Visiting LIGO 40m and LHO

Koji Arai

National Astronomical Observatory of Japan

2008-Sept-5

Overview

Visiting LIGO (2008/6/16-2008/8/18)

- Caltech 40m Lab (2W)
- LIGO Hanford Observatory (3W)
- Caltech 40m Lab (4W)

- Official purpose of the visit

Come and do anything you like (Rana)

- Personal purpose

To be a witness of LIGO technologies

Works at LHO/40m

- **LIGO Hanford**

  Enhanced LIGO installation / shakedown

  Replaced the laser to 35W PSL.
  Noise got worse ~ x100

  => Task: Restore the noise level to reasonable level

- **Caltech 40m Lab**

  Development of advanced techniques

  => Task: Precise measurement of cavity mode spacings

LHO: Activities

- LIGO Hanford
  - **H1 Enhanced LIGO installation / shakedown**
    - 35W laser
    - OMC & DC Readout scheme
    - New TCS
    - SmCo magnets (against Barkhausen noise)
  - **H2 Astrowatch**
    - LSC students on shifts
  - **@LHO**
    - Laser: replaced the laser to 35W PSL
    - Noise: got worse ~ x100 => Task: Noise hunting

- LIGO H1 IFO team
  - **Osamu Mitakawa / Matt Evans / Koji Arai**
  - **Keita Kawabe / Nick Smith (GS)**
  - \+ many engneers/operators/technitians

