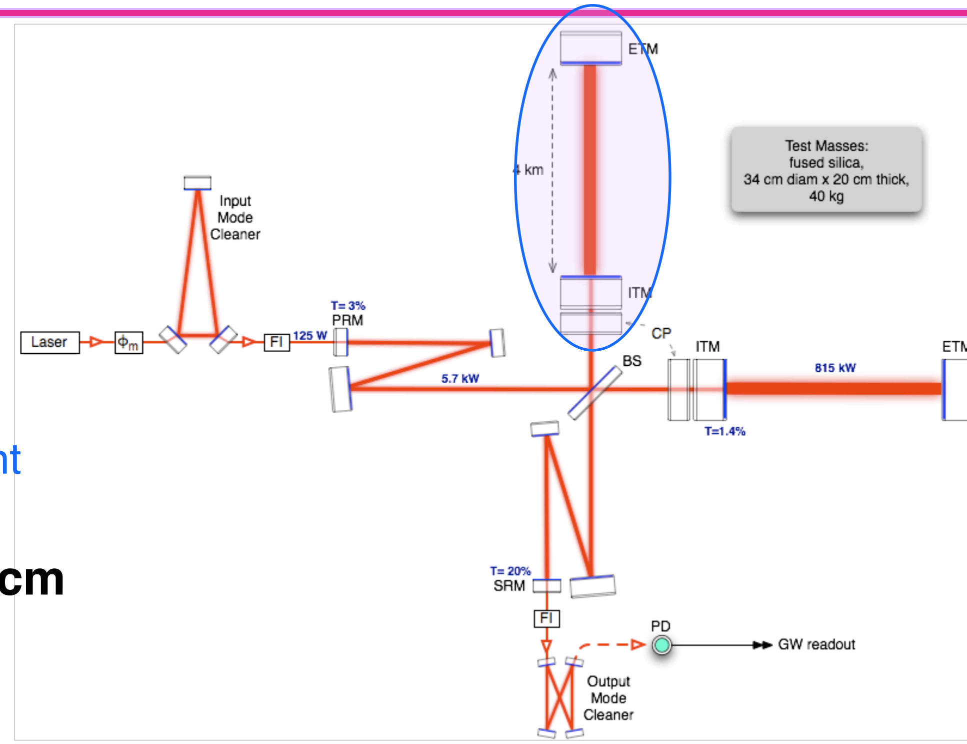


LIGO

Key Interferometer Features

Arm cavity design

- **Finesse: 450**
  - 2x higher than iLIGO
  - Value involves trade-offs between optical loss, sensitivity to noise in other degrees-of-freedom, and interferometer sensitivity in different modes of operation
- **Beam sizes: 6.2 cm on ETM, 5.3 cm on ITM**
  - Approx. 50% larger than iLIGO, to reduce thermal noise
  - Smaller beam on the ITM to allow smaller optic apertures in the vertex
- **Cavities are made to be dichroic**
  - Low finesse cavity for 532 nm to aid in lock acquisition



- **Near-confocal design**

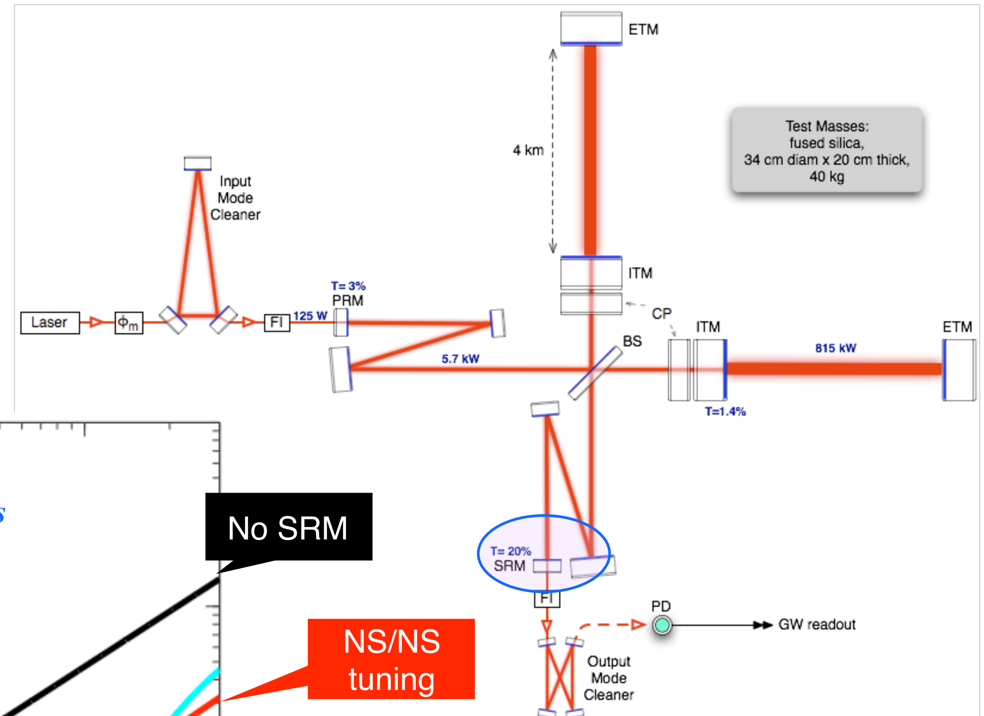
$$R_{ITM}, R_{ETM} \approx L$$

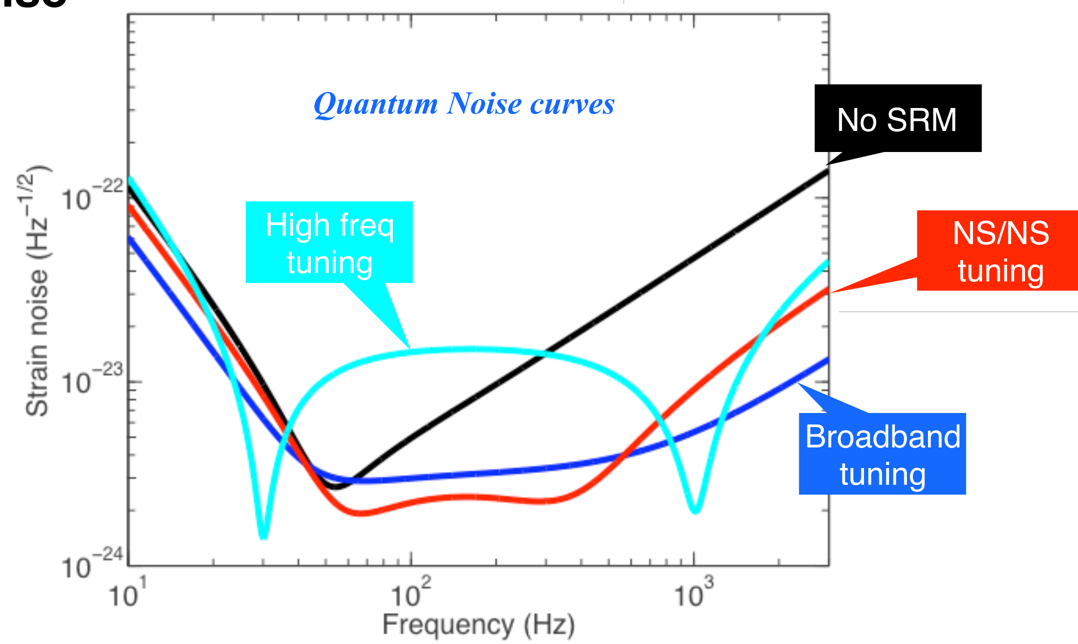
  - Gives better angular stability than the near flat-flat case

Key Interferometer Features

Signal Recycling

- **Add a partially transmitting mirror to the anti-symmetric port**
- **Provides some ability to alter the interferometer frequency response**



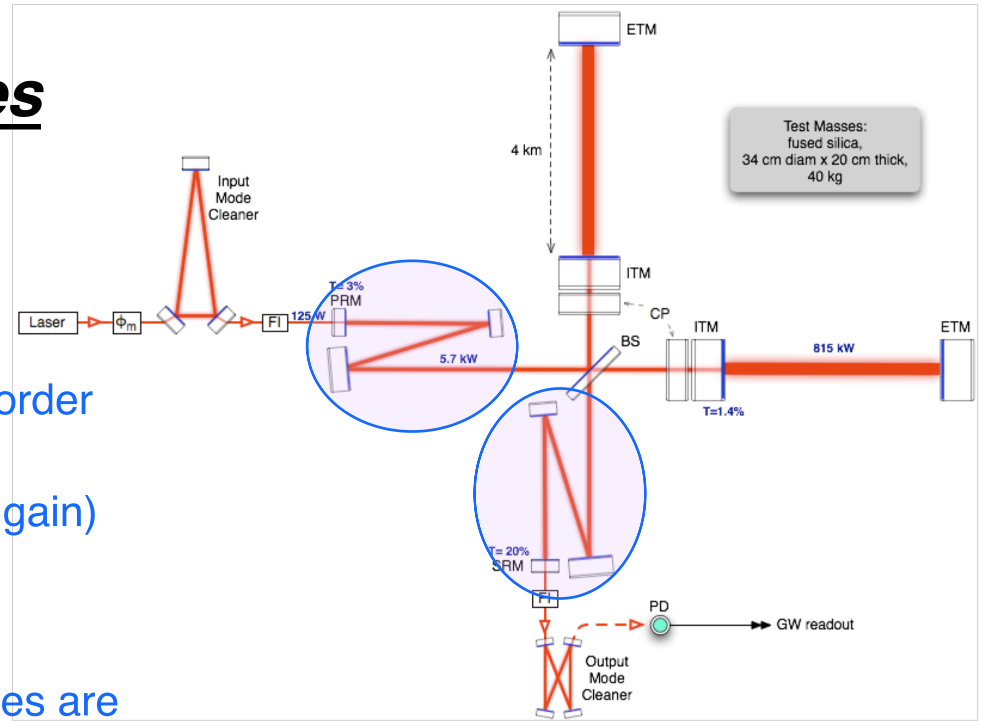


Baseline is broadband tuning

Key Interferometer Features

Stable Recycling Cavities

- **iLIGO has a marginally stable recycling cavity**
  - Nearly a plane-plane cavity; higher order spatial modes are nearly resonant
  - Spatial mode quality (& thus optical gain) suffers
- **Stable geometry for AdvLIGO**
  - Beam expansion/reduction telescopes are included in the recycling cavities
  - Higher order spatial modes are suppressed
  - Configuration is more tolerant to optical distortions



Pre-stabilized laser (PSL)

- High power laser: 180 Watts
- Laser frequency pre-stabilization & frequency actuation
- Pre-mode cleaner for spatial clean-up and high-frequency filtering
- Diagnostic tools

Supplied by Albert Einstein Institute (Hannover)

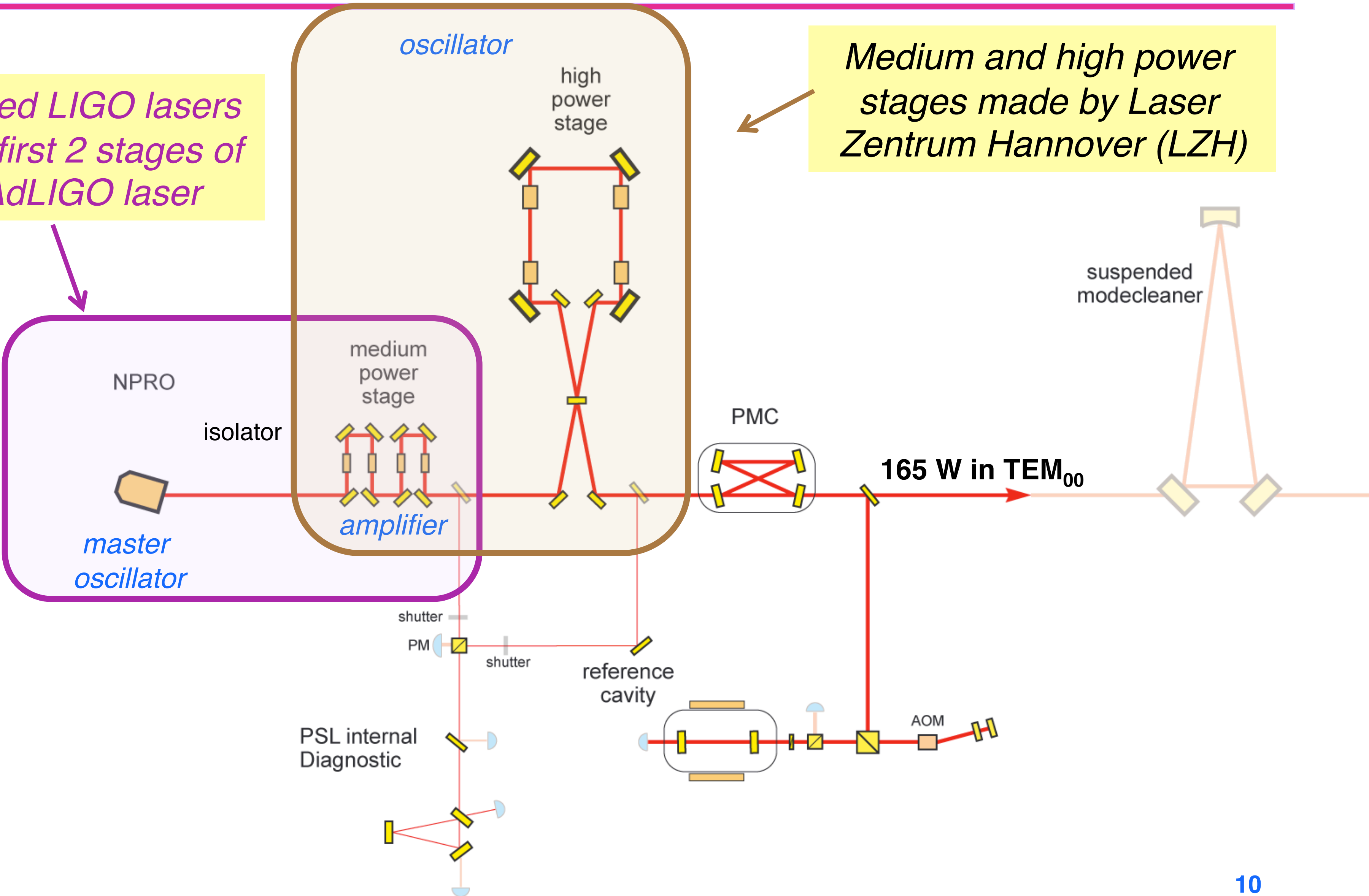
- Laser power stabilization
- Laser safety measures
- Facility infrastructure
  - Laser and laser diode enclosures
  - Instrument racks, crates, power supplies
  - Supervisory controls & DAQ interfacing

