# 40m Laboratory Upgrade Progress Report

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40m Technical Advisory Committee
LIGO-G030405-00-R

Primary objective: full engineering prototype of optics control scheme for a dual recycling suspended mass IFO, as close as possible to the Advanced LIGO optical configuration and control system

# Advanced LIGO technical innovations tested at 40m

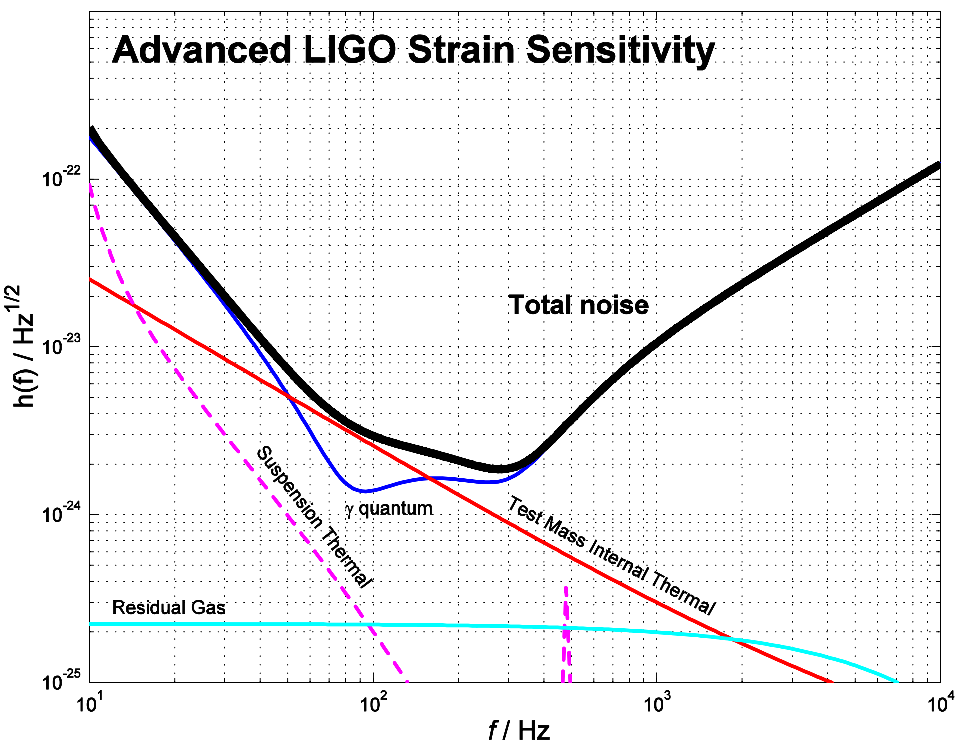
- **a seventh mirror for signal recycling**
  - » **length control goes from 4x4 to 5x5 MIMO**
- **detuned signal cavity (carrier off resonance)**
- **pair of phase-modulated RF sidebands**
  - » **frequencies made as low and as high as is practically possible**
  - » **unbalanced: only one sideband in a pair is used**
  - » **double demodulation to produce error signals**
- **short output mode cleaner**
  - » **filter out all RF sidebands and higher-order transverse modes**
- **offset-locked arms**
  - » **controlled amount of arm-filtered carrier light exits asym. port of BS**
- **DC readout of the gravitational wave signal**

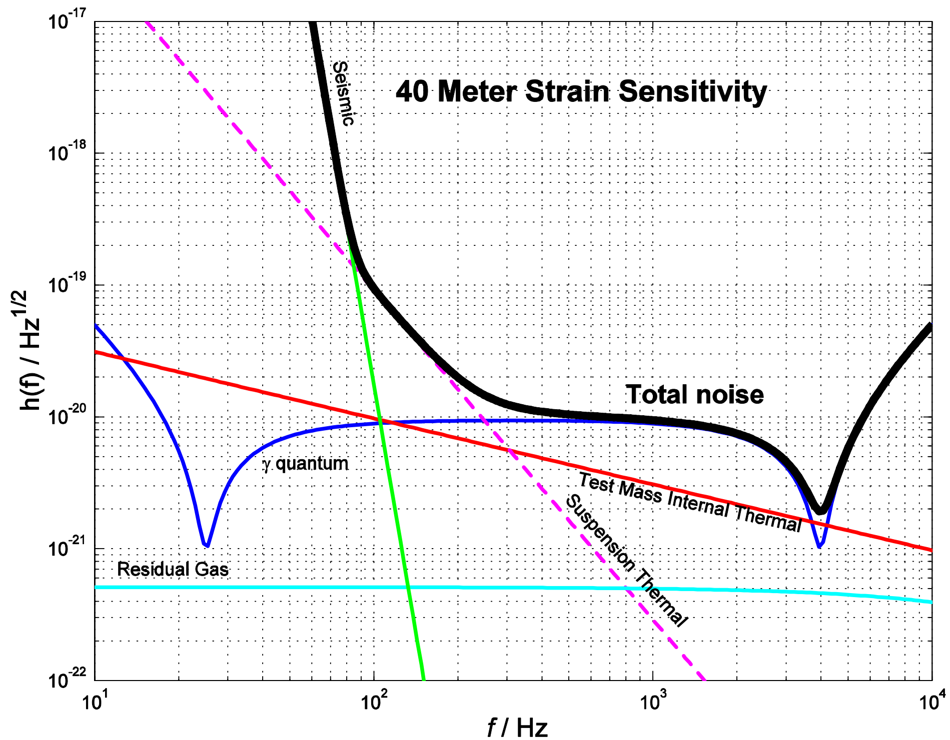
Much effort to ensure high fidelity between 40m and Adv.LIGO!

# Differences between AdvLIGO and 40m prototype

- **Initially, LIGO-I single pendulum suspensions will be used**
  - » No room for full scale AdvLIGO multiple pendulums – to be tested at LASTI
  - » Scaled-down versions to test controls hierarchy in 2004?
- **Only commercial active seismic isolation**
  - » STACIS isolators in use on all test chambers, providing ~30 dB of isolation from 1-100 Hz
  - » No room for anything like full AdvLIGO design – to be tested at LASTI
- **LIGO-I 10-watt laser, negligible thermal effects**
  - » Other facilities will test high-power laser (LASTI, Gingin)
  - » Thermal compensation also tested elsewhere
- **Small (5 mm) beam spot at TM's; stable arm cavities**
  - » AdvLIGO will have 6 cm beam spots, using less stable cavities
  - » 40m can move to less stable arm cavities if deemed useful
- **Arm cavity finesse at 40m chosen to be = to AdvLIGO**
  - » Storage time is x100 shorter
  - » significant differences in lock acquisition dynamics, in predictable ways
- **Control RF sidebands are 33/166 MHz instead of 9/180 MHz**
  - » Due to shorter PRC length
  - » Less contrast between PRC and SRC signals

# Target sensitivity of AdvLIGO and 40m prototype



# 40m Lab Staff


Dennis Ugokini (Trinity Univ.)

Alex Ivanov

Lisa Goggin (student)

Aidan Crook (SURF)

Larry Jones

Janeen Romie

Rich Abbott

Armandula Helena

etc.

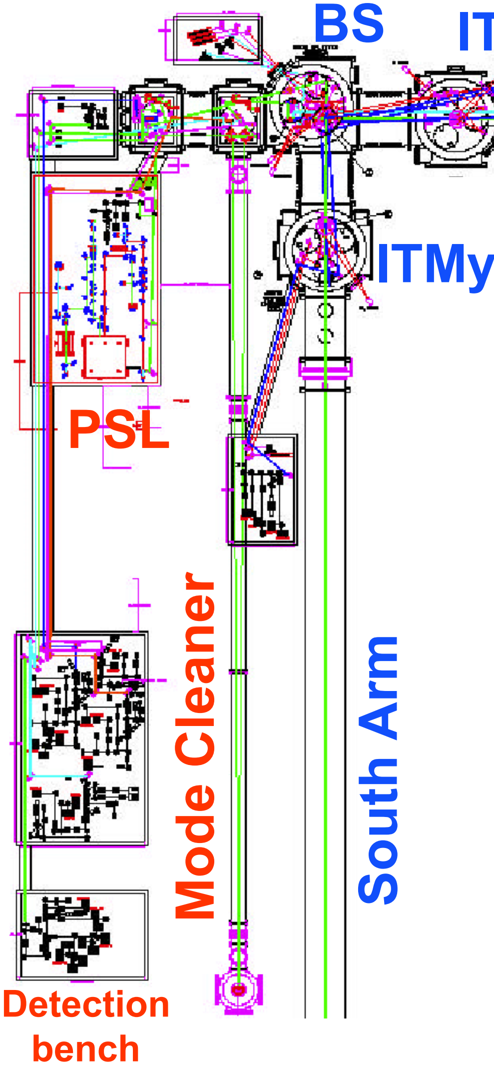
# Milestones Achieved as of Summer LSC Meeting

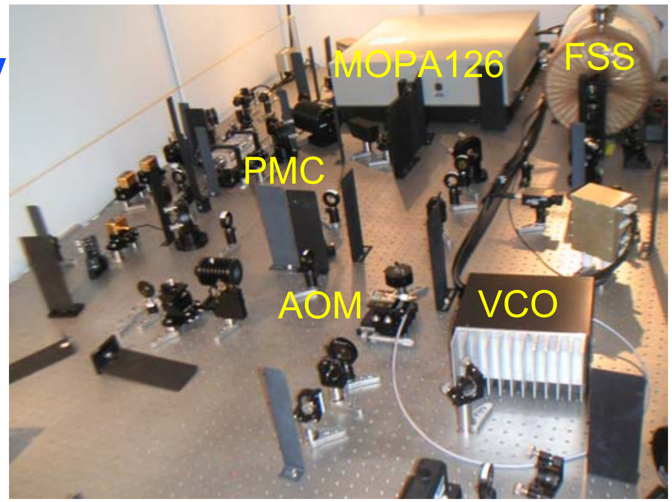
- The laboratory building, electrical power, control room, vacuum envelope and equipment and controls, electronics racks, optical tables, environmental monitoring, and other utilities are in place.
- Graduate students, REU summer students, SURF students, visiting students and visiting scientists have contributed to all aspects of the project
- The Initial-LIGO-like **Pre-Stabilized Laser (PSL)** and **13-meter suspended mass input mode cleaner** are installed, fully commissioned, and operating regularly, robustly, and according to specifications.
- **A new PSL layout** with less mirrors has been designed and commissioned.
- Digital controls for the input mode cleaner **auto-alignment (WFS) system**
- An Initial-LIGO-like **data acquisition system (DAQS)** , slow control and **monitoring system (EPICS)** , and **Global Diagnostics systems (GDS)** are all in place.
- All **seven core suspended optics** and suspensions are completed. All optics except the two recycling mirrors are installed in **vacuum chambers**.
- **Digital suspension controllers** are completely commissioned.
- **Active seismic pre-isolation (STACIS)** is installed and operational.