LHO: H1 noise

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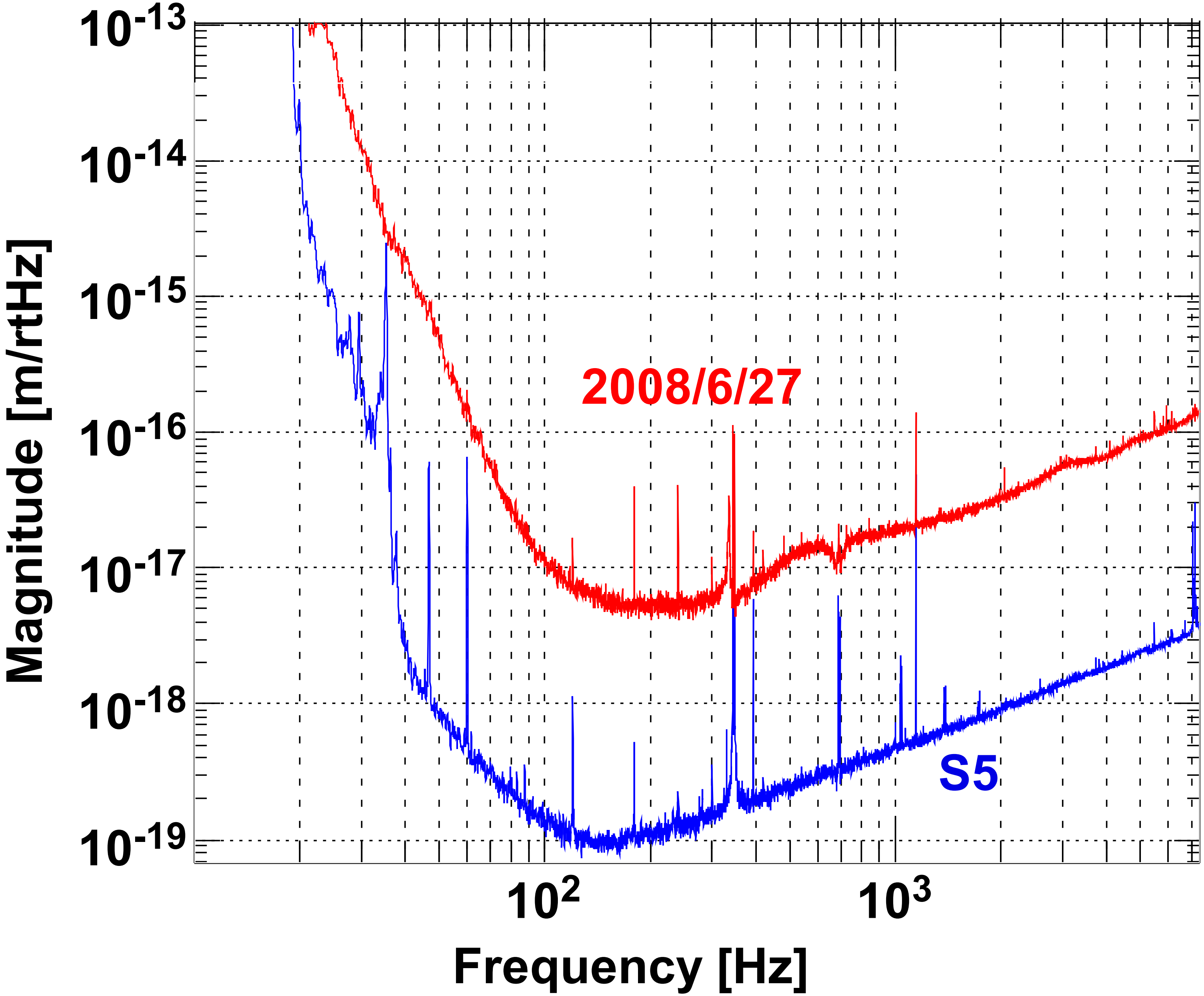
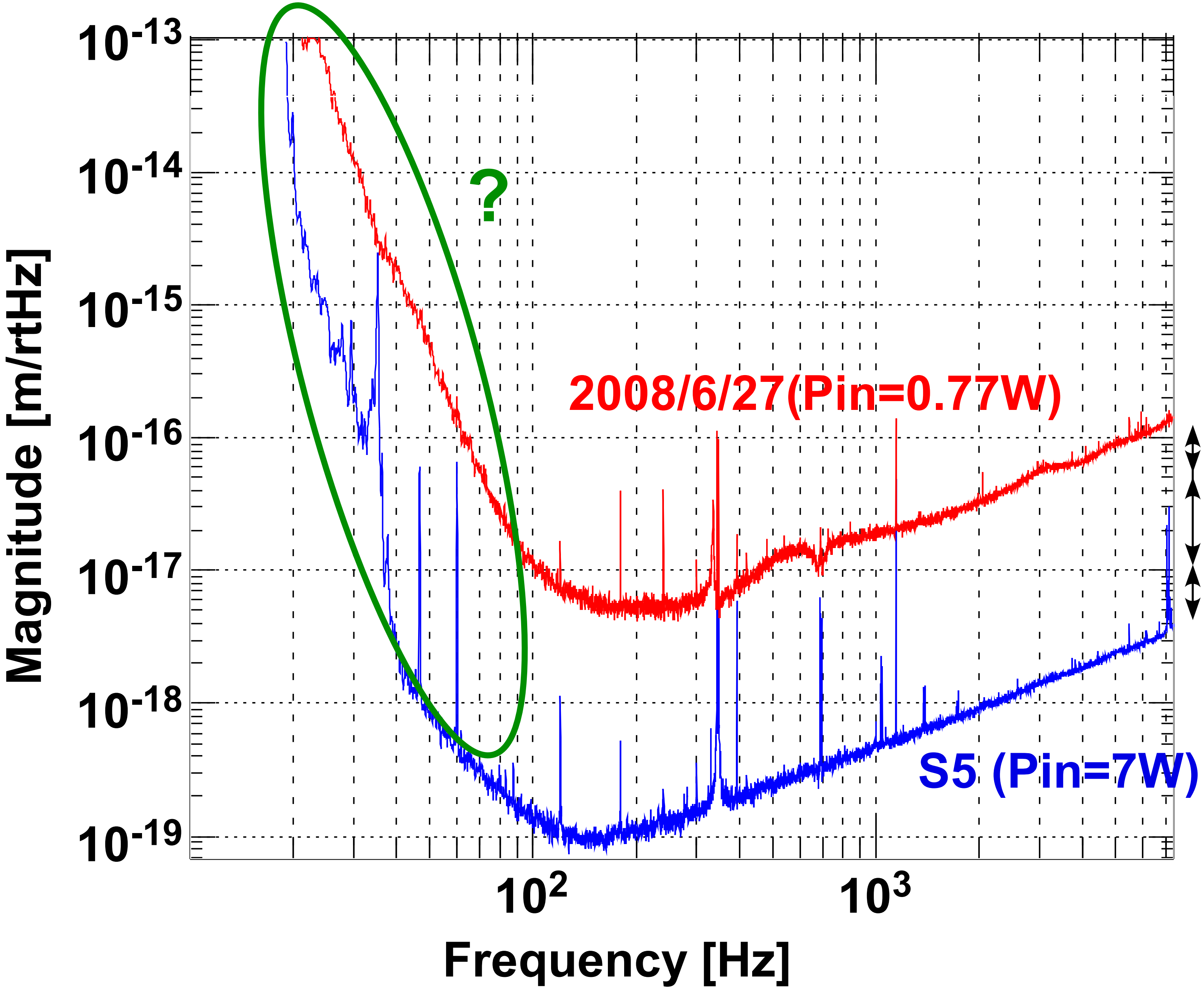


LHO: H1 noise



calib error x 2.27

weaker magnet x1.1

shot noise x4.6
smaller power
1/2 by a BS
0.8/0.95 additional loss

dark noise x 2.6

LHO: Low freq noise

- **TCS removed => lower power**
  Causes...
  MICH(dl-)/PRC(dl+) lower S/N
    - **Saturation in the actuation**
    - **ADC noise (whitening gain)**