Supplied by LIGO Lab

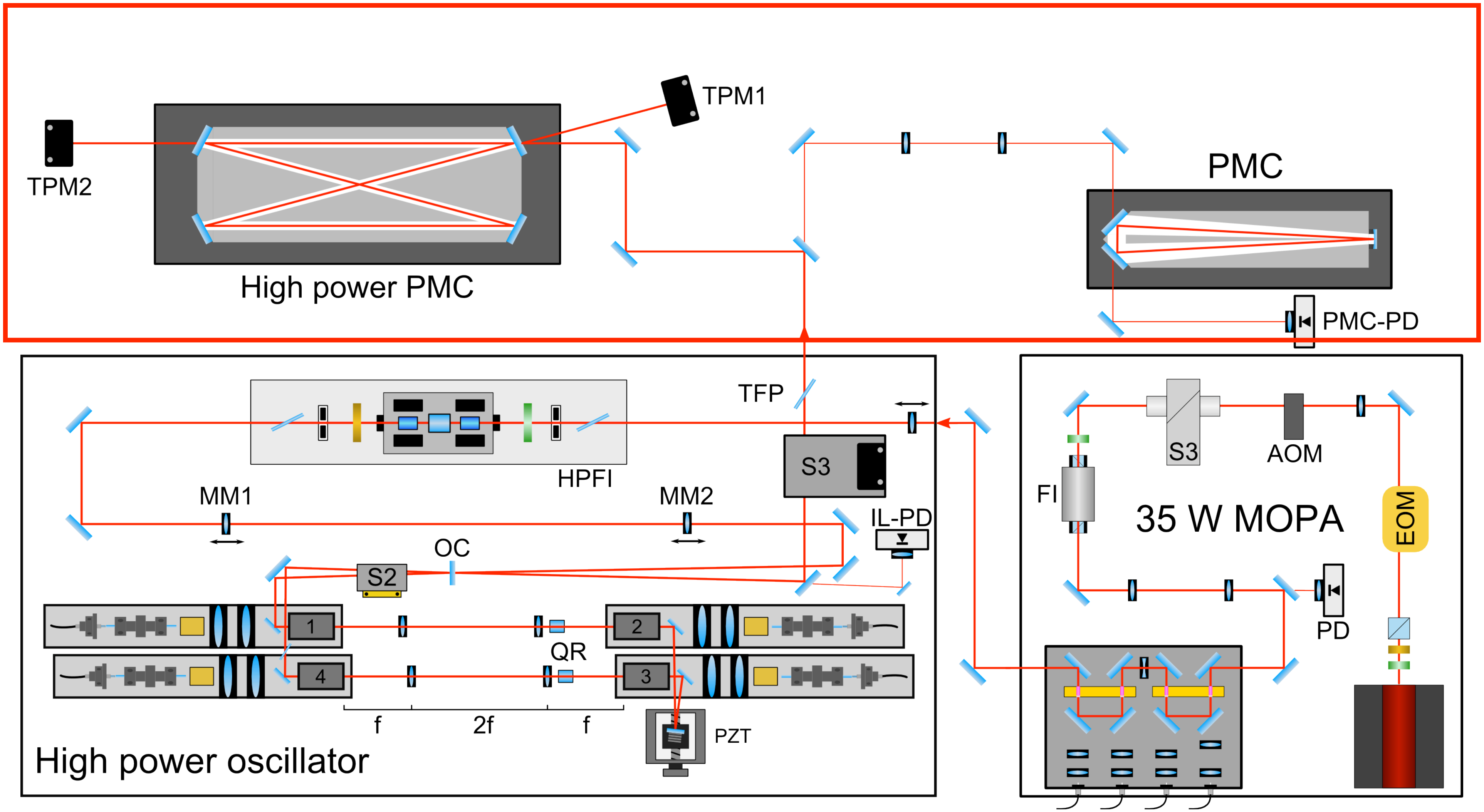
Pre-stabilized laser

Enhanced LIGO lasers are the first 2 stages of the AdLIGO laser

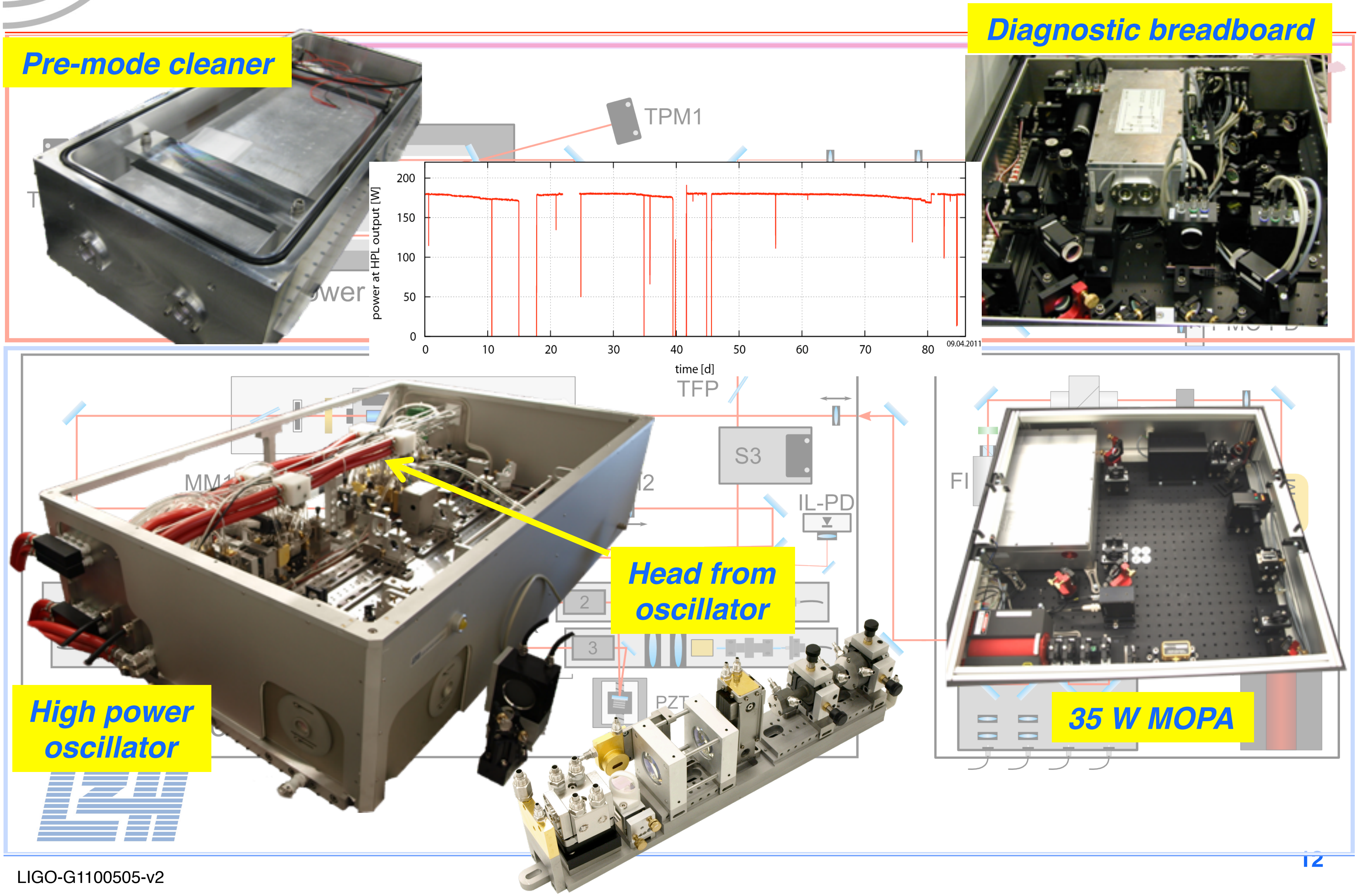
Medium and high power stages made by Laser Zentrum Hannover (LZH)



Pre-stabilized Laser

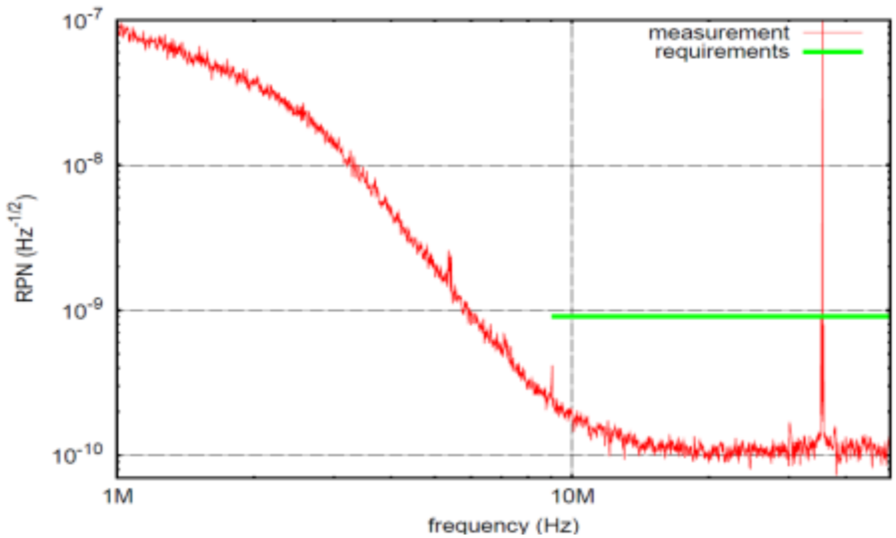


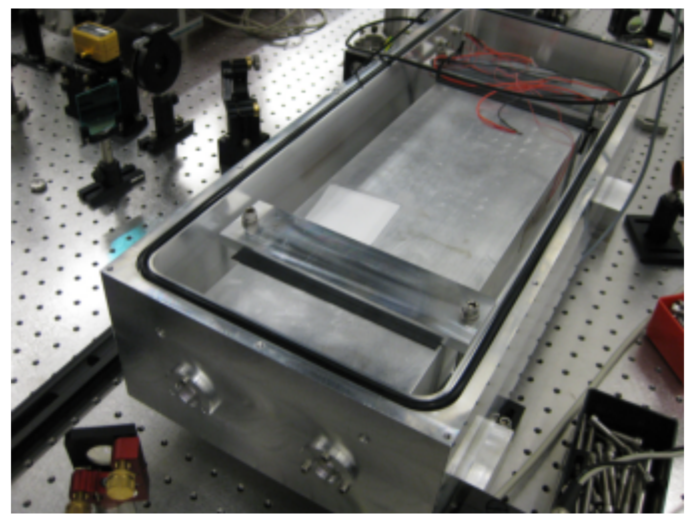
Pre-Stabilized Laser

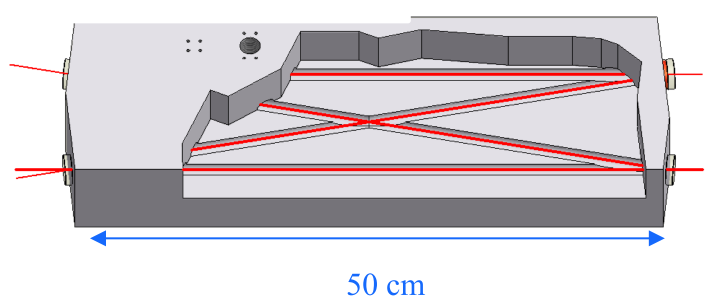


Pre-mode cleaner: spatial & temporal filtering

- bow tie configuration, round-trip length of 2m
- Finesse of 124, circulating power 9kW (200W input)
- Linewidth 575 kHz (HWHM)
- Length control with automatic lock acquisition
- PZT actuator / thermal actuator to off-load PZT