# Milestones Achieved as of Summer LSC Meeting

- **Enhanced digital filtering capabilities** for the front-end servos using commodity Linux computers.
- Key input optics systems (in-vacuum **Faraday Isolator** and **mode-matching telescope**) have been designed, constructed, installed, and commissioned in the vacuum chambers.
- **Alignment of Fabry-Perot Michelson** in vacuum chamber complete. PRM and SRM will be installed after FPMI commissioned.
- Currently, the first-generation **Length Sensing and Control system** is under construction.
- Begin commissioning of the interferometer in stages, with simple sub-systems short **Michelson, Fabry-Perot arms**) by fall 2003.
- Development of the **E2E** model of the 40 Meter and Advanced LIGO **dual-recycled interferometers** in parallel.

# Pre-Stabilized Laser(PSL) and 13m Mode Cleaner(MC)

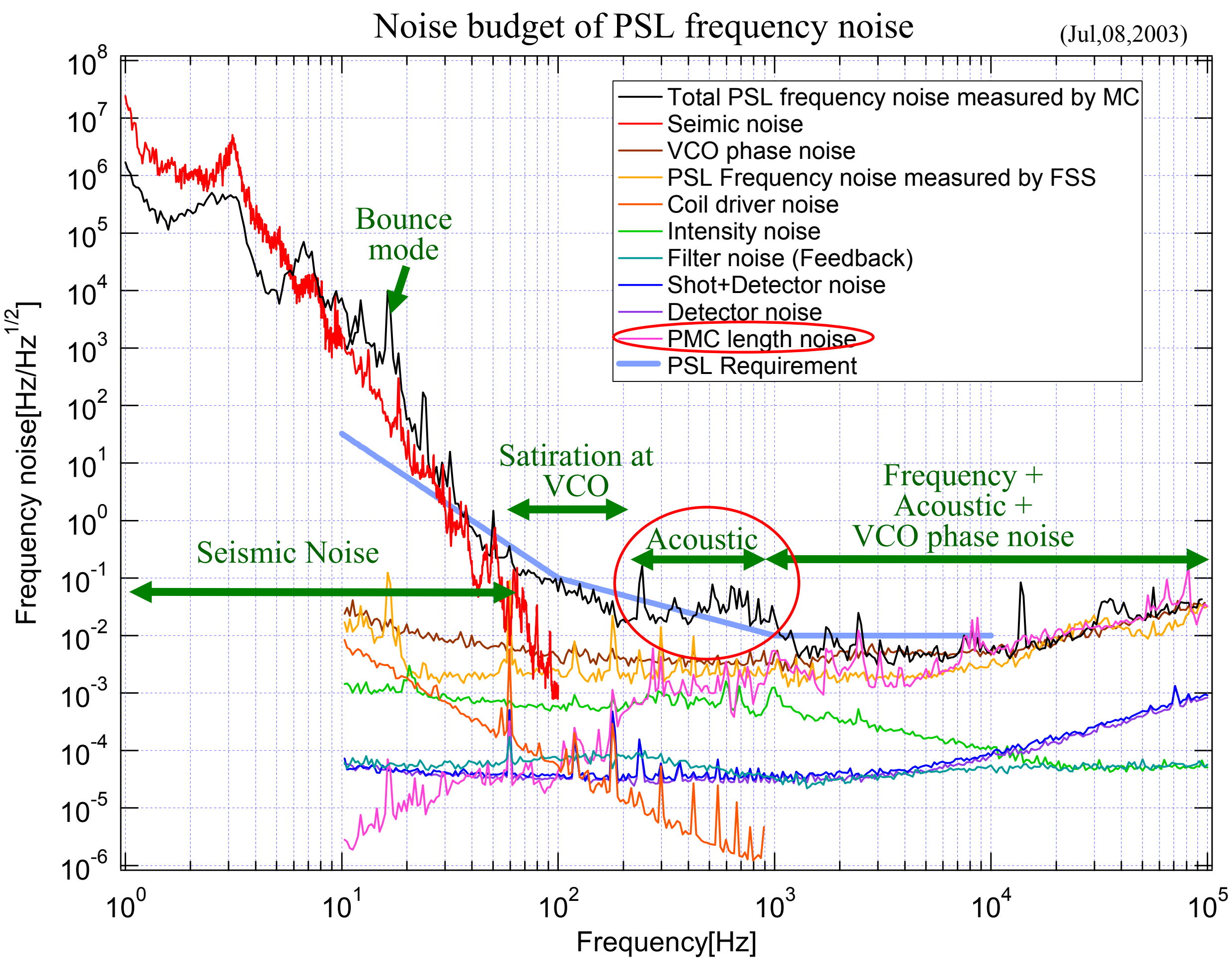




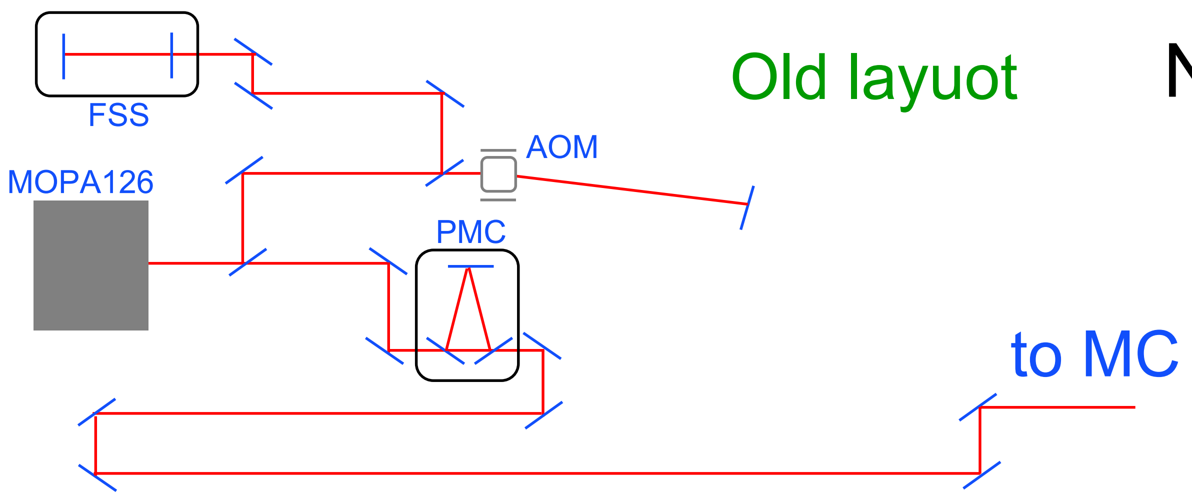
- 10W MOPA126
- Frequency Stabilization Servo (FSS)
- Pre-Mode Cleaner (PMC)
- 13m Mode Cleaner with digital controlled suspension
- Stable and good noise performance

# Total PSL frequency noise measured by 13m MC

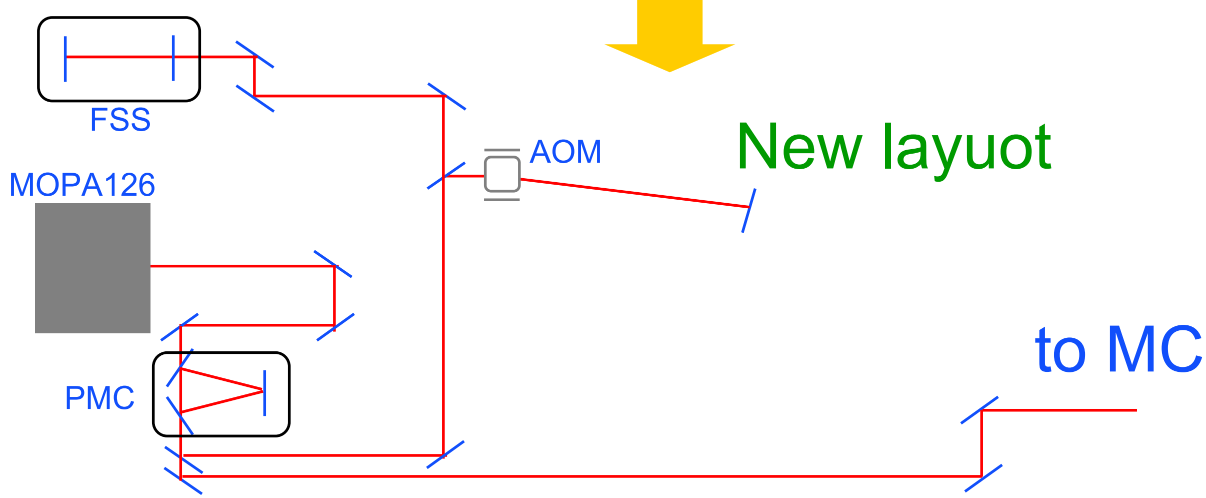



- Total noise reached at seismic noise of MC2 until 50Hz.
- Total PSL noise meets requirement above 40Hz except for a bump around 800Hz.
- **Resonance of mirror mounts** shaken by **acoustic noise** limit around 800Hz.
- VCO phase noise, Frequency noise and **PMC length fluctuation noise** limit the high frequency.
- Coil driver noise, Intensity noise, Feedback filter noise, Shot noise and Detector noise are lower than total noise.