  DARM(dL-) whitening

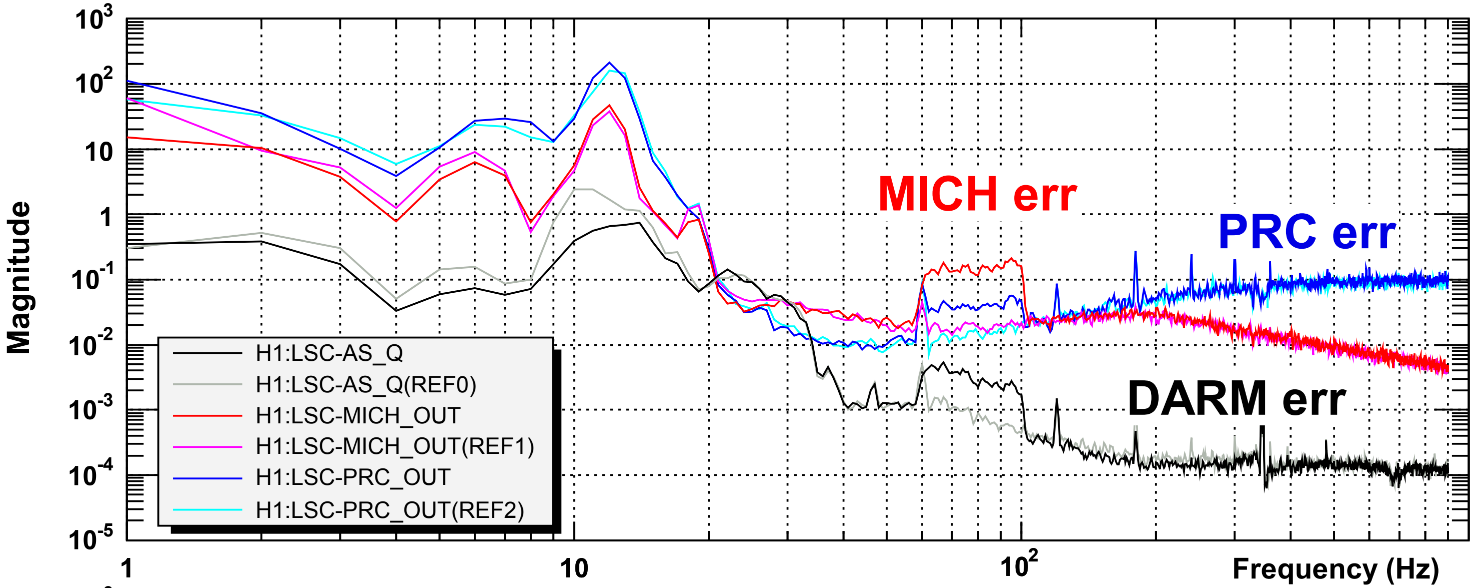
- **MICH/PRC->DARM couplingow power**
  Tuning of the compensation (feedforward) path
    - **band limited noise injection**
    - **super fine tuning of compensation TF**

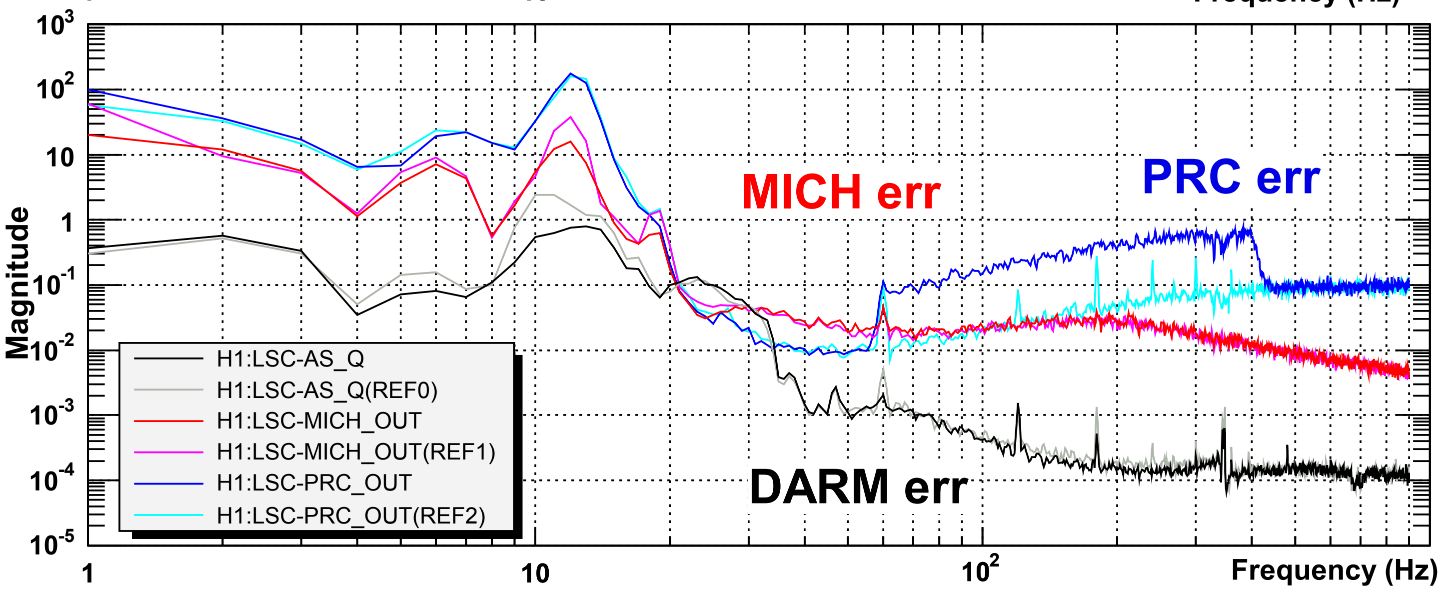
- **A2L (angle to length) coupling**
    - **=actuator balance tuning**