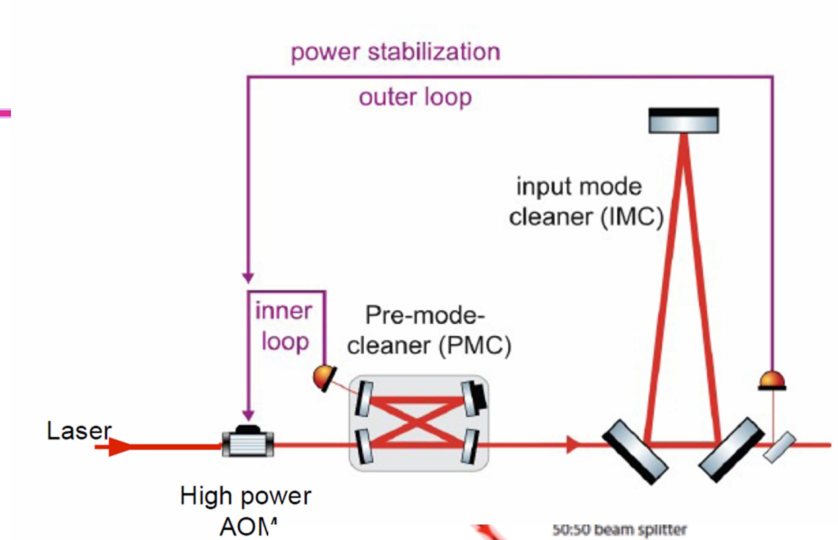


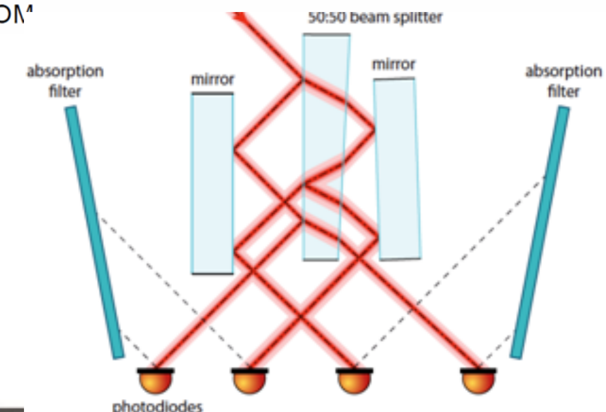


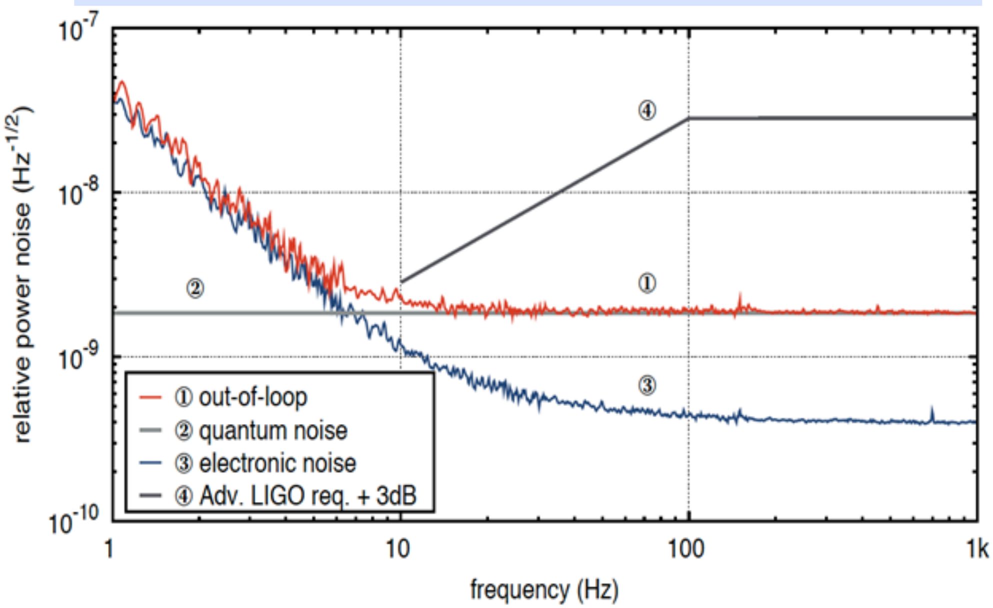


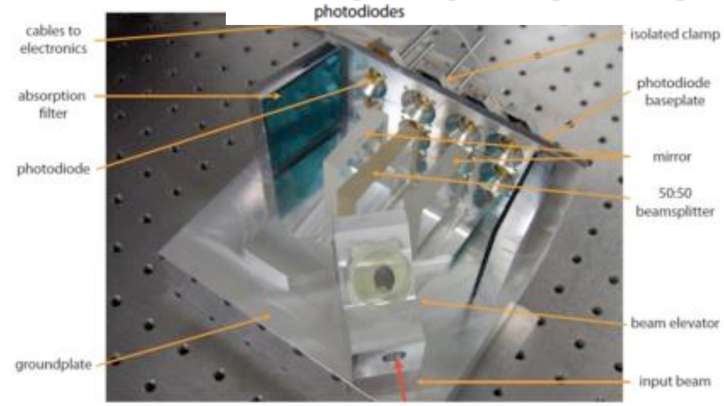
Laser Power Stabilization

- **High power acousto-optic modulator provides actuation**
- **Prototype power stabilization photodetector (outer loop)**
- **Stabilized noise requirement of RIN < 2x10^{-9} / Hz$^{1/2}$ at 10 Hz: demonstrated w/ NPRO laser**









LLO PSL currently being installed

Laser Area Enclosure: HEPA filtered airflow & acoustic shielding

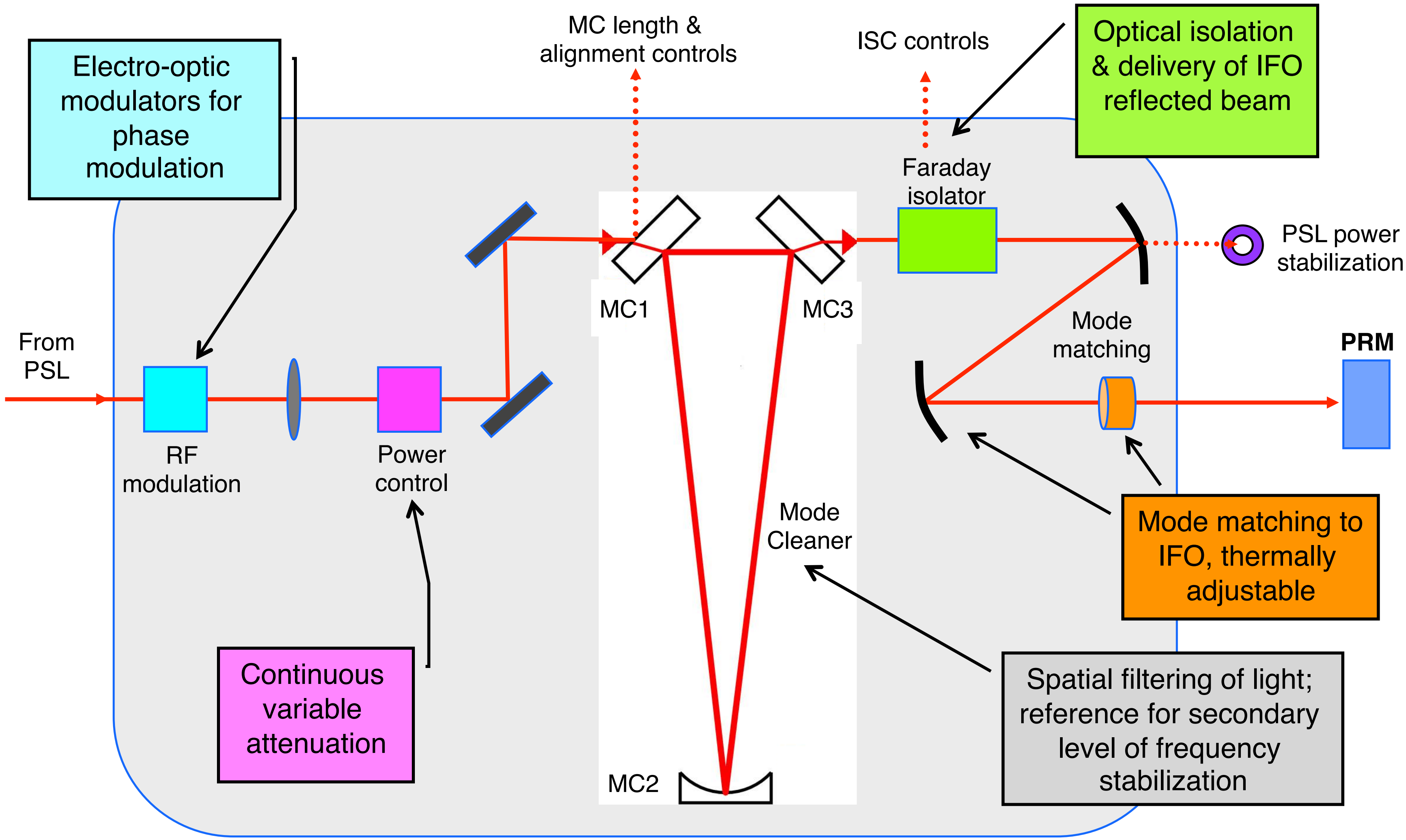
Laser Stabilization Electronics

Pump Laser Diodes in remote room

PSL Status

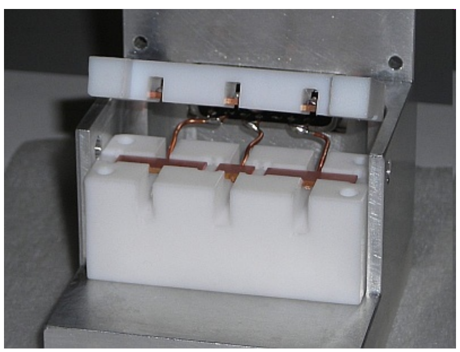
- **First laser arrived in January 2011 & is being installed**
  - H2 laser to ship in June 2011
- **Fabrication continues at LZH**
  - All 35 W MOPA's have been fabricated
  - 2nd and 3rd High Power Lasers have been assembled
- **A full PSL 'Reference Laser' remains in operation at AEI**
  - Long term testing
  - Control loop tuning and other testing
- **Final design review of outer-loop photodetector in near term**
- **No significant technical issues remaining**

Input Optics

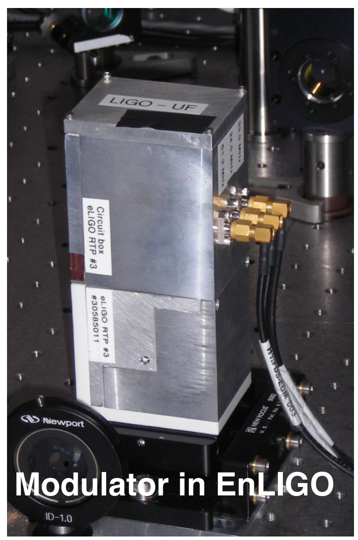


IO: Modulators and Isolators

- **Phase modulator is rubidium titanyl phosphate (RTP)**
  - » Electro-optic response similar to $LiNbO_3$
  - » lower absorption → lower thermal lensing
  - » Large aperture: 4 mm x 4 mm
  - » Multiple electrodes on single crystal for multi-RF drive