# PSL modification 1: Fewer mirrors




Old layuot



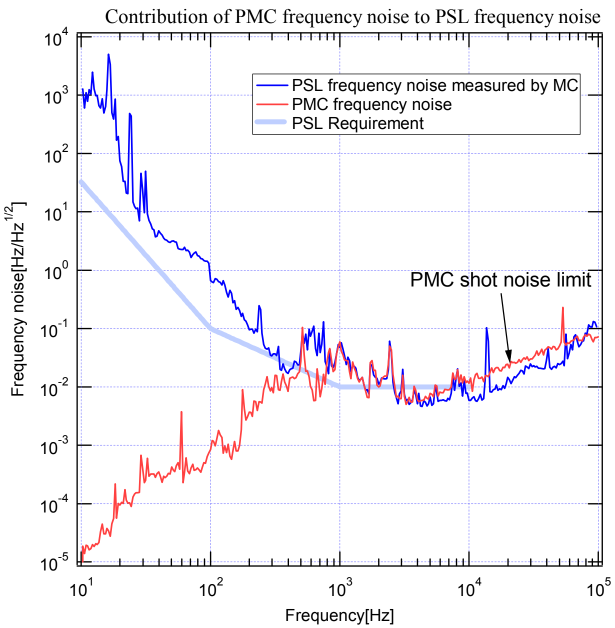

New layuot

Number of mirrors after PMC

6

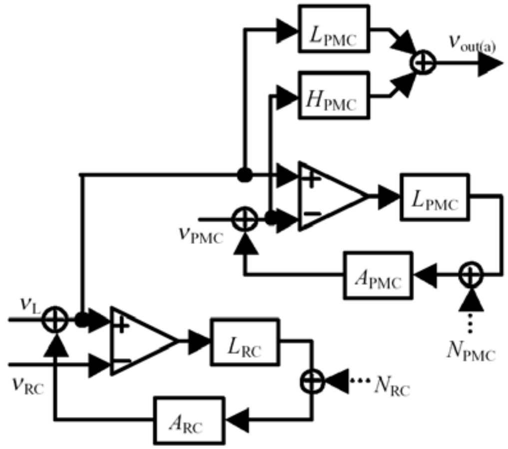
3

# PSL modification 2: PMC loop inside FSS loop

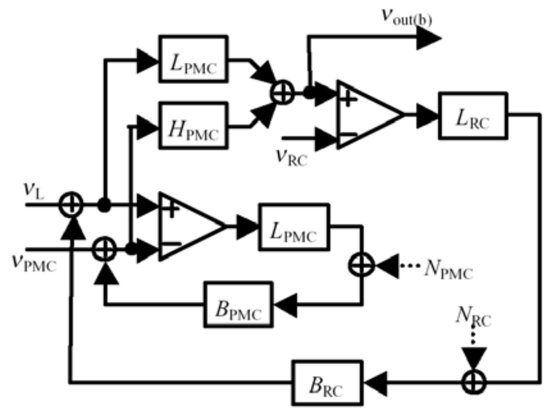



- Total PSL frequency noise is limited by PMC length fluctuation noise. This contribution depends on the PMC gain.

(a) Old PSL layout



(b) New PSL layout



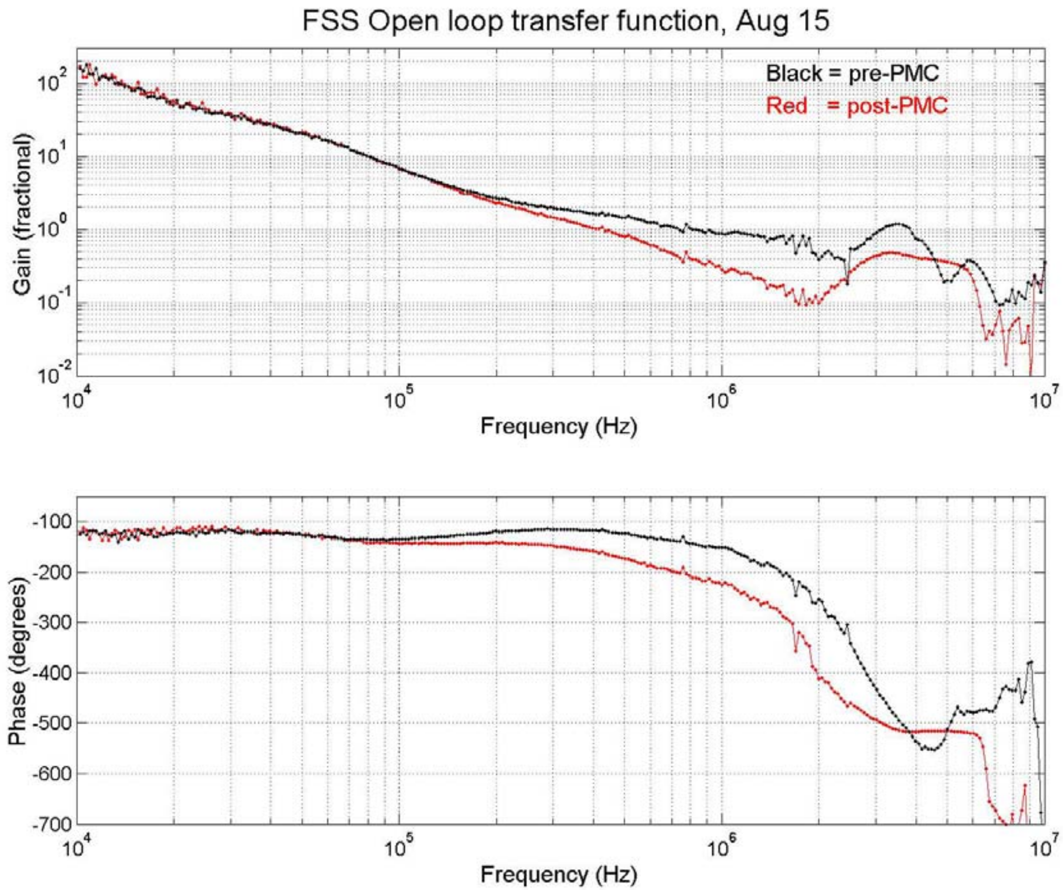
$$\frac{\nu_{out(a)}}{N_{PMC}} = \frac{A_{PMC} H_{PMC}}{1 + A_{PMC} L_{PMC}}$$

$$\frac{\nu_{out(b)}}{N_{PMC}} \approx \frac{A_{PMC} H_{PMC}}{(1 + A_{PMC})\underline{(1 - A_{RC} L_{RC})}}$$

- PMC noise with new PSL layout will be suppressed by a factor of FSS gain.
- PMC inside FSS will add a cavity pole for FSS.

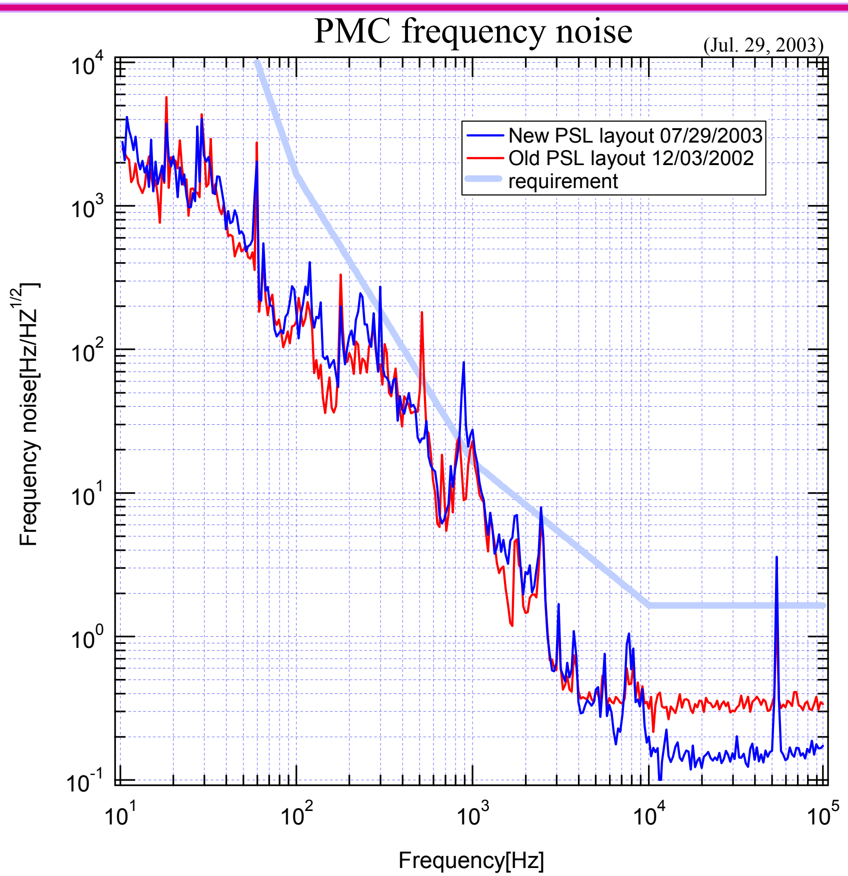
T030149-00-R Seiji Kawamura

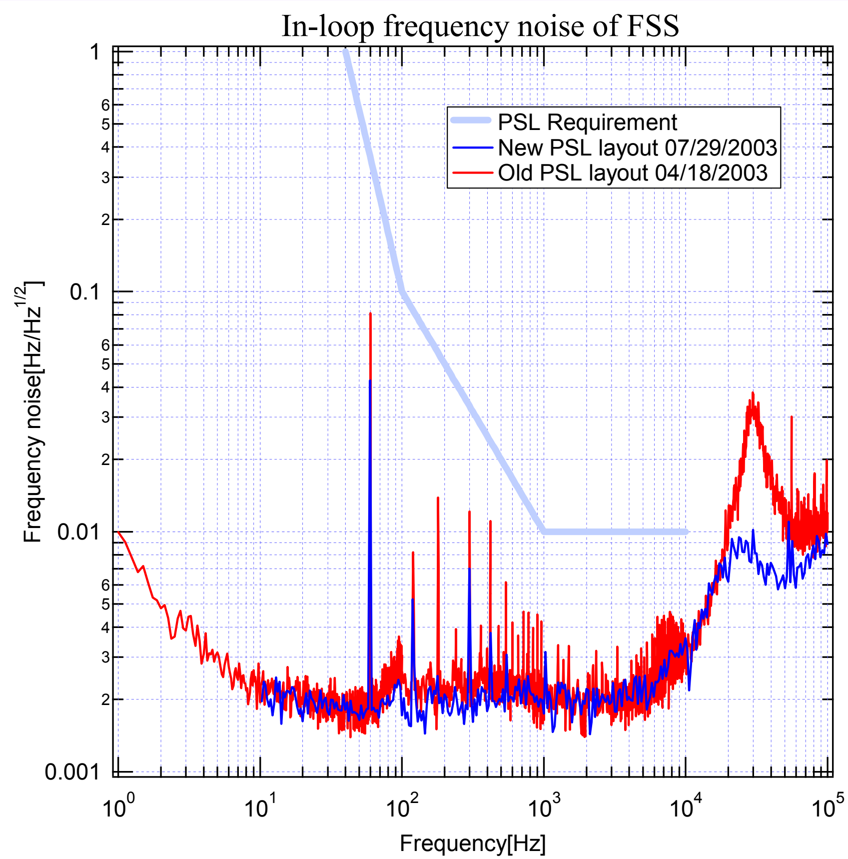
# Cavity pole of PMC show up in FSS open loop T.F




- Difference between red and black line is with and without PMC. Cavity pole of PMC was measured by another experiment and it was 330kHz.