LHO: MICH/PRC compensation

● Band limited noise injection

noise estimation ~ beyond linear coupling

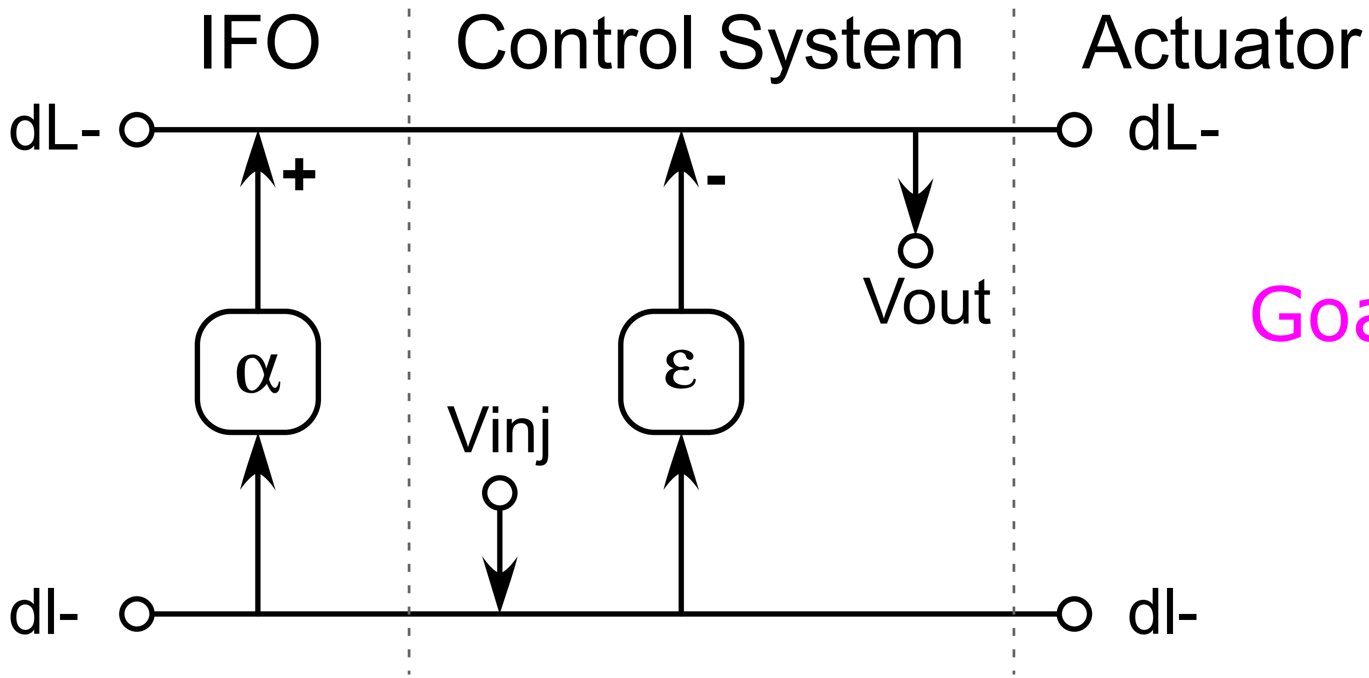




Injection settings can be stored anyone can reproduce it

LHO: MICH/PRC compensation

How to decide compensation path TF?