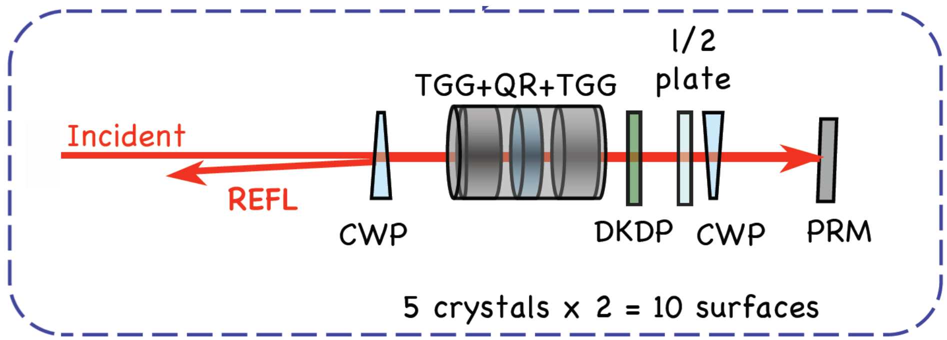


  - » Tested to 140 W

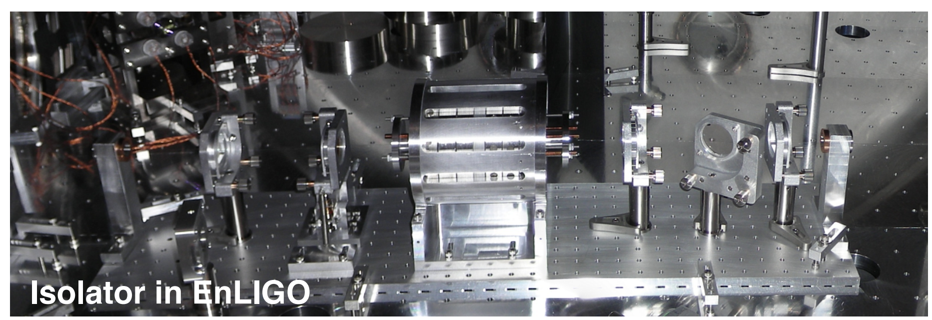


Modulator in EnLIGO

- **In-vacuum Faraday Isolator**
  - » Thermal birefringence compensation using two crystals and a quartz rotator



  - » *–dn/dT* element (DKDP) to compensate thermal lensing

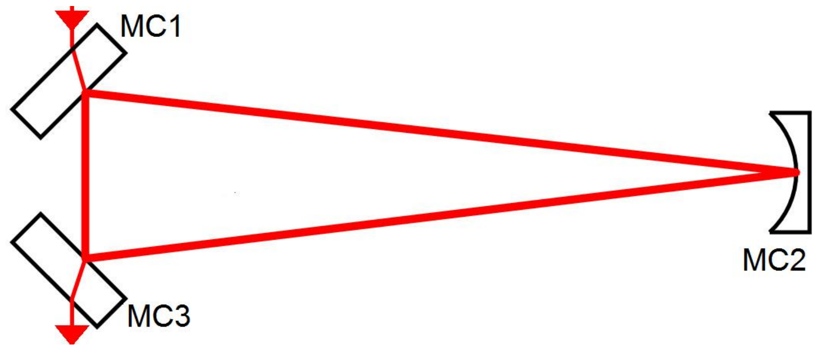


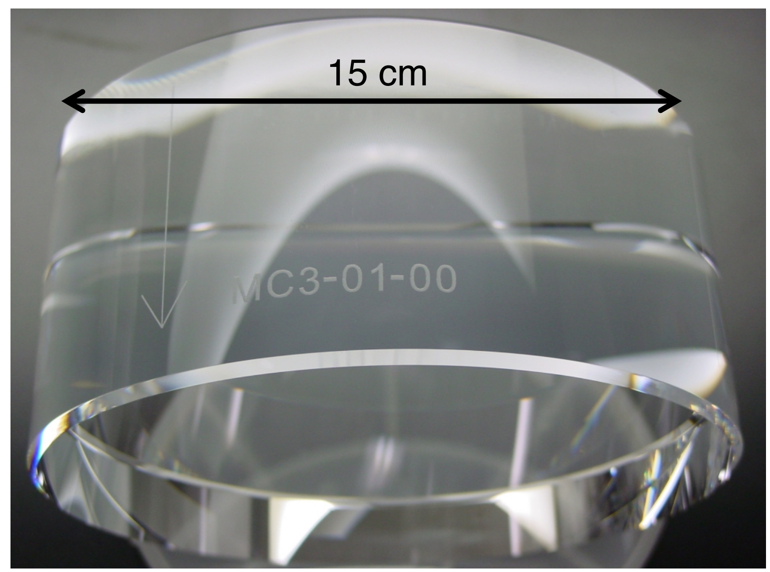
Isolator in EnLIGO

LIGO

Input Mode Cleaner Design

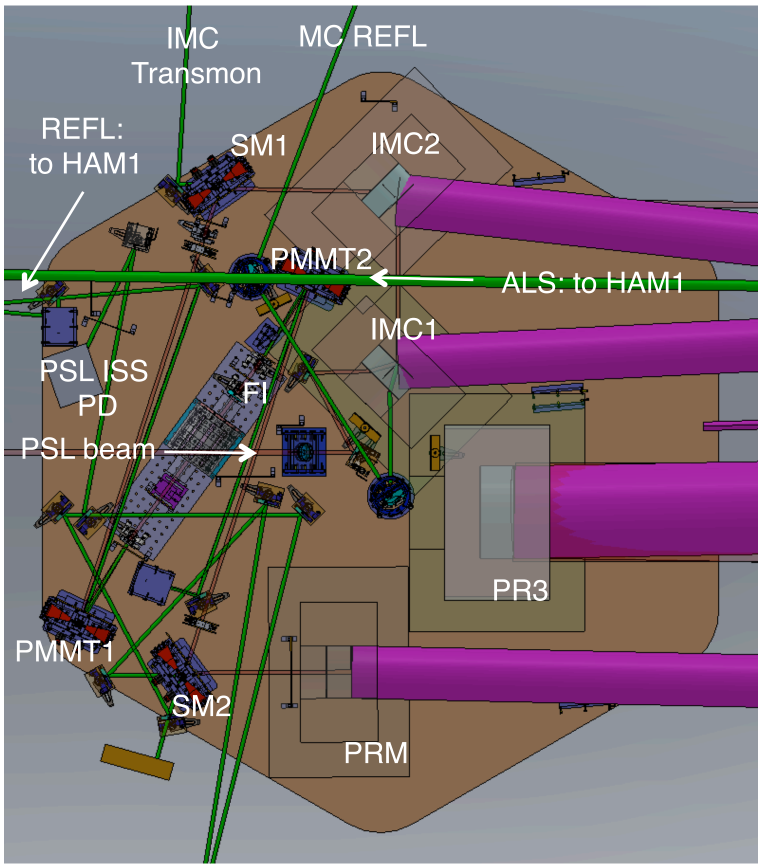
- **Triangular ring cavity**
- ***L/2* = 16.5 m**
- **FSR = 9.1 MHz**
- **Finesse = 520**
- **P_{stored} = 23 kW (@ 165 W input)**
- **MC mirrors suspended from triple suspensions**
- **MC mirrors**
  - » 15 cm diameter x 10 cm thick
  - » 3 kg: 12x heavier than iLIGO, to limit noise due to radiation pressure



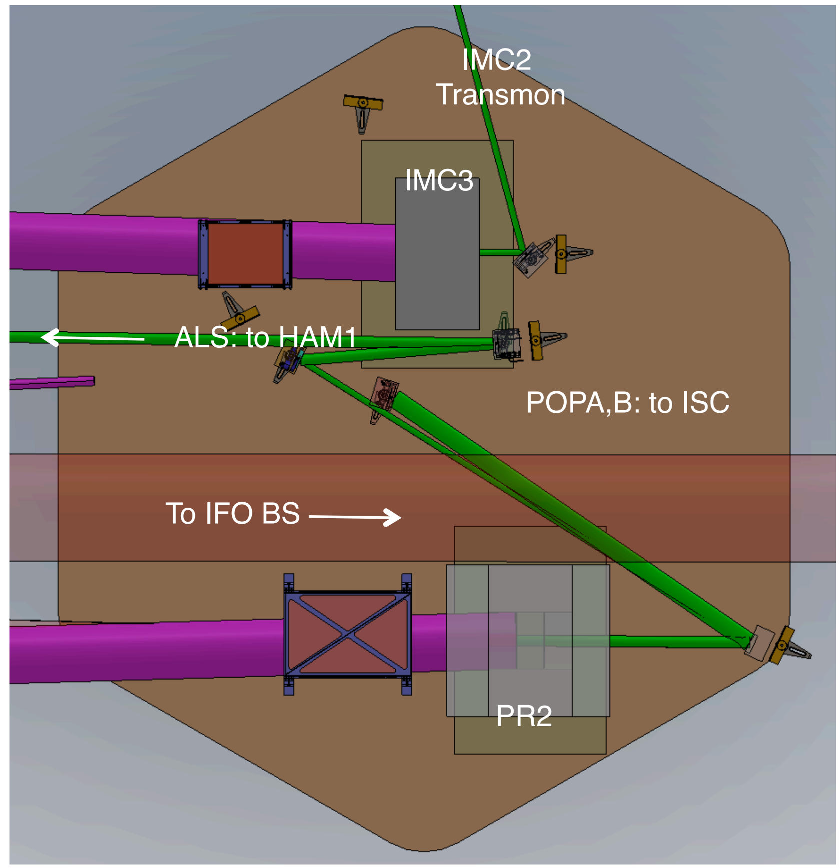


Fitting It All In …

HAM2



HAM3

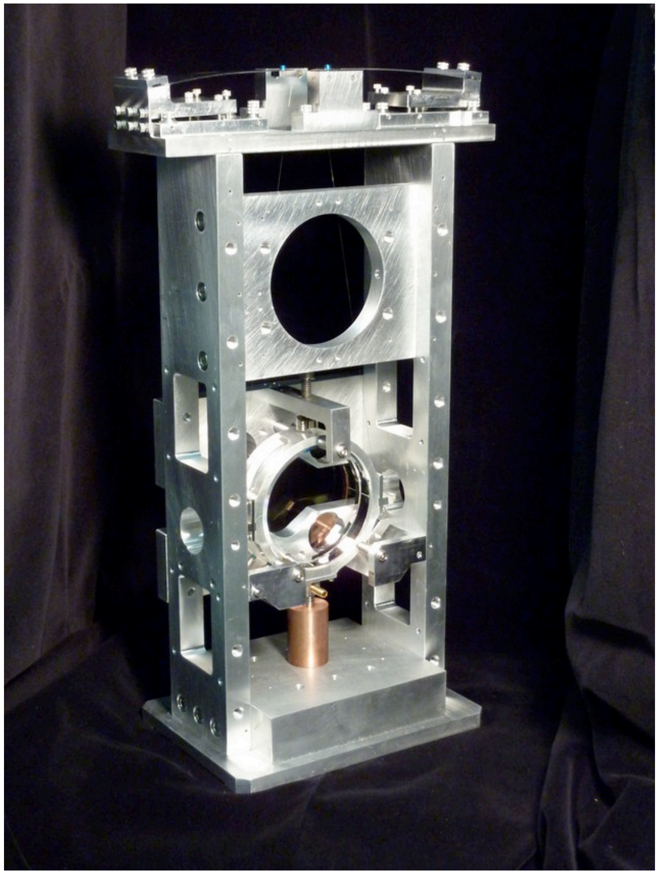


Ham Auxiliary Suspensions

- **Steer the beam between the IMC output and the Power Recycling Mirror (interferometer input)**
- **Final design review completed in fall 2010**

Single stage suspension, including blade springs for vertical compliance

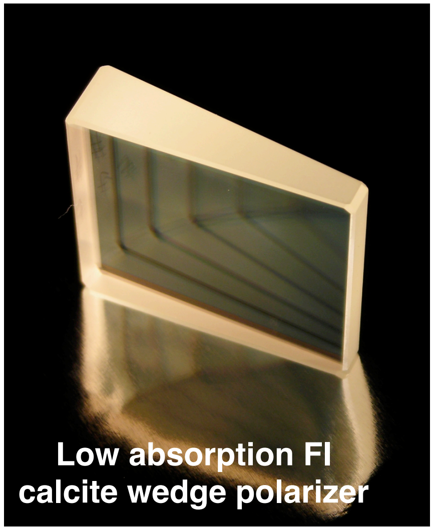
Suspension provides isolation to maintain low beam pointing fluctuations, & active control of beam pointing