# Noise performance

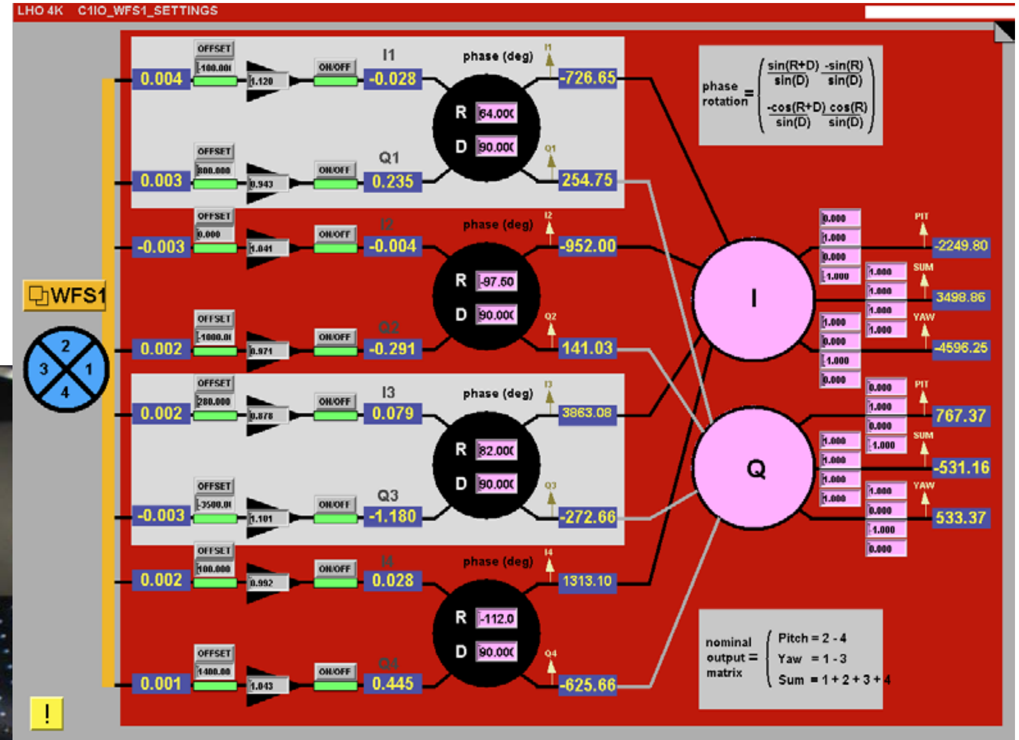


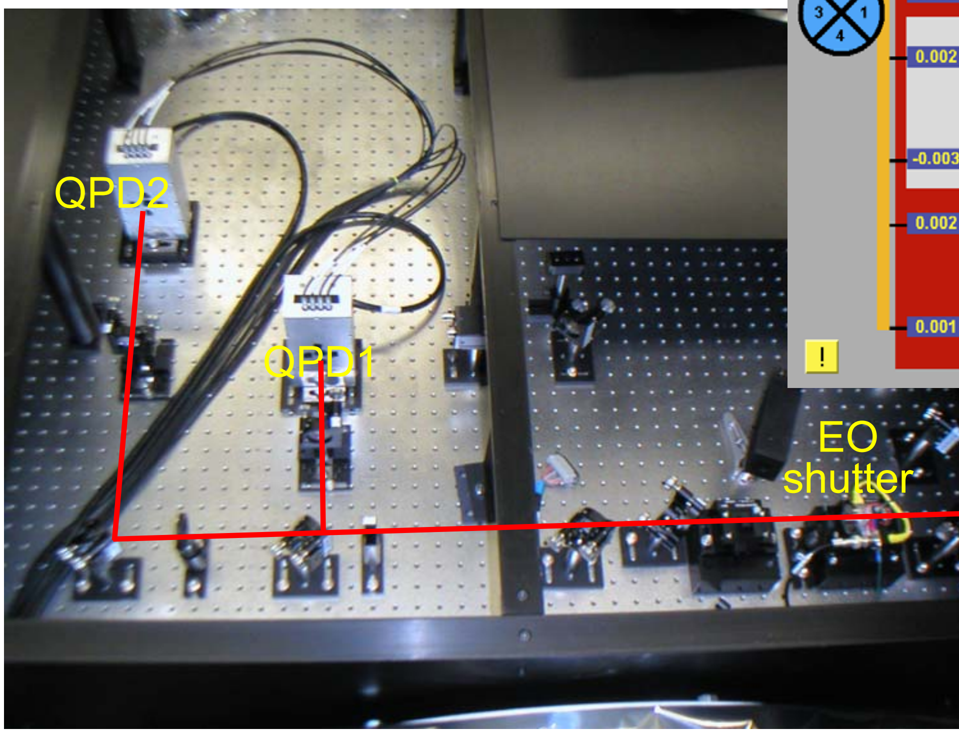




- Both PMC and FSS are essentially unchanged with respect to the re-layout configuration.
- True test for total frequency noise of PSL will come when we finish installation, pump down, and analyze the frequency noise with the mode cleaner.

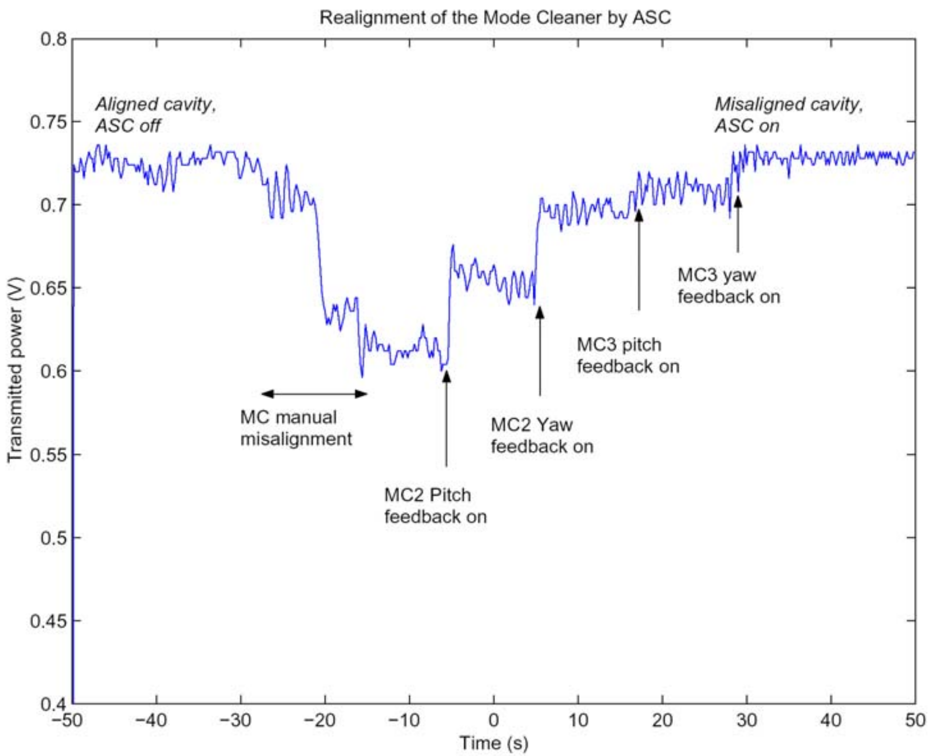
# Alignment sensing control for MC

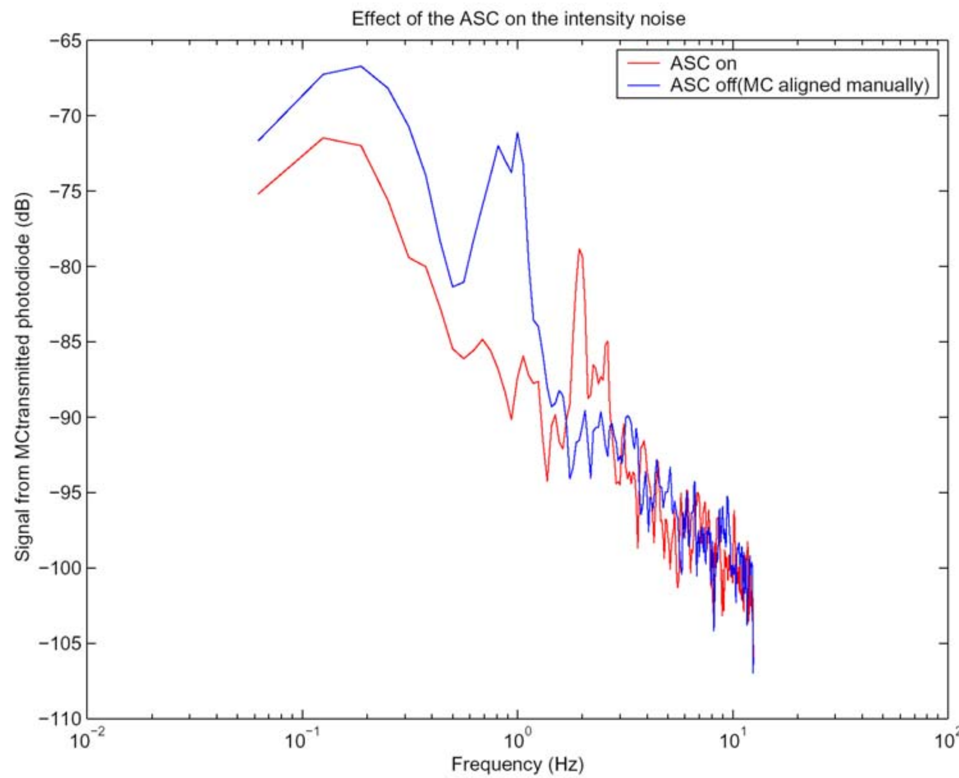
- WFS for MC was commissioned in June 2003.