Goal: $\varepsilon=\alpha$

Trial $\varepsilon=\varepsilon_0$: $\quad Vout = dL- + \alpha\, dl- + \varepsilon_0\, dl-$ => $\quad Vinj/Vout = \alpha - \varepsilon_0 = \delta\varepsilon$

New $\varepsilon=\varepsilon_0\varepsilon_1$, $\varepsilon_1=(\varepsilon_0+\delta\varepsilon)/\varepsilon_0$:

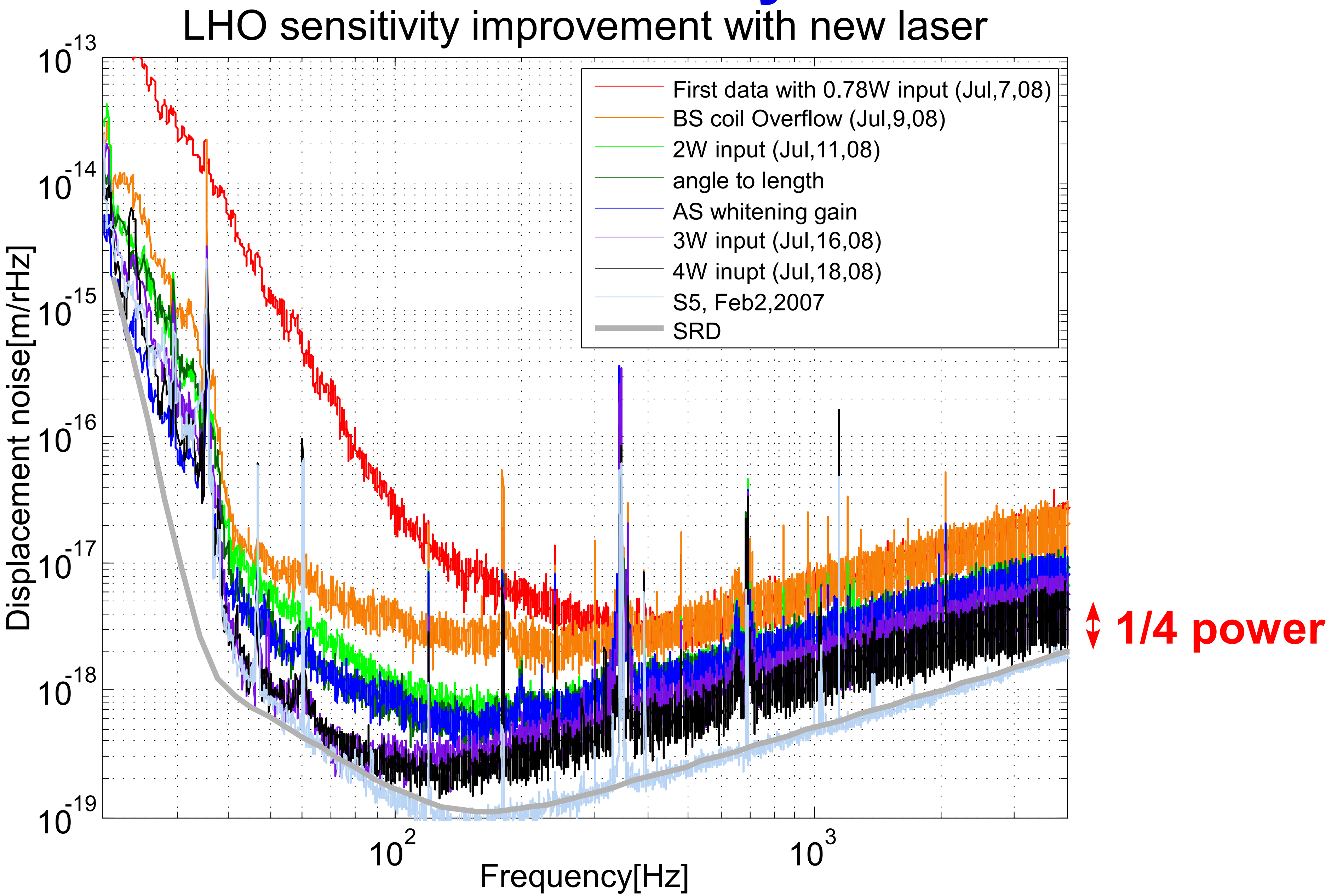
$$Vout = dL- + \alpha\, dl- + \varepsilon_0\varepsilon_1\, dl-$$

$$Vout = dL- + 0$$

ε_1 is very small correction, which can not be measured directly without first trial ε_0