Input Optics Status

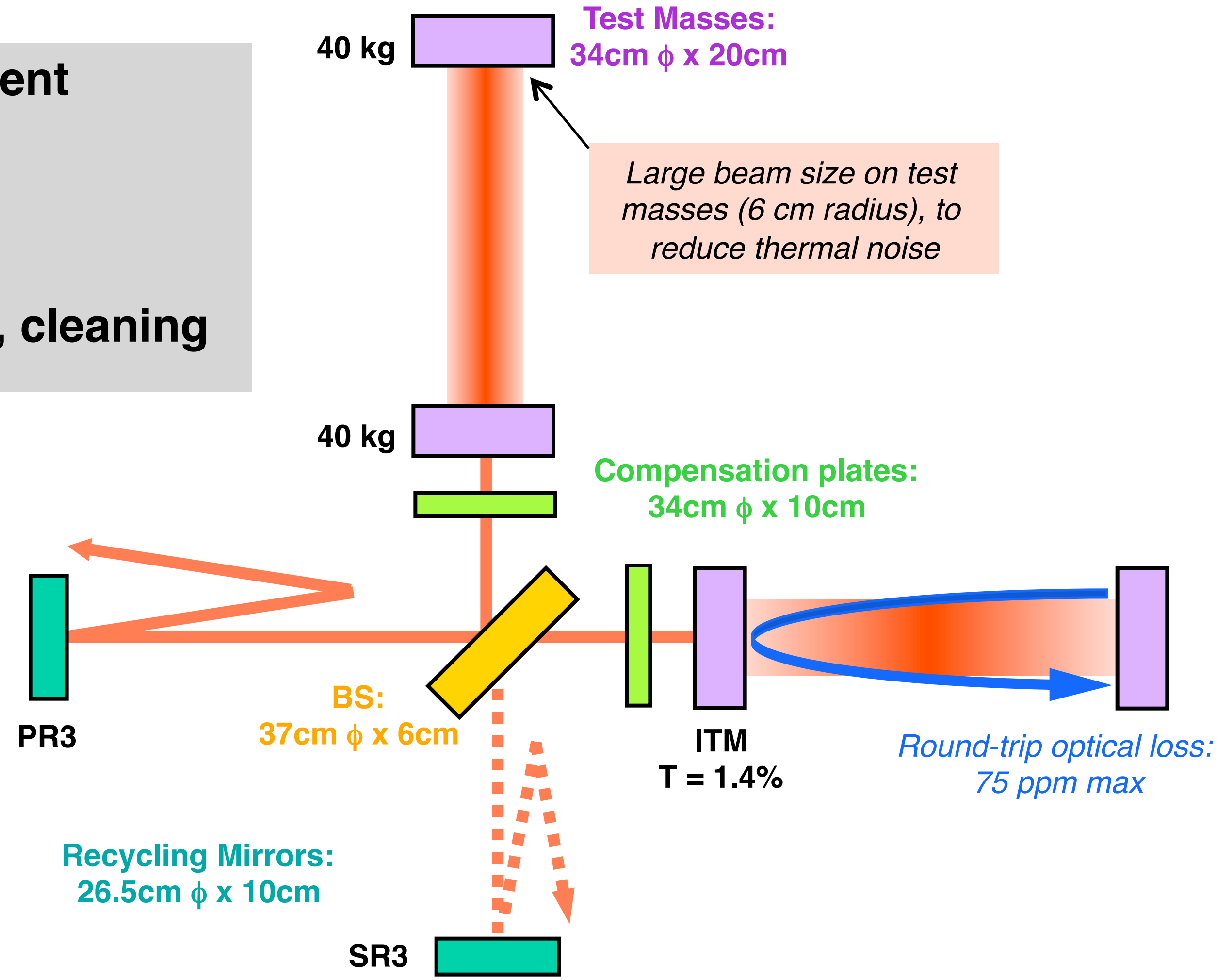
- **Final design elements completed in past ~6 months**
  - » HAM Auxiliary Suspensions & IO section baffles
- **Production status**
  - » All Input Mode Cleaner mirrors and small recycling cavity mirrors (PRM, SRM, PR2, SR2) have been polished and coated
  - » In-house Metrology in progress: IMC mirrors show suitably low absorption, 0.4-0.5 ppm
  - » HAM Aux suspension components all fabricated
  - » Modulator crystals and custom polarizers received
- **No significant technical issues remaining**


RTP crystals


Low absorption FI calcite wedge polarizer

Core Optics Components

- Substrate procurement
- Substrate polishing
- Dielectric coatings
- Metrology
- Transport, handling, cleaning



All COC are fused silica substrates with ion-beam sputtered dielectric coatings

Core Optic production flow

mid-2008

Fused silica blanks

Ultra-low absorption mat'l from Heraeus: ITM, CP, BS

Other mat'l from Corning: ETM, RM, ERM

Apr 2009

Substrate polishing

<u>Tinsley: prime contractor</u>

Coastline: superpolishing

ASML: ion beam figuring

Jul/Aug 2009

Coatings

Test Masses: LMA-Lyon
IBS dielectric coatings

All other COC: CSIRO
IBS dielectric & gold coatings

mid-2011

Characterization Metrology

<u>Caltech</u>

Phase maps with full aperture interferometer

Surface maps of Transmission, Scatter

Absorption sampling

COC Polishing

- **Arm cavity loss goal: 75 ppm round-trip (2x lower than iLIGO)**
  - » Requires low micro-roughness, low mid-spatial frequency distortion, good ROC matching between optics

Test mass specifications:

- < 0.3 nm rms figure (tilt, astig., power removed)
- Matching of ROCs to +/- 3 m (out of 2000 m)
- < 0.16 nm rms micro-roughness

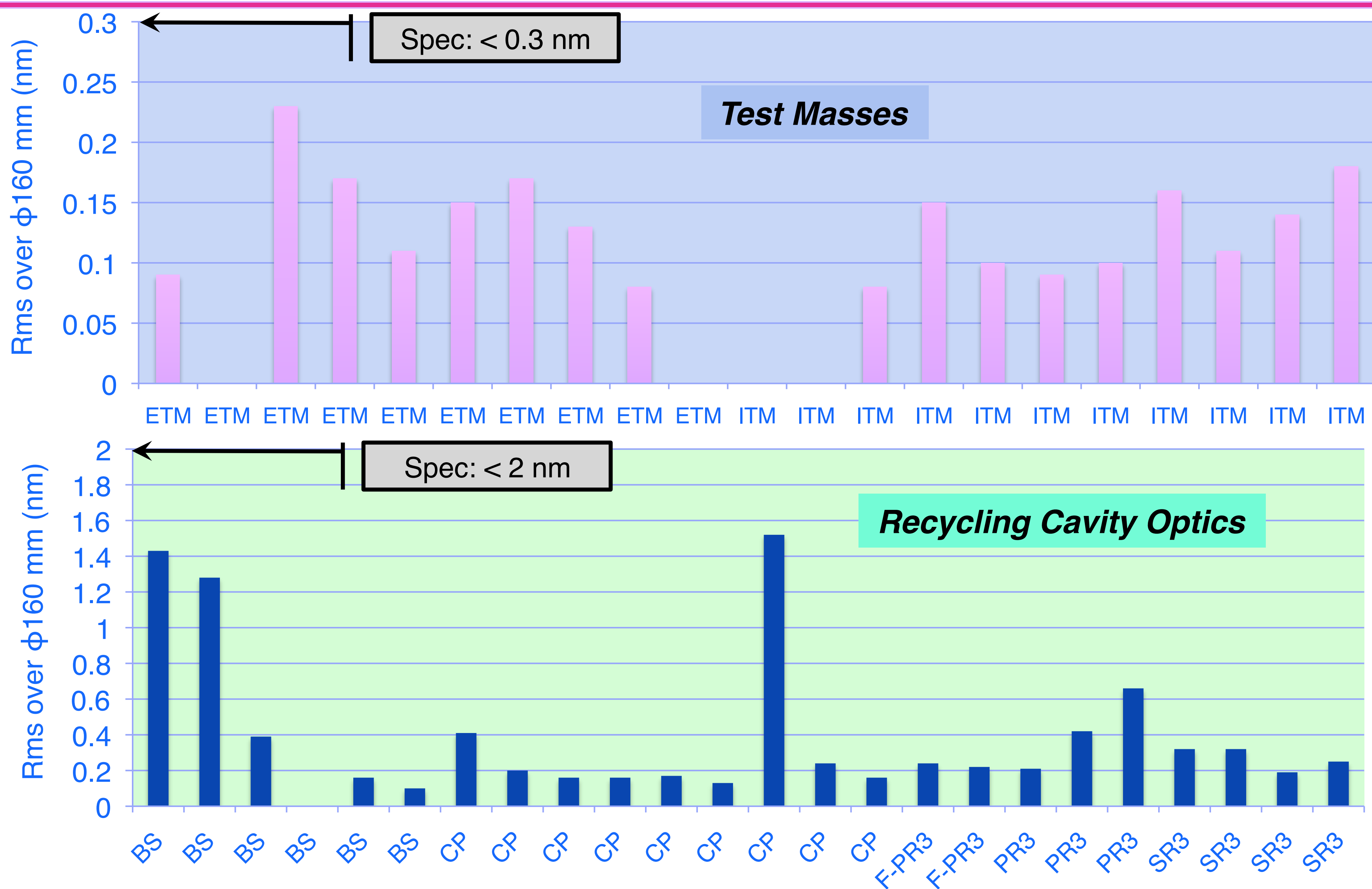
Technique:

- Initial figuring and superpolishing done at Coastline Optics
- Final ion beam figuring at ASML

Polishing Results:

- **12 of 20 polished Test Masses received – factoring in some to be redone**
  - » Radius of curvature is being met to **+/-0.6 m** on average (vs 3 m spec)
  - » Micro-roughness is **0.12 nm rms** on average (vs 0.16 nm spec)

Polishing: wavefront error
(power & astigmatism removed)



COC Coatings: Test Masses

- **Baseline Requirements for Test Mass coatings**
  - Low scatter: < 2 ppm
  - Low absorption: < 0.5 ppm
  - Low mechanical loss

  } *Rely on IBS coating technology from qualified vendors*
    - Several years of LSC R&D resulted in a better coating formula
    - Alternating layers of silica and titanium-doped tantala (25%); gives approx. 40% lower loss than non-doped tantala (20% reduction in thermal noise amplitude)
  - Low wavefront distortion
    - Radius-of-curvature change: < 8 nm sag over central area
    - Higher order Zernikes: < 0.5 nm rms
- **LMA coating designs for the test masses are completed**
  - Non-¼-wave stack: accommodates arm locking w// green beam & reduces thermal noise

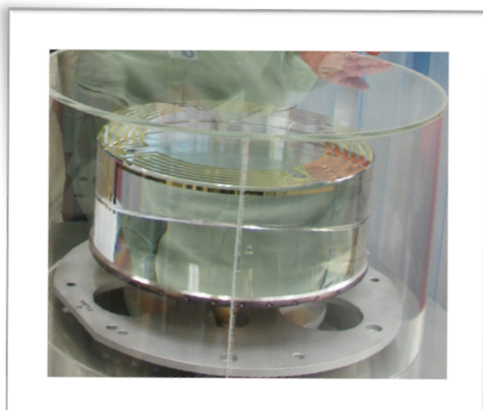
	ETM	ITM
1064 nm	**T = 5 ppm**	**T = 1.4 %**
532 nm	**T = 5%**	**T = 1%**
Thermal noise w.r.t. ¼-wave design	**-2.5%**	**-5%**

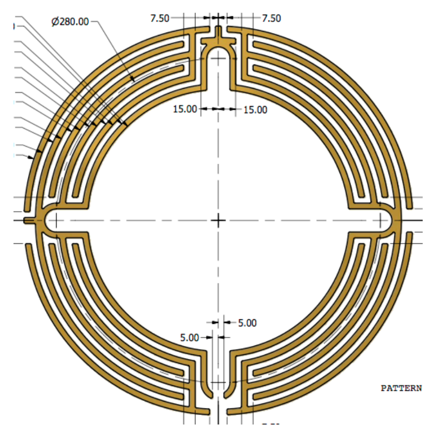
  - Absorption has been proven on first TM coating: **0.3-0.35 ppm**
  - Wavefront distortion spec not yet met – factor of ~2 off; LMA is actively pursuing techniques to improve this

COC coatings: Recycling Cavity optics

- **CSIRO coating designs for other optics nearly complete**
  - Dielectric coatings also need to accommodate Hartmann sensor probe beams (near IR) & 532 nm beams
- **Tooling/fixturing complete**
  - Sample coating runs made to prove fixturing
- **Anti-Reflection coatings in the Recycling Cavities: need low AR and low absorption**
  - Much work to understand initial high absorption (~10 ppm); now understood and able to produce < 1 ppm absorption
  - AR < 50 ppm req'd: indications are this will be achieved
- **Gold coatings on Reaction Masses for the Electro-Static Drive**

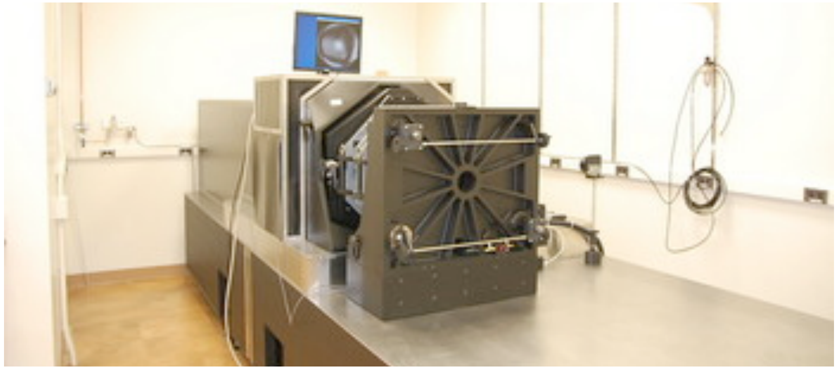
End Reaction Masses are completed & delivered