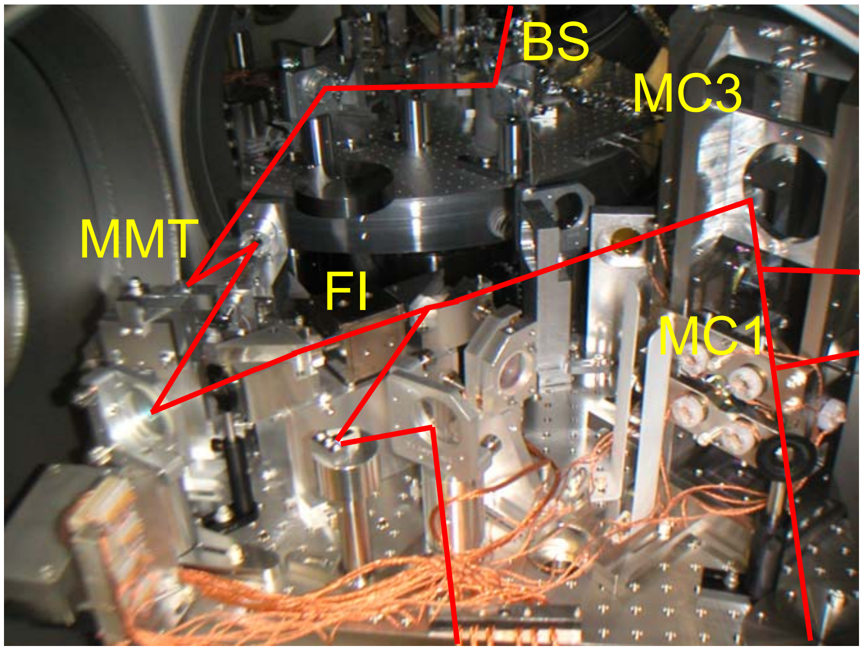



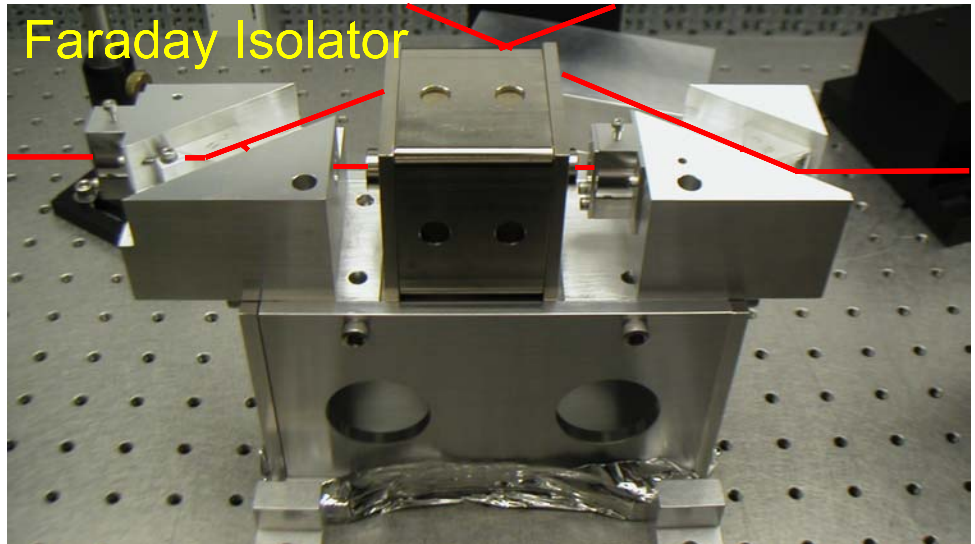
# Preliminary result of Alignment sensing control for MC

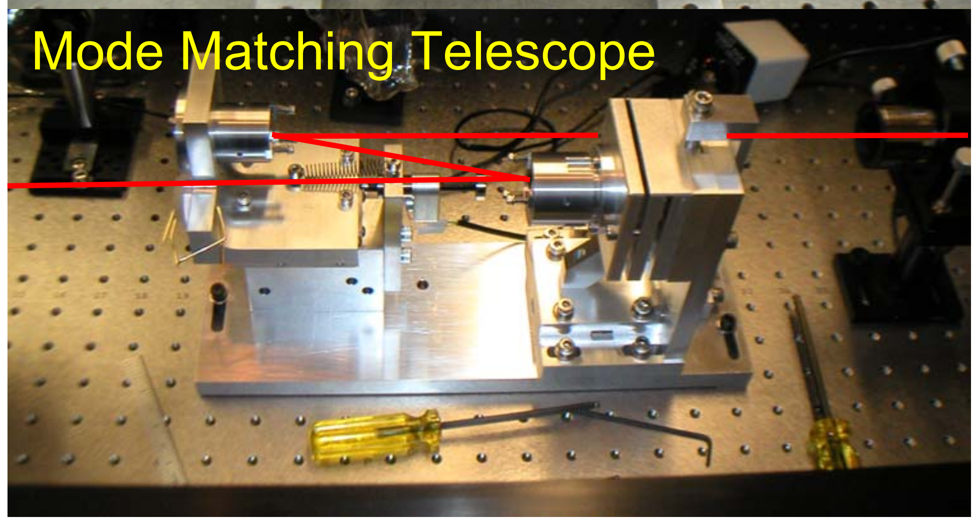


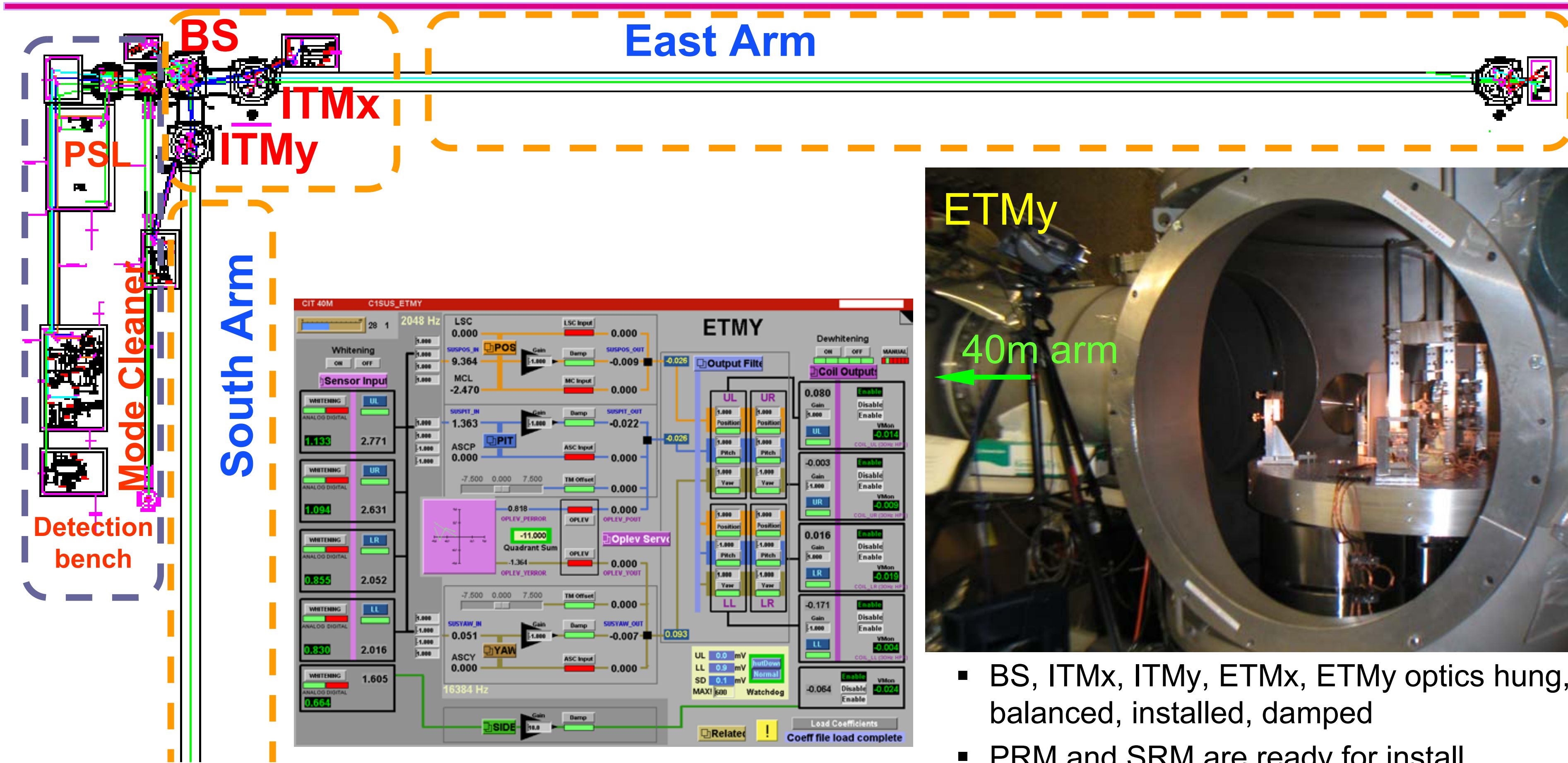
# In-vacuum Faraday Isolator and In-vacuum Mode Matching Telescope



# Core optics




- BS, ITMx, ITMy, ETMx, ETMy optics hung, balanced, installed, damped
- PRM and SRM are ready for install.
- Begin commissioning of the interferometer with 1 degree-of-freedom, short Michelson or Fabry-Perot arm.