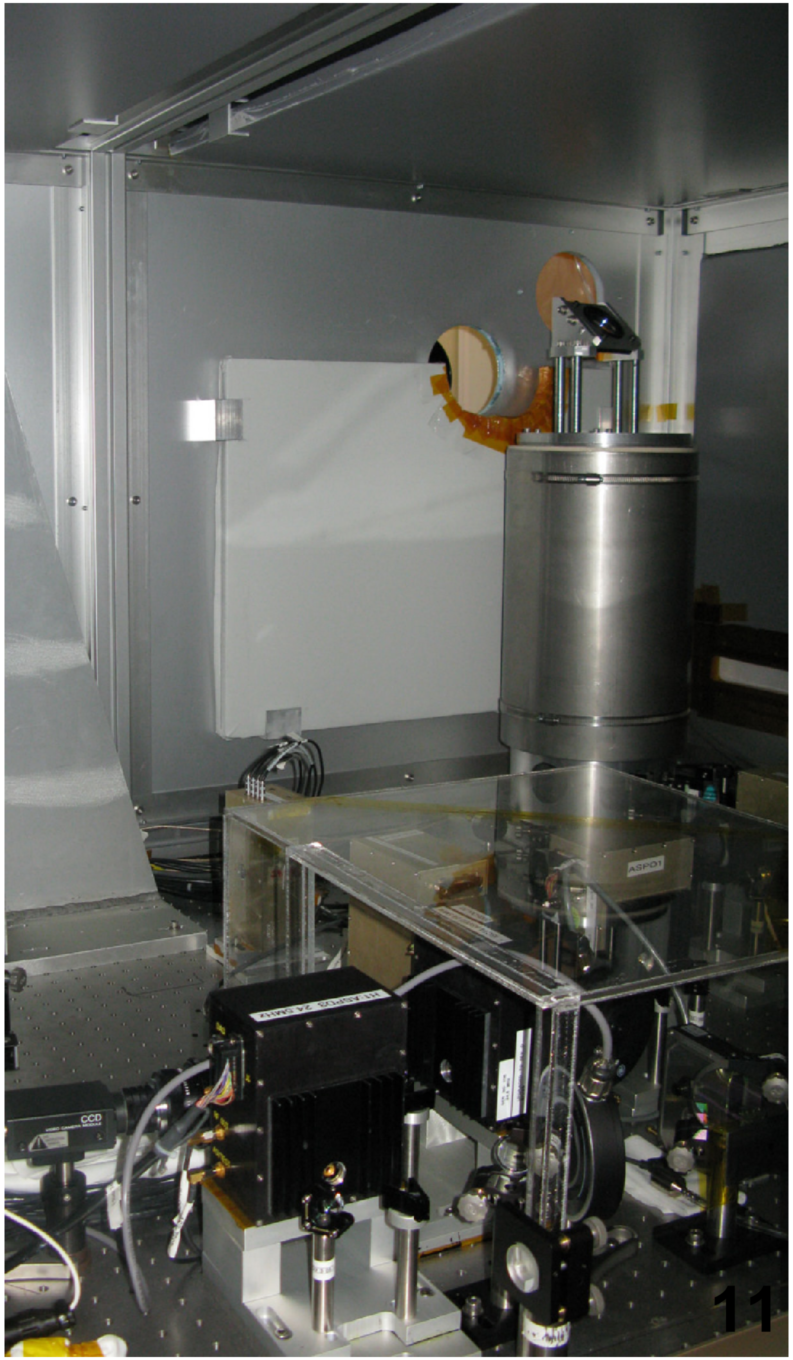
LHO: After the work

● S5 level was essentially recovered



LHO: Dark port

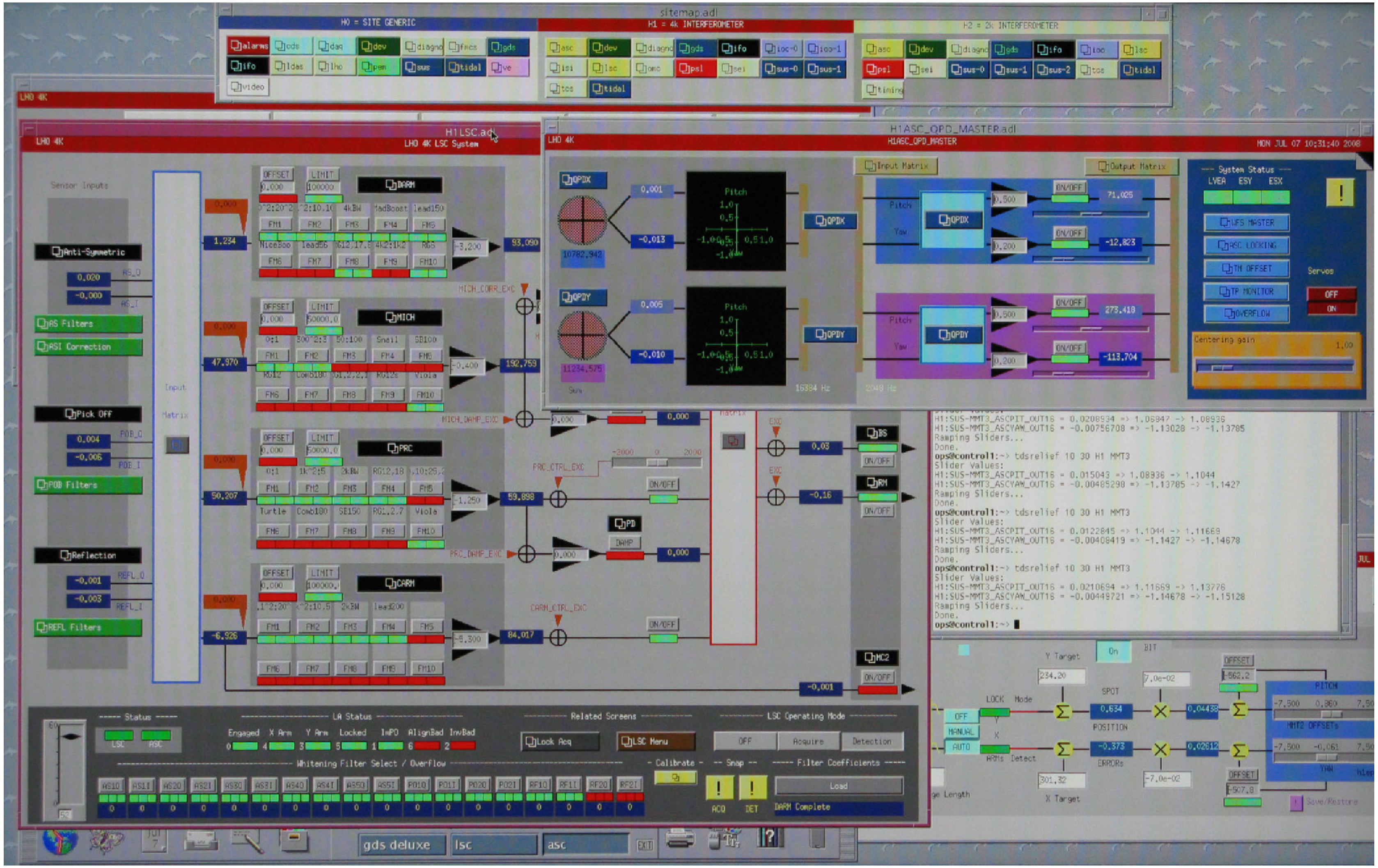
- **Acoustic shield room**
  + shield box + stiff periscope
  + dust cover



LHO: Digital control

● ... is not for everyone