COC Status

- **Polishing of initial set of mirror blanks nearly complete**
- **Replacement blanks being supplied for Fold Mirrors and some ETMs**
  - Corning material found to change sagitta (warp) under annealing: first at CSIRO with FMs, than at LMA with ETMs
  - Both types are being replaced with Heraeus material that is stable under annealing
- **Dielectric coatings**
  - Several technical issues have been found and fixed at both CSIRO and LMA
  - *Critical remaining issue is achieving wavefront smoothness on the Test Masses (LMA)*
  - First Test Mass, for the H2 Y-arm ITM, recently delivered to LHO; suitable for first arm cavity test, will need to be replaced in the long term
- **Characterization Metrology**
  - Zygo full aperture phase-shifting interferometer up and running at Caltech

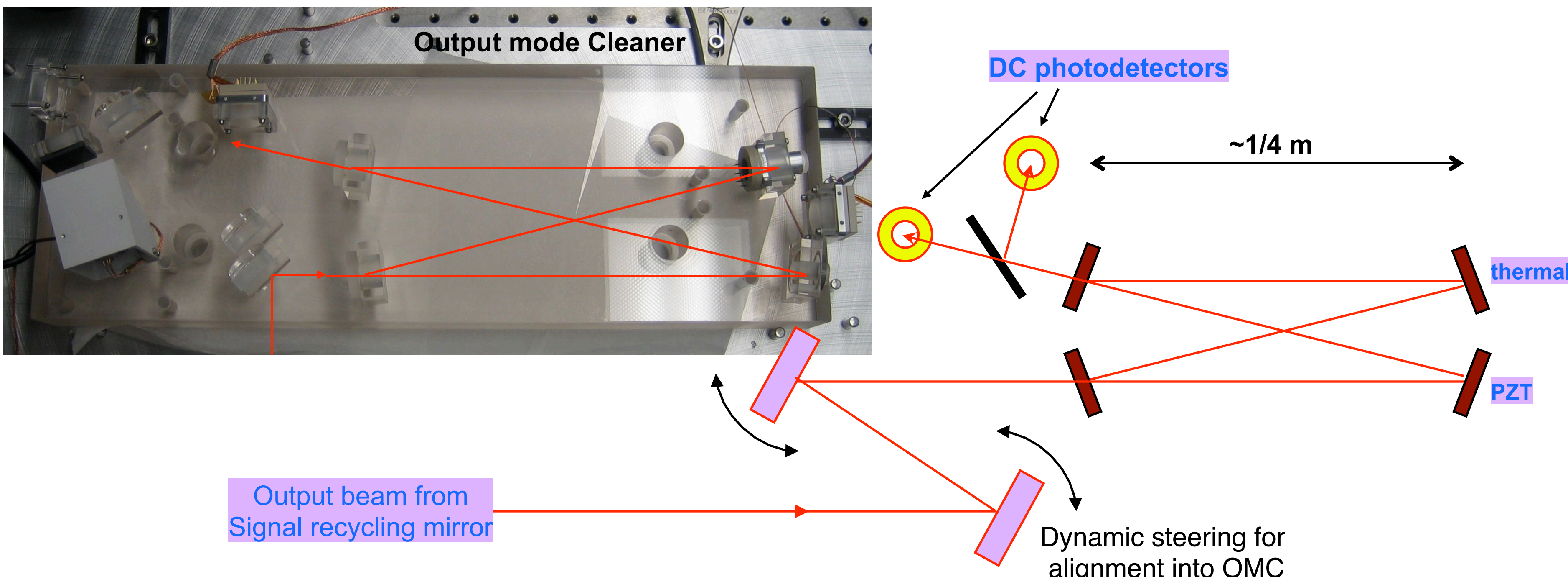


Interferometer Sensing & Control (ISC)

- **Global sensing & control of the interferometer length degrees-of-freedom**
  - » LSC: Length Sensing & Control
  - » 4km arm lengths, recycling cavity lengths, Michelson, final stage of frequency control
  - » ***Readout of the gravitational wave channel***
- **Global sensing & control of the interferometer alignment**
  - » ASC: Alignment Sensing & Control
  - » 4 test masses + 1 beamsplitter + 2 recycling mirrors = 7
- **Lock acquisition of the interferometer**
  - » Arm Length Stabilization system
- **Detection tables for all senses beams**
  - » Opto-mechanical hardware; photodetectors
- **RF components: sources, distribution, demodulation**
- **Digital controls hardware and software for all length and alignment controls**

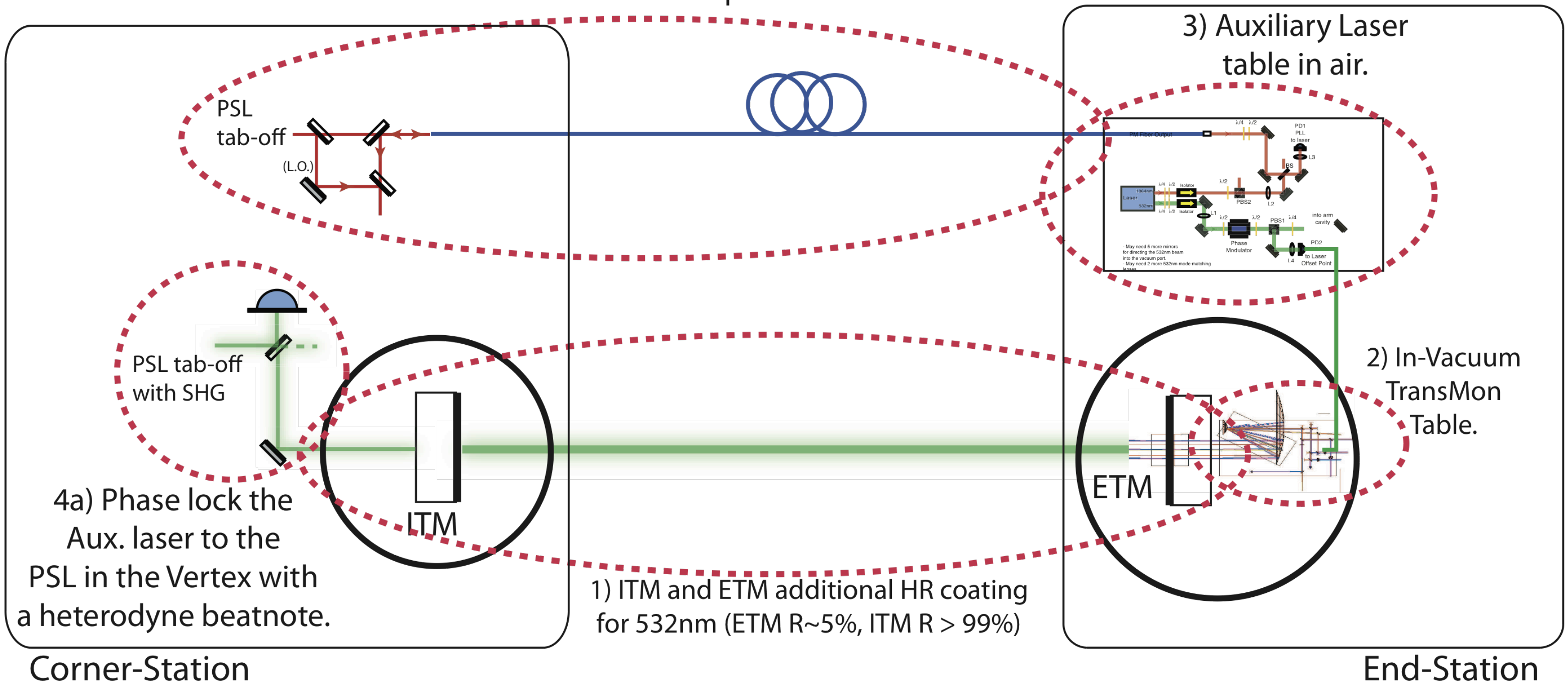
ISC: Gravitational Wave channel readout

- **DC (homodyne) detection**
  - » Offset the arm from the dark fringe, to get a signal linear in strain
  - » Use an output filter cavity to reduce shot noise (OMC = Output Mode Cleaner)
  - » Two OMCs made for and operated in Enhanced LIGO; these will be re-used for first 2 aLIGO interferometers
  - » Next generation OMC will be made for 3rd interferometer, & eventual replacement of other 2



ISC: Lock Acquisition & Arm Length Stabilization

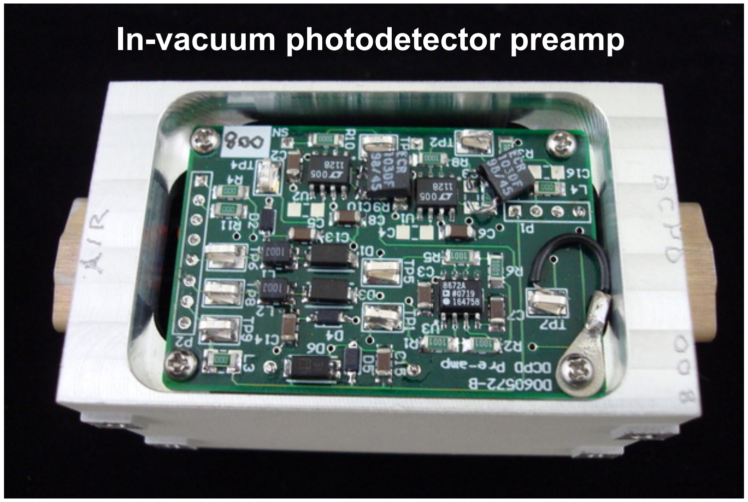
ALS being designed and delivered by ANU



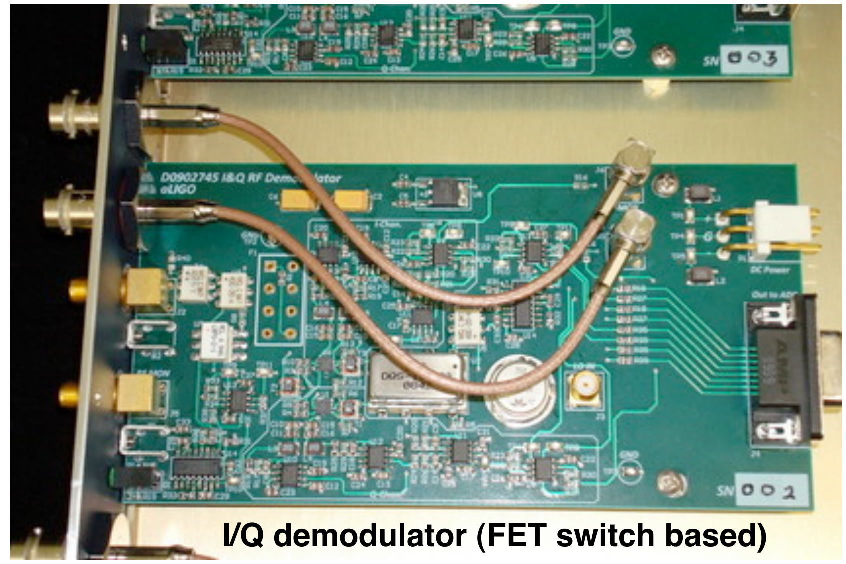
- **Lock Acquisition: strategy developed with E2E time-domain simulation**
  - ALS stabilizes the arms to ~10 nm off-resonance, to ~ 1nm residual motion
  - Three DOF in the corner are controlled using RF signals
  - Arms are brought into resonance in a controlled fashion

ISC Electronics Development

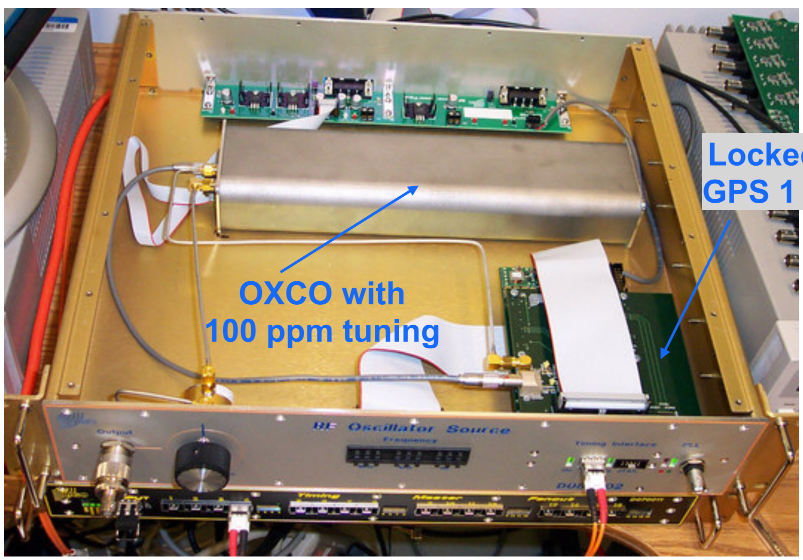
approximately 20 types of custom electronics modules