Completed

Installing

# STACIS Active seismic isolation

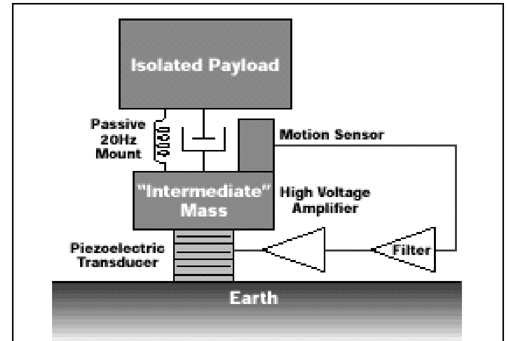
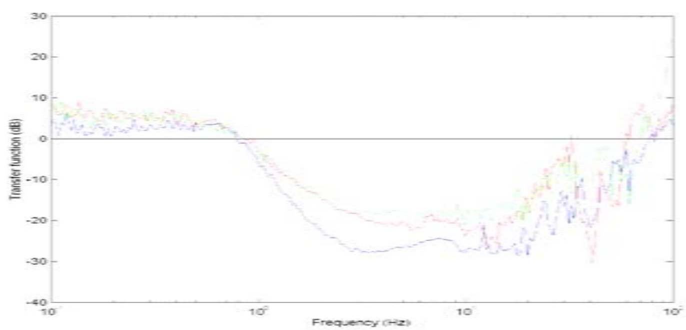
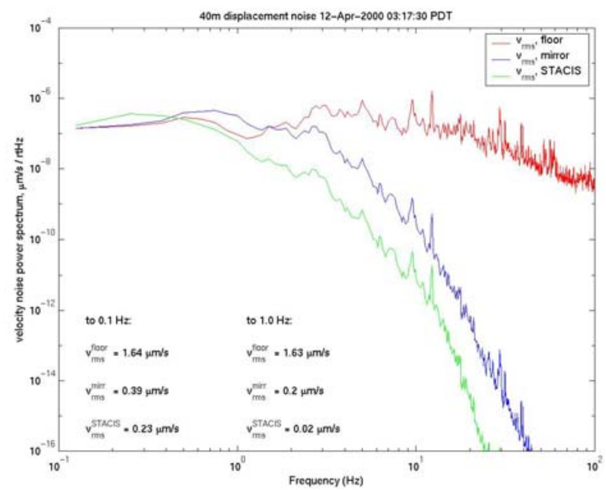


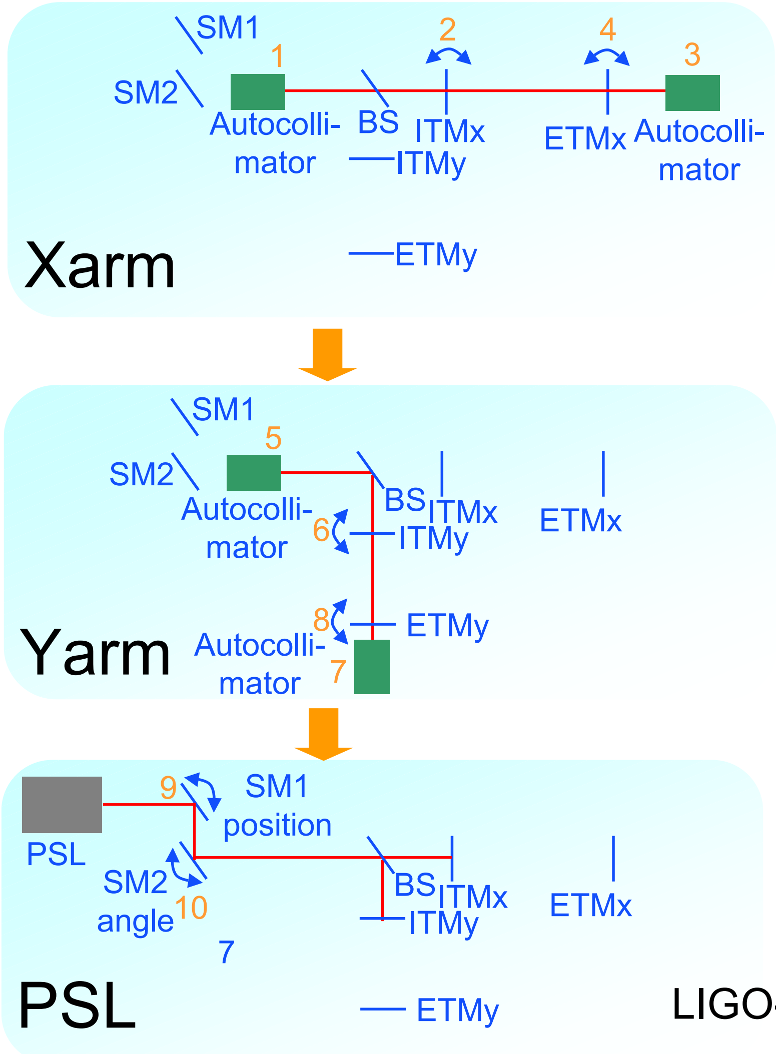

Figure 18

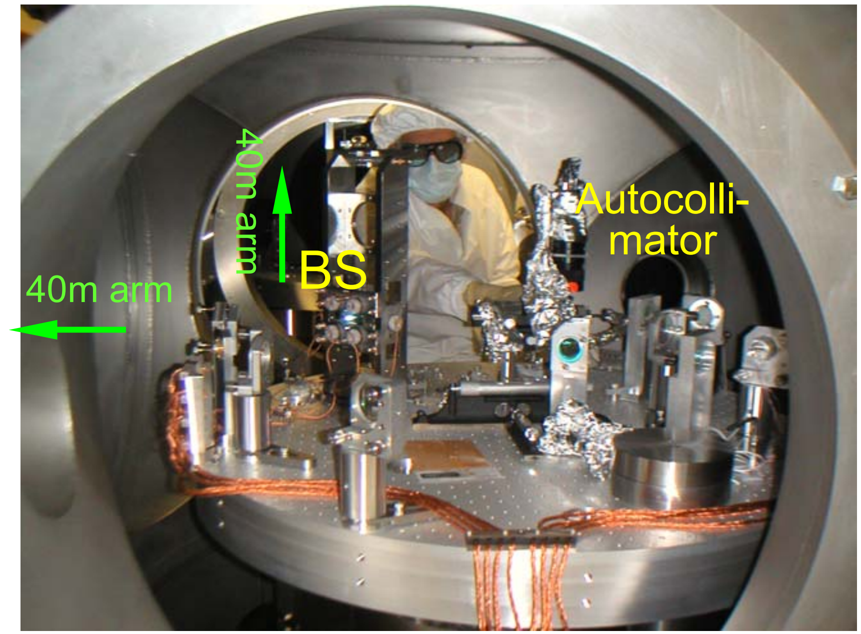
- One set of 3 for each of 4 test chambers
- 6-dof stiff PZT stack
- Active bandwidth of 0.3-100 Hz,
- 20-30dB of isolation
- passive isolation above 15 Hz.



# Alignment procedure using Autocollimator

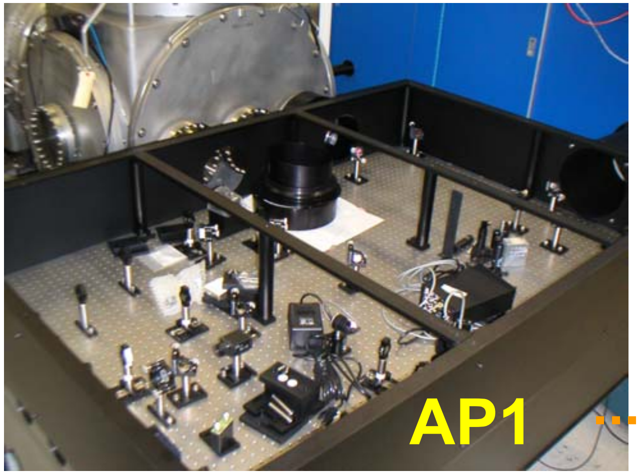



- Begin commissioning of the interferometer in stages, with simple sub-systems short Michelson, Fabry-Perot arms) by fall 2003.