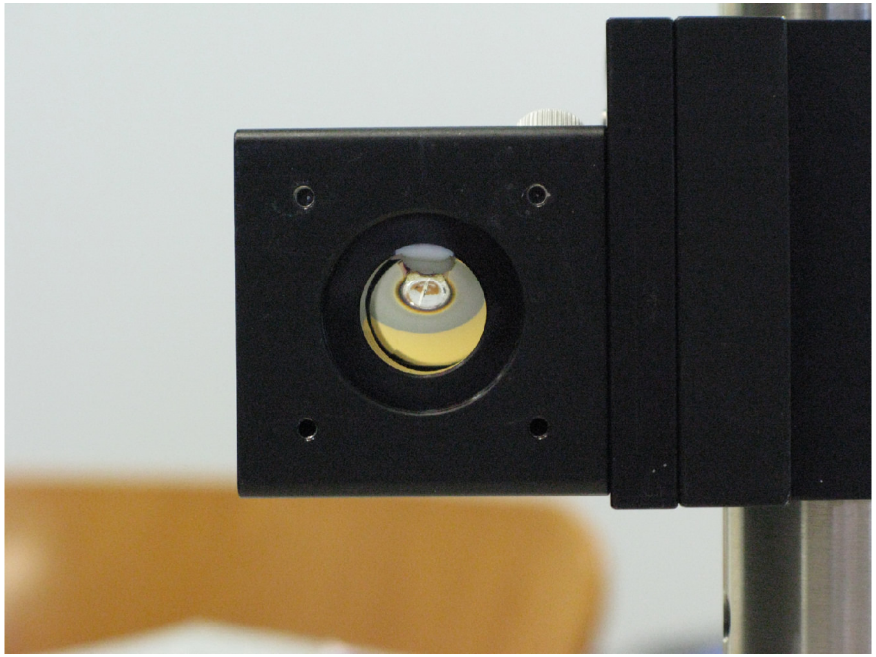
but for experts to concentrate on the top topics



LHO: new TCS and H2 Grec

● 20W CO_2 laser

treatment is not straight foward
steering mirror melt...



● Recent news from H2

Drag wiping of the test masses
=> Increase recycling gain to 80 (!)