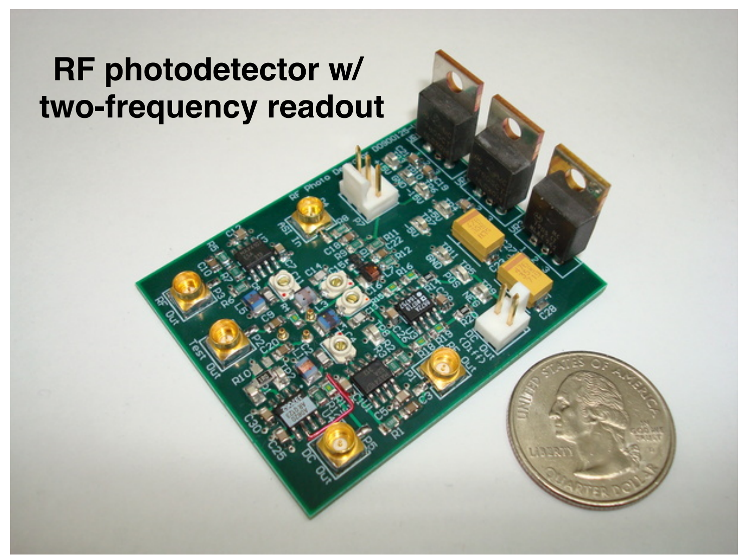


In-vacuum photodetector preamp



I/Q demodulator (FET switch based)

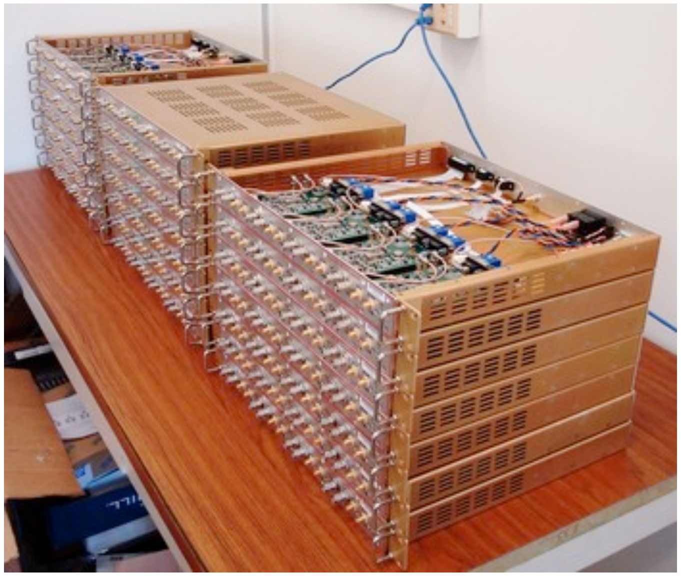




RF photodetector w/
two-frequency readout

ISC Status

- **Final design review completed in June 2010**
- **Electronics production underway**
  - RF oscillators and distribution amplifiers complete
  - RF I&Q demodulators complete
  - Quadrant photodetector transimpedance amplifier
  - Whitening / VGA chassis
- **Custom optics all ordered**
  - 1" & 2" mirrors, splitters, lenses: super-polished, IBS coated
- **Opto-mechanical components largely procured**
  - In-vacuum mirror mounts, piezo-actuators, etc.
- **Current focus is preparations for the first Arm Cavity**
  - Arm Length Stabilization: optics table at End Station
  - Transmission Monitor optical breadboard

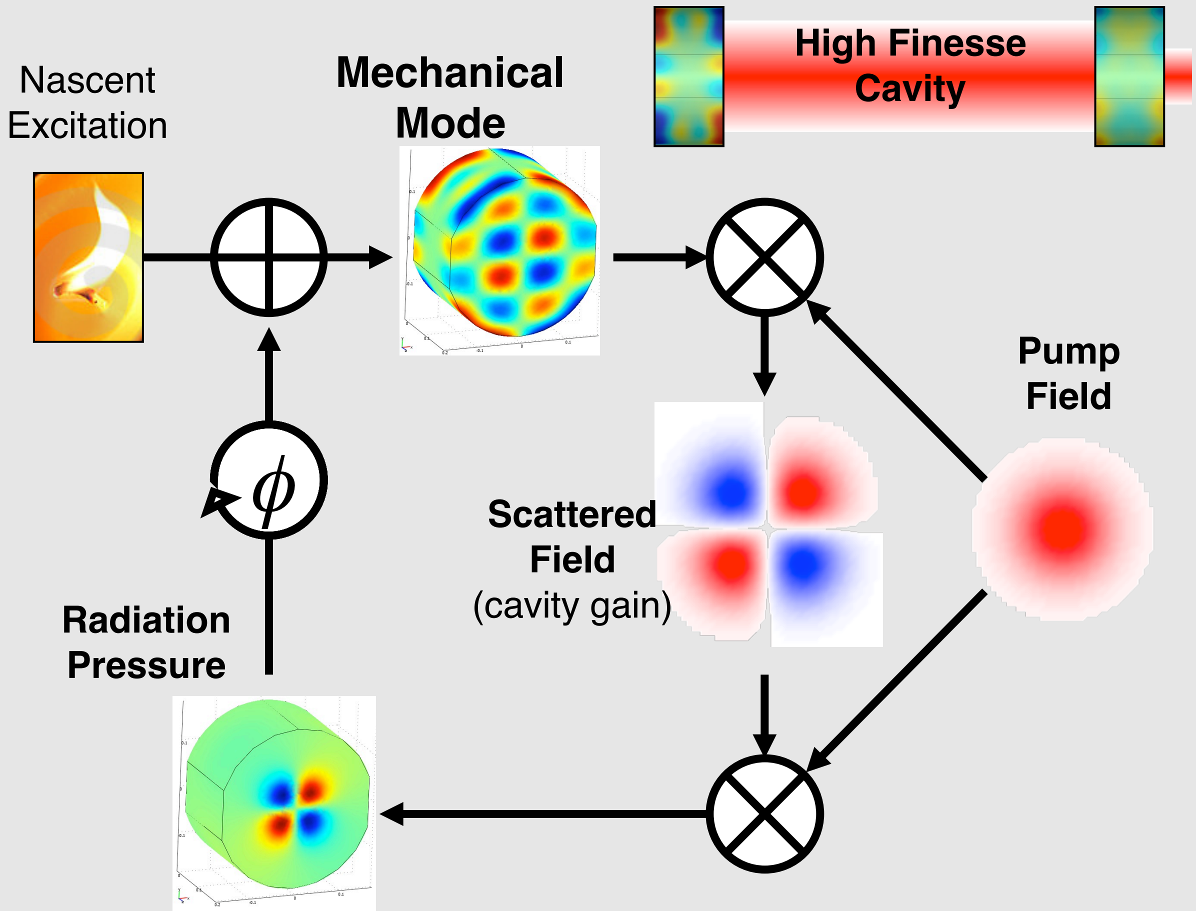


Systems design: high power operation issues

- **Operational complexities associated with increasing power**
  - » Enhanced LIGO serves as a stepping stone: operation achieved at 25 W into vacuum system
- **Excess absorption in the high-reflector coatings**
  - » Thermal Compensation System being designed to handle 2x specified coating absorption level
  - » Concern that contamination could go beyond that – see Dennis' talk
- **Parametric Instabilities**

Parametric Instabilities

Combination of high stored optical power and low mechanical loss could cause an instability:



Model predictions:

A few – 10 modes per test mass could be unstable

Models assume very high acoustic mode Q-values: 10-30 million

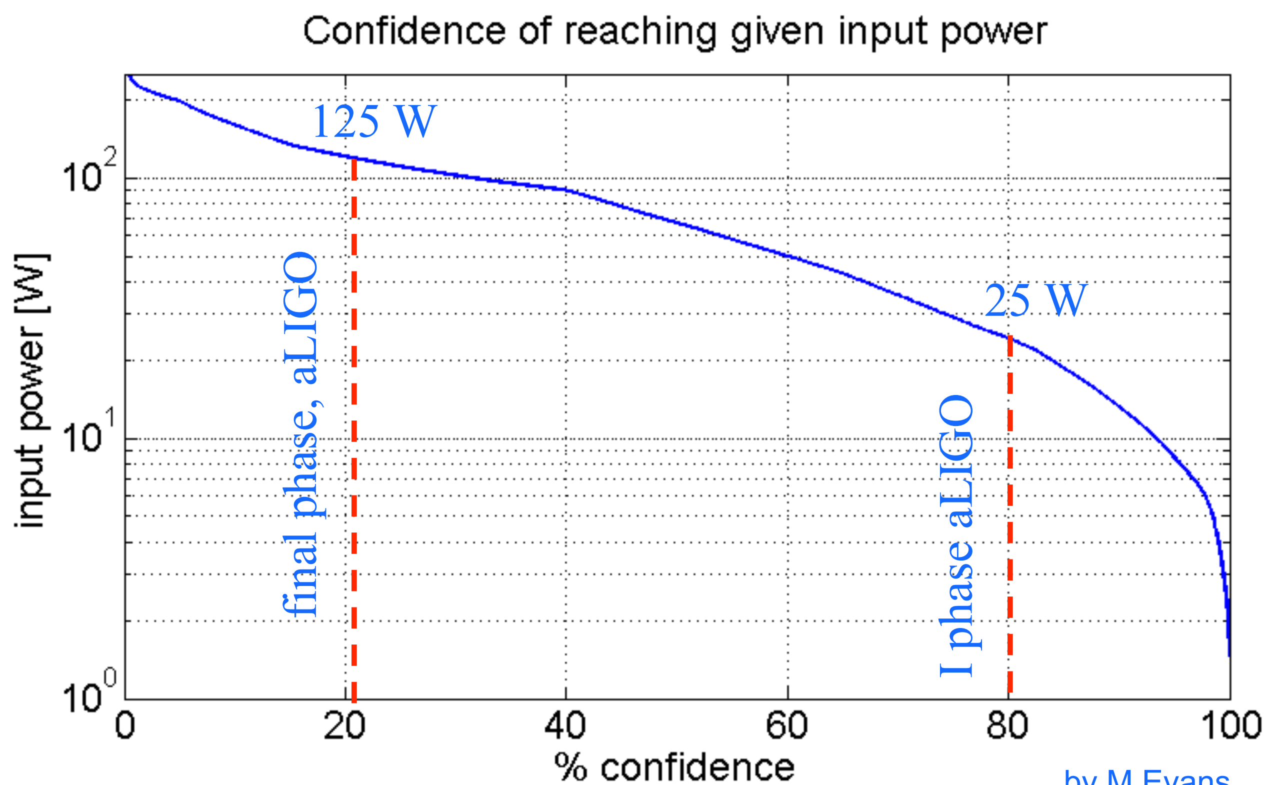
Best defense is to reduce the acoustic mode Q's

Parametric Instability: Modeling & predictions

- **High parametric gain relies on close frequency matching of acoustic & optical modes**
  - » These frequencies not known well enough to accurately calculate PI