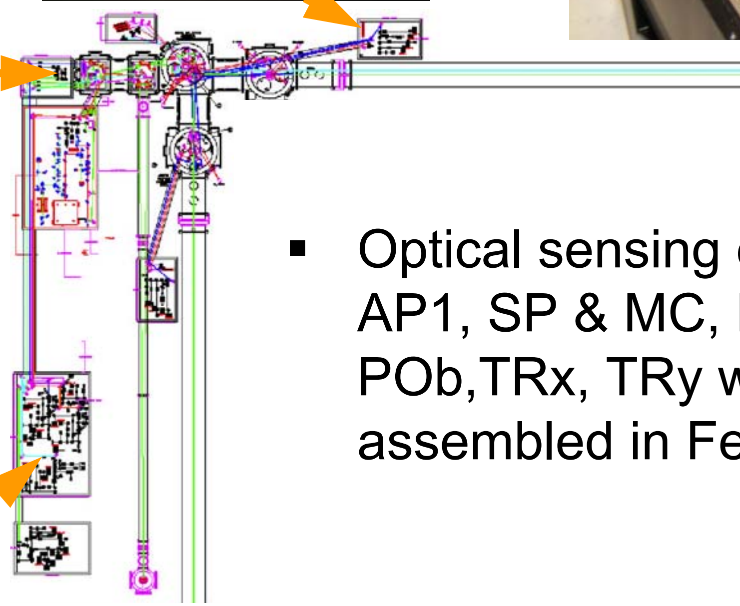
LIGO-T030141-00 Mike Smith

# Further Infrastructure



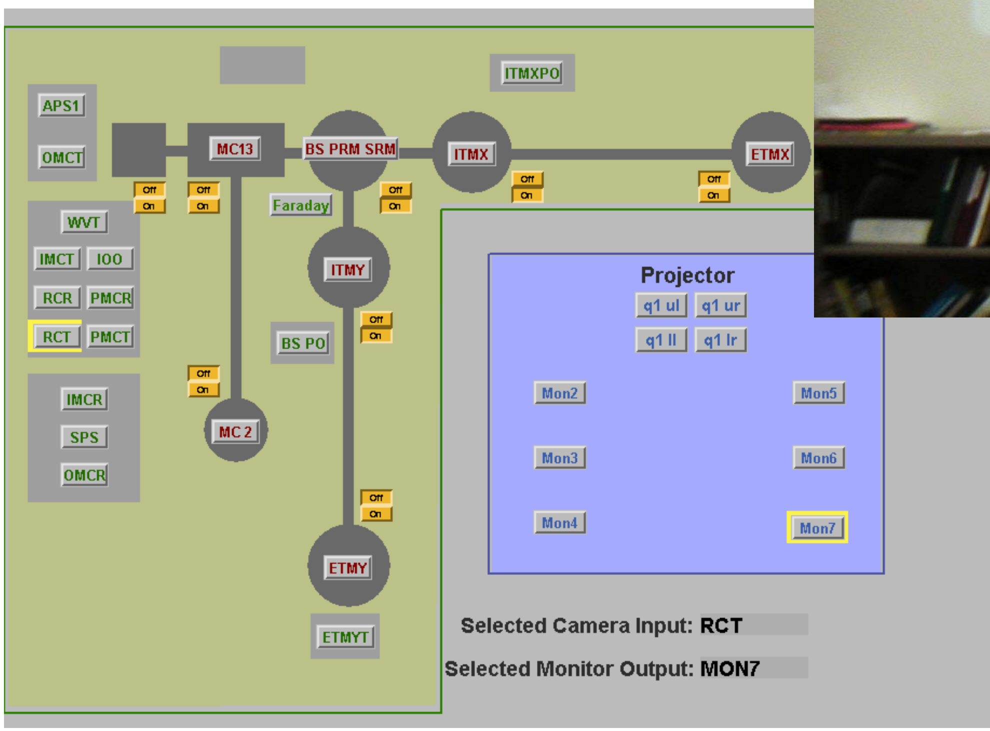




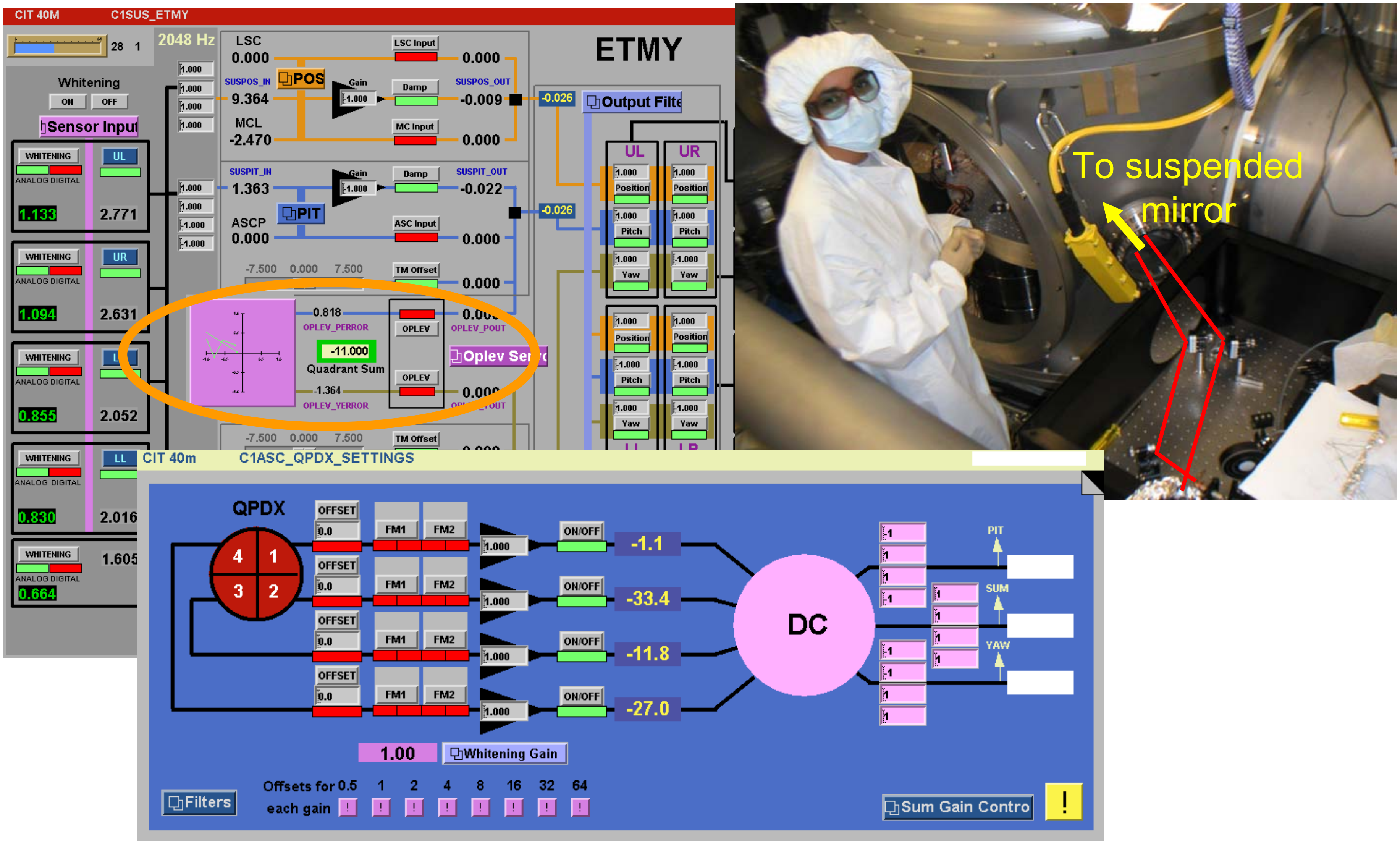


- Optical sensing equipments of AP1, SP & MC, Pox, POy, POb,TRx, TRy were assembled in February 2003.

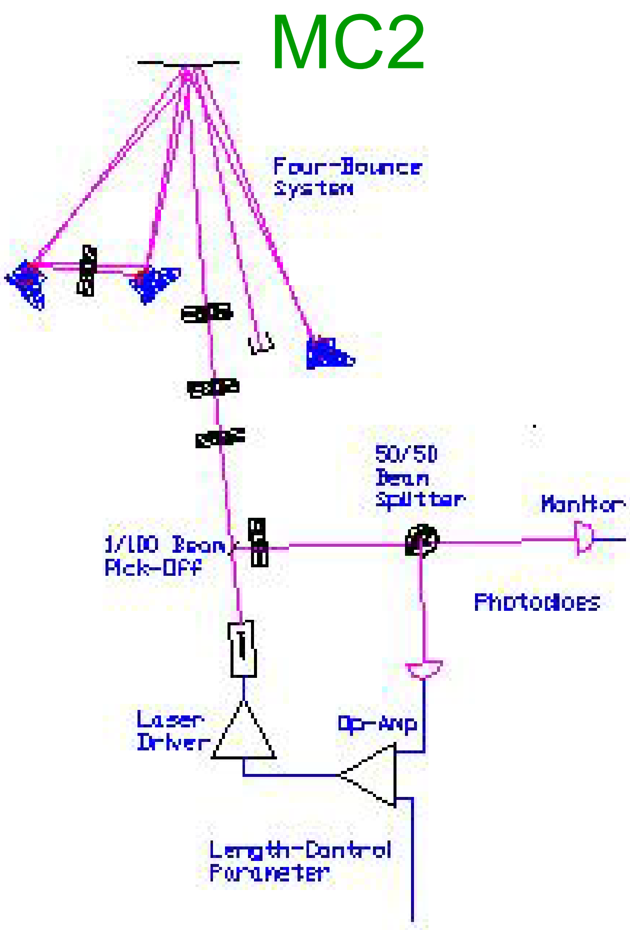
# Video monitor & Illuminator

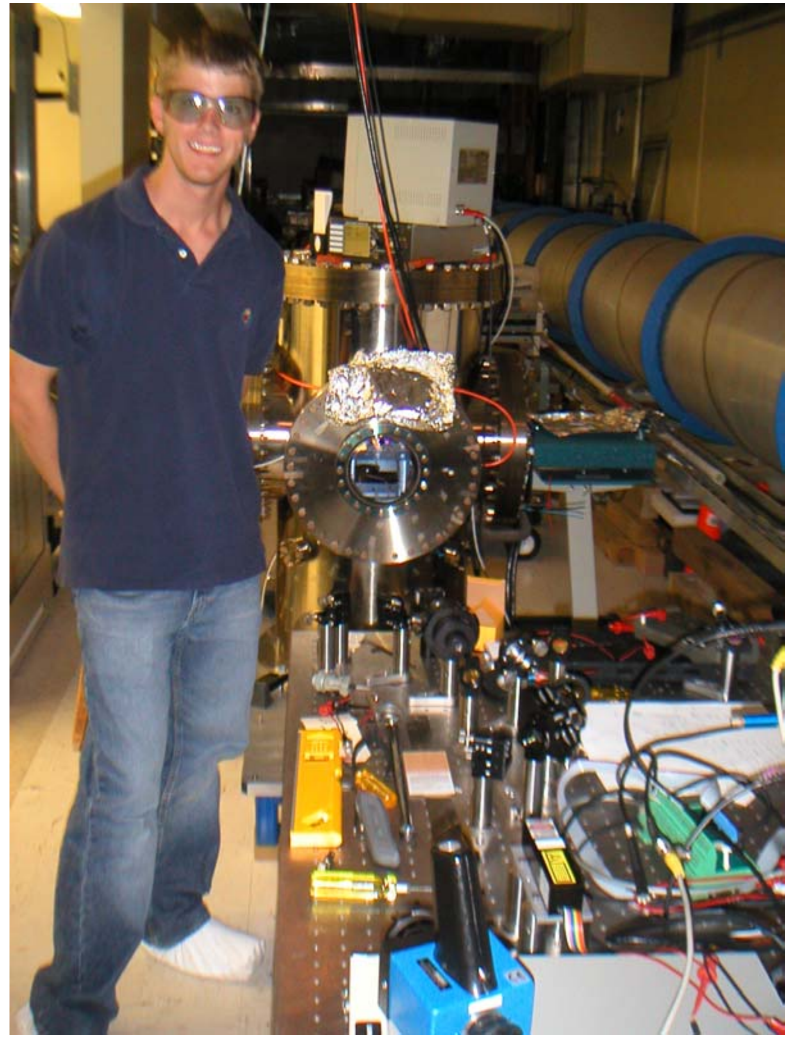



# Optical lever



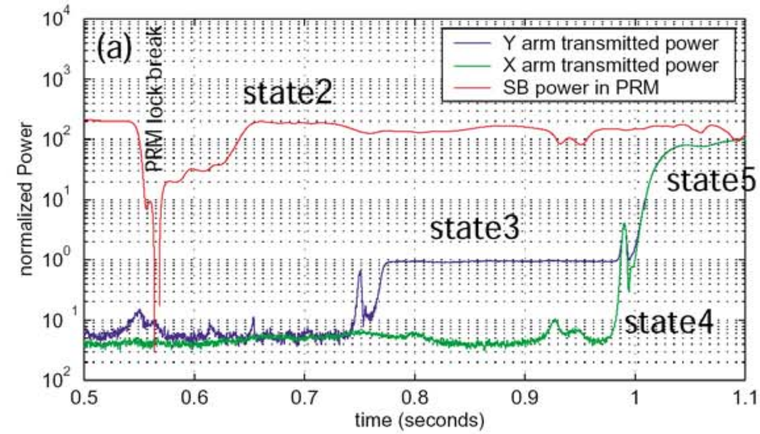
# Photon Actuator



# Lock acquisition real and simulated

Figure 1. LHO 2k IFO data




Arm powers are normalized by the power when one arm is locked.
SB power is normalized by the input SB power.