Monte Carlo simulation
with parameters varied
over their plausible ranges

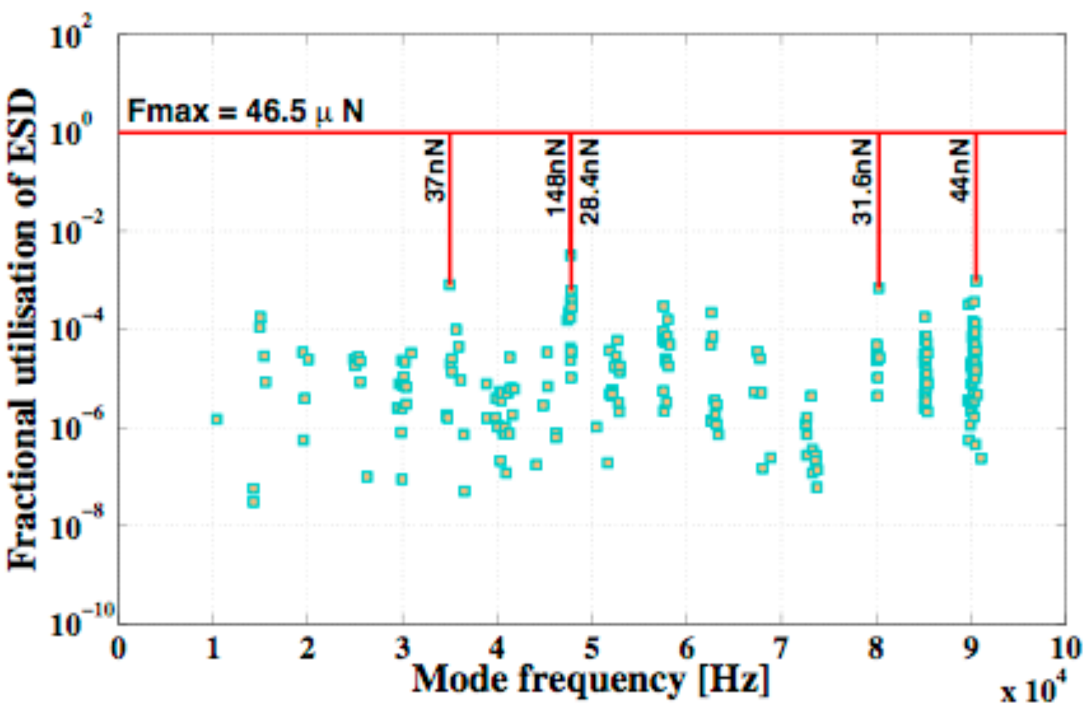
Plot shows result of
~100,000 trials



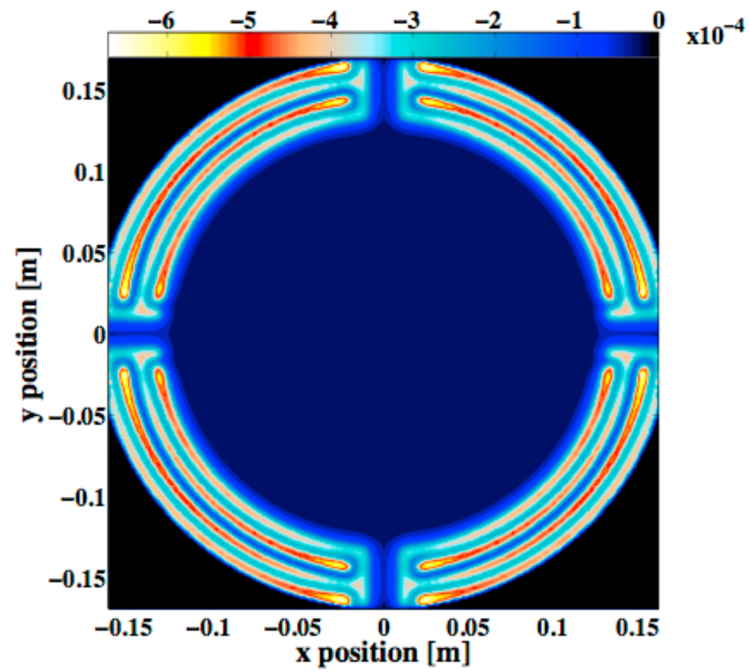
by M.Evans

Active Acoustic Mode Damping

- **Active damping using the electro-static actuators on the test masses**
  - » FEA modeling of actuator force density & acoustic modes
  - » Calculate ESD force required to damp acoustic modes so that parametric gain is reduced to 0.1

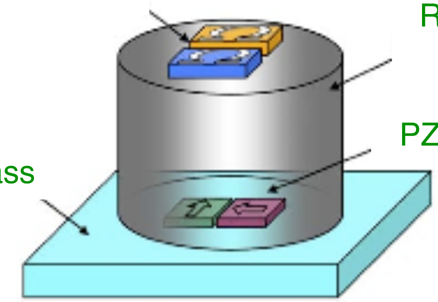


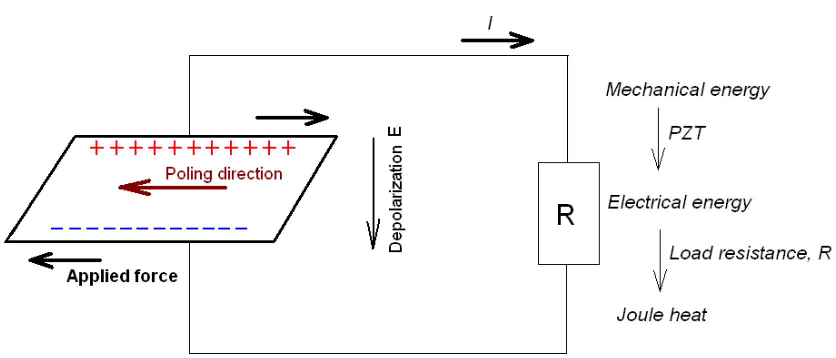
Modeled force density



Passive Acoustic Mode Damping

- **Add a few resonant mechanical dampers to the Test Mass**
  - Resonant frequencies > 10 kHz
  - Damper resonances are fairly broad (not 'tuned' dampers)
  - Mounted to the barrel of the optic

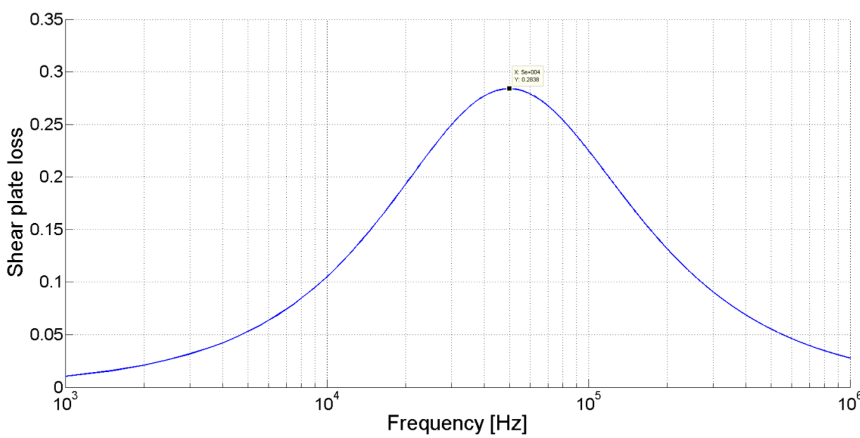




Shunted shear plate.

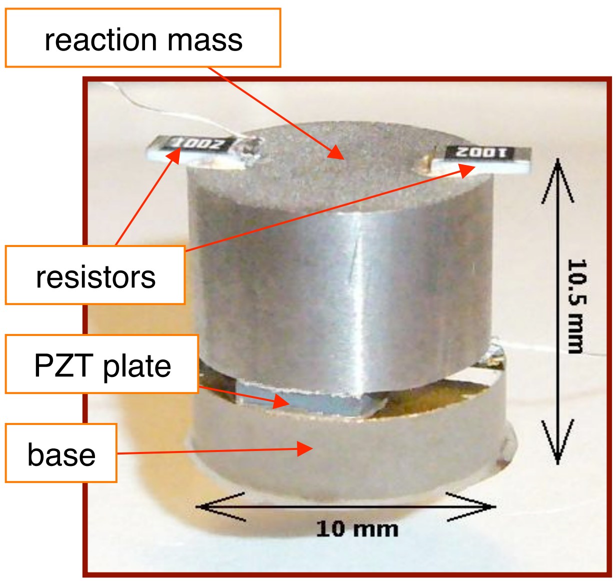
AMD: Acoustic Mode Damper

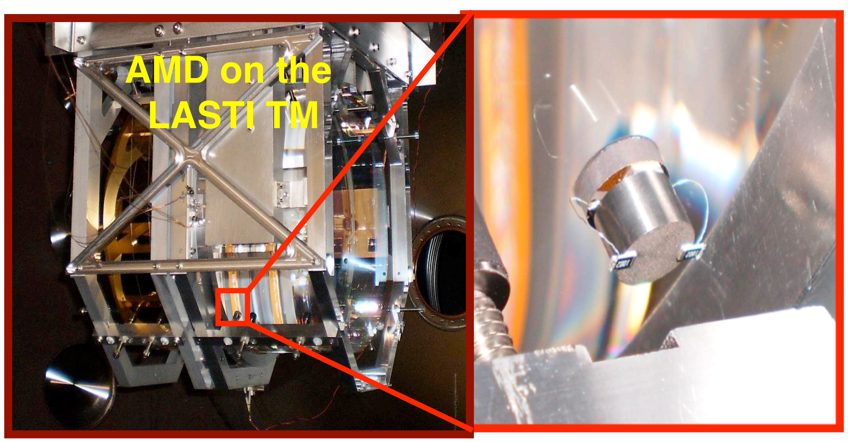
Principal resonances designed to be between 10 – 60 kHz



Acoustic Mode Damper development

AMD prototyped on LASTI's quad suspension





- Test Mass Q's are very high: **10-20 million** measured for a dozen modes
- AMD damps these by 1-2 orders of magnitude
- However, most of this damping due to something other than resistor dissipation: PZT material & epoxy; these would produce **excess thermal noise**
- Concept still viable if **lower loss PZTs and epoxy** used; currently researching better materials

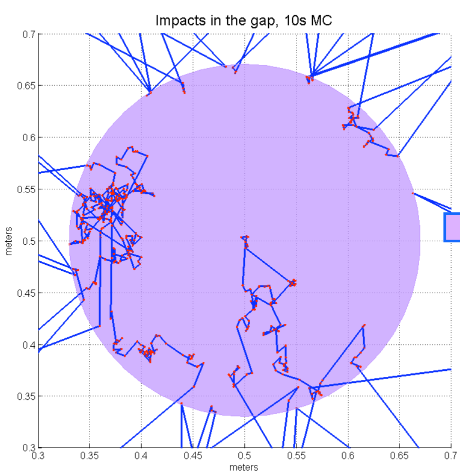
Summary of PI control strategy

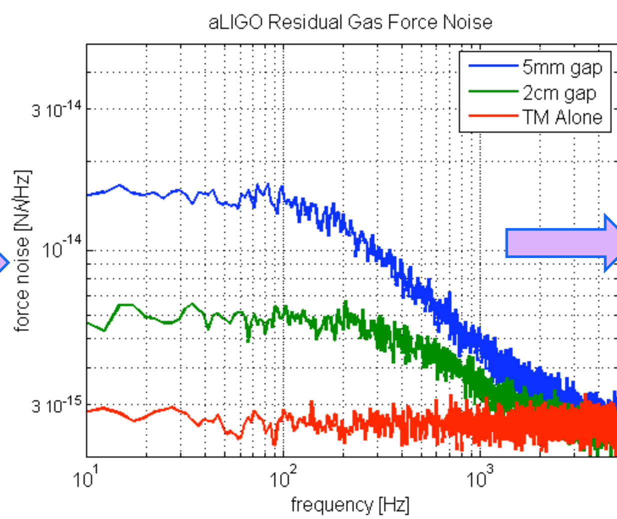
- **Active damping with Electro-Static Actuators is currently the first option**
  - » Feasible if 1 or 2 modes per test mass are unstable; beyond that it gets complicated
- **Acoustic Mode Dampers: better approach if we had a low noise AMD in hand**
  - » Continued R&D on low noise AMDs
  - » Possible retrofit on installed Test Masses

System design: squeezed-film gas damping

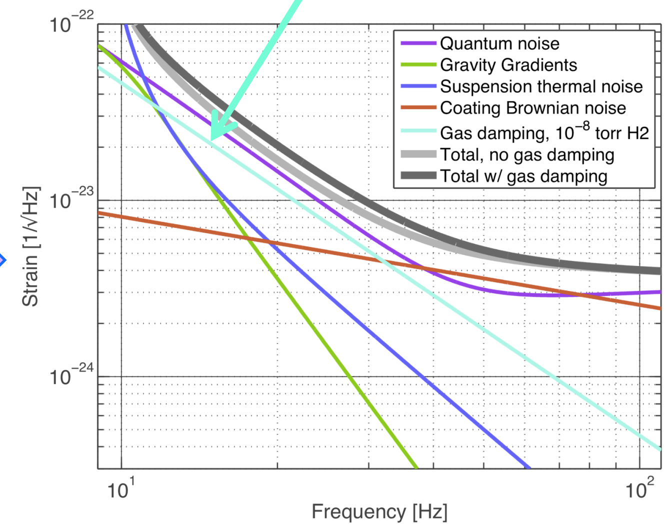
- **Residual gas in the gap between Test Mass and Reaction Mass produces increased damping of the TM pendulum motion**
  - » Increased damping means higher suspension thermal noise, could be important for frequencies below about 50 Hz
  - » Monte Carlo simulations following gas particles in the gap used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

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





Strain noise assuming 10^{-8} torr of molecular hydrogen



Mitigation of squeezed-film damping

- **Gap between ITM & CP was increased from 5 mm to 2 cm**
  - Reduced the thickness of the CP
  - Minor changes to accommodate in the quad suspensions
  - ESD force reduced as a consequence, but there was margin to spare for the ITMs
  - Force noise reduced by factor of 2.6
- **ETM-ERM 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