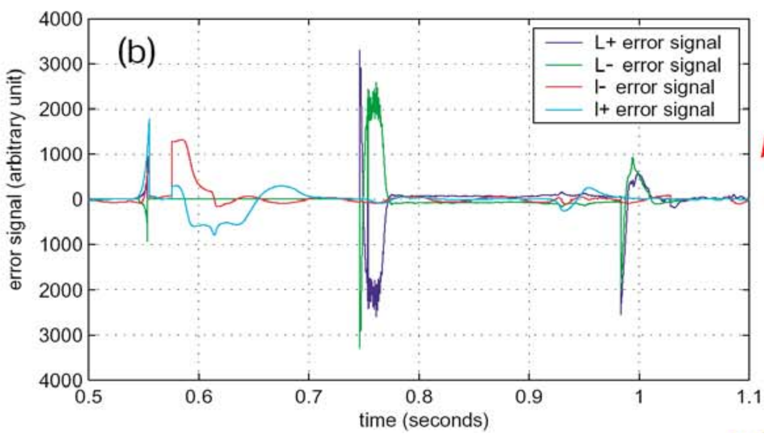
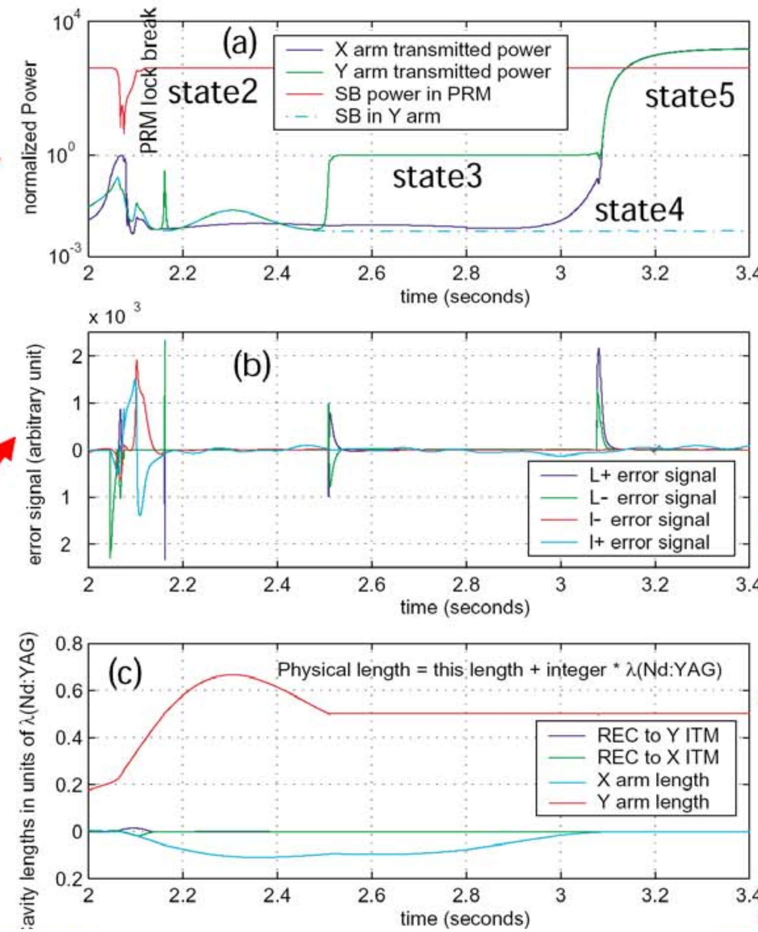



Figure 2. Simulated signal




observable

Not experimentally observable

40m and AdLIGO need similar model.

# Dual Recycling Summation cavity for End to End model

Calculation time is determined by shortest cavity (Michelson) length.

$$\tau = \frac{L_{\mathrm{arm}}}{c} >> \frac{l_{\mathrm{Mi}}}{c}$$

Calculating many time steps at once in Michelson part

➡ Summation cavity

$$\left.\begin{aligned} E(t) &= \mathbf{M}\cdot E(t-\tau) \\ &= \mathbf{M}^2 \cdot E(t-2\tau) \\ &\vdots \\ &= \mathbf{M}^N \cdot E(t-N\tau) \end{aligned}\right\}$$

N step

⬇

1 step

$$N = \frac{L_{\mathrm{arm}}}{l_{\mathrm{MI}}}$$

$$\mathbf{M} = \mathbf{M}_0 + \delta\mathbf{M}$$

$\mathbf{M}$ : matrix for DR summation cavity

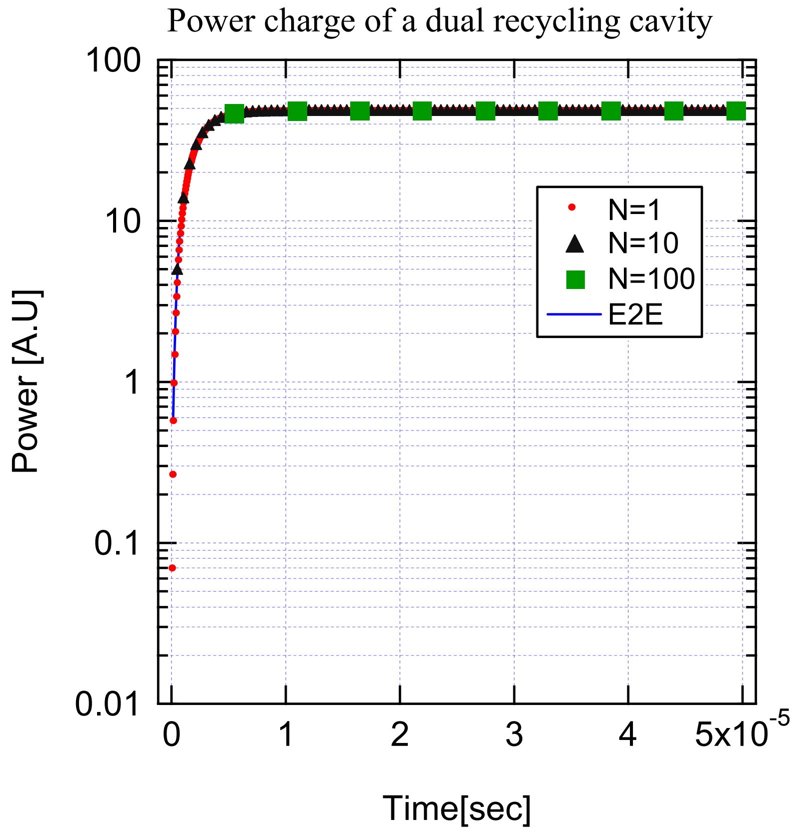
$$\mathbf{M}_0 \cdot \delta\mathbf{M} \neq \delta\mathbf{M} \cdot \mathbf{M}_0$$

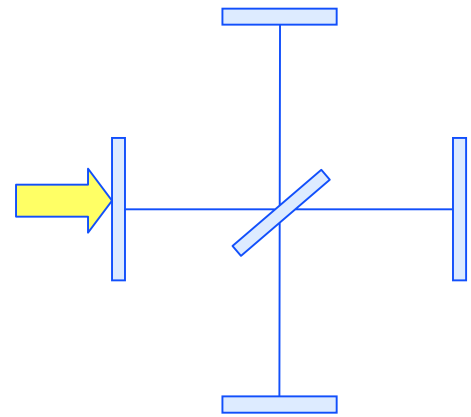
$\mathbf{M}$ : scalar for PR summation cavity

$$\mathbf{M}_0 \cdot \delta\mathbf{M} = \delta\mathbf{M} \cdot \mathbf{M}_0$$

- 400 times faster for LIGO
- 40 times faster for 40meter

# Preliminary result on Matlab



Velocities of all mirrors = 0

- Bright port side (E1) power build up can be seen
- Same result as E2E calculation
- When Iteration number N goes bigger, interval goes larger (~N)
- Total simulation time becomes shorter (~1/N)

# Next 9 months

- Fabrication and commissioning of the auxiliary optics systems: scattered light control, initial alignment system, optical levers, video monitoring, all will be done in next month.
- Fabricate and install LIGO I-like length sensing and control system.
- Begin commissioning of the interferometer in stages, with simple sub-systems short Michelson, Fabry-Perot arms) by fall 2003.
- Continue development of the E2E simulation, and refine lock acquisition procedure and controls plant design based on lessons learned.
- Begin commissioning the full dual-recycled Fabry-Perot Michelson, by this winter. Measure transfer functions, interferometer response, and noise.
- Fabricate and install wavefront-sensing-based alignment sensing and control system for the main interferometer.

# Milestones revisited

- 2Q 2002:
  - » All in-vacuum cables, feedthroughs, viewports, seismic stacks installed. Done
  - » 13m input MC optics and suspensions, and suspension controllers. Done
- 3Q 2002:
  - » Begin commissioning of 13m input mode cleaner. Done
  - » Acquisition of most of CDS, ISC, LSC, ASC. Done
- 4Q 2002:
  - » Core optics (early) and suspensions ready. Ten Suspension controllers. Some ISC. Done
  - » Glasgow 10m experiment informs 40m program In progress
  - » Control system finalized In progress
- 2Q 2003:
  - » Core optics (late) and suspensions ready. Done
  - » auxiliary optics, IFO sensing and control systems assembled. In progress
- 3Q 2003: Core subsystems commissioned, begin experiments
  - » Lock acquisition with all 5 length dof's, 2x6 angular dof's
  - » measure transfer functions, noise
  - » Inform CDS of required modifications
- 3Q 2004: Next round of experiments.
  - » DC readout. Multiple pendulum suspensions?
  - » Final report to LIGO Lab.

# (Some) outstanding issues and action items (40m, AdvLIGO)

- Any significant changes in people's thinking re: optical configuration, controls, CDS architecture??
- 166 MHz PD's for WFS, LSC. Double demodulation(166 ⊕ 33 MHz).
- Model of 40m and AdvLIGO with FINESSE. Develop servo lock acquisition strategies.
- Design servo filters for LSC, ASC
- Detailed noise model (RSENOISE, Jim Mason)
- Lock acquisition studies with E2E/DRLIGO. Develop lock acquisition algorithms, software.
- Output mode cleaner – will PSL-PMC-like device be adequate? (For 40m, for AdvLIGO). Suspended?
- Offset-lock arms - algorithms, software.
- DC GW PD – in vacuum? Suspended?

We expect that LSC members, as well as students, will participate in this most interesting phase of the project.