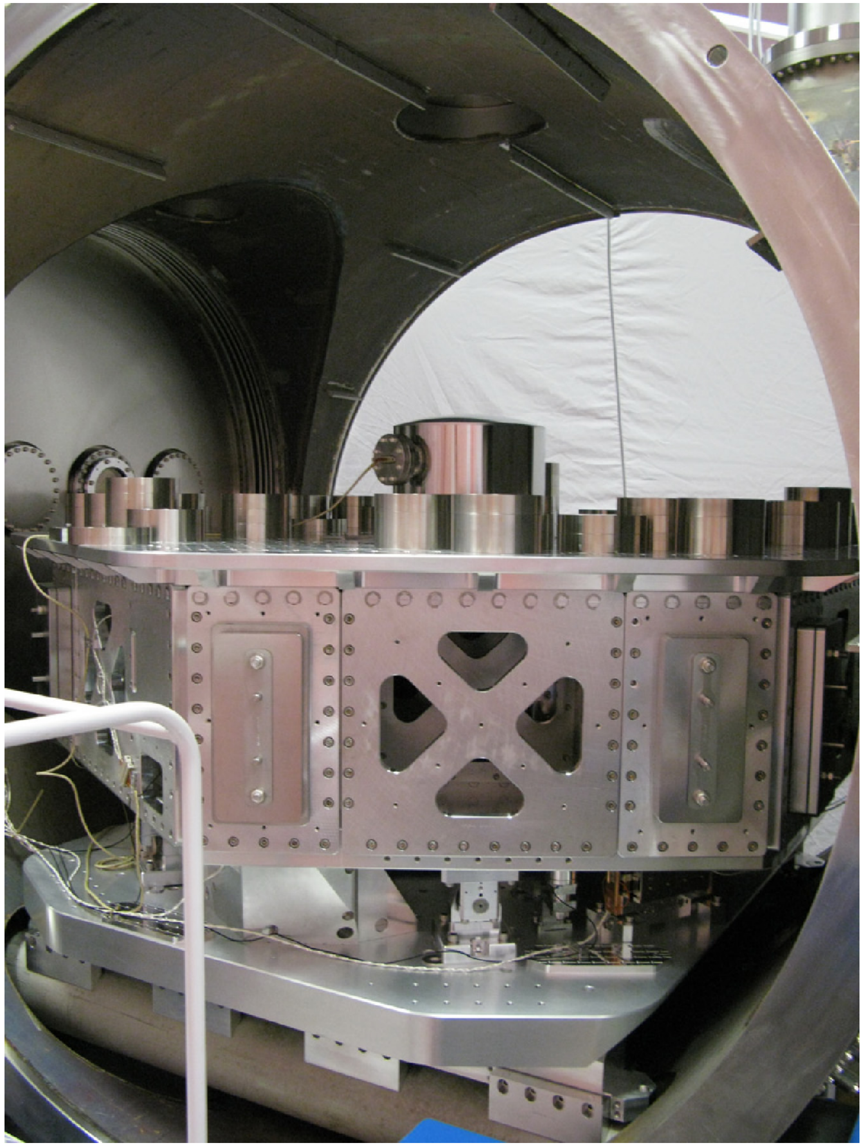
LHO: Vac work / ISI

● Opening HAM chamber

Super technique of the fork!

● ISI: replacement of stacks

Testing at the detection chamber



LHO: Optical lever

- **Opt levs need to be standing on the ground** for stability.

Laser:
fiber coupled.
670nm

Caltech 40m

- **Caltech 40m Lab**
  - Development of advanced techniques
    - RSE / OMC / DC Readout
    - Advanced LIGO
    - Adaptive FIR feedforwarding

    => Task: Precise measurement of cavity mode spacings

- **Mode spacing teams**
  - Koji Arai / Alberto Stochino (GS)
  - Rana Adhikari / John Miller (GS) / Yoichi Aso

Overview

- **Mode spacings of an optical cavity**
  - **Londitudinal mode spacing** (FSR: Free Spectral Range)
    Determined by **the abusolute length** of the cavity
  - **Transverse mode spacing**
    Depends on **the radius of the curvature** of the cavity mirrors

- **Measurement of lond. and trans. mode spacings**
  - **With one of the LIGO 40m arm cavities**
  - **Using auxiliary laser, being injected from the dark port**
  - **RF beating detection at the cavity transmission**

- **Result**
  - **Londitudinal mode spacing & cavity length:**
    ν_{FSR} = 3878678 +/- 30 [Hz] => L = 38.6462 +/- 0.0003 [m]
  - **Transverse mode spacing & mirror cavatures (flat-concave cavity):**
    $\delta\nu_{TEM10}$ = 1207788 +/- 22 [Hz] => R_H = 56.1620 +/- 0.0013 [m]
    $\delta\nu_{TEM01}$ = 1189070 +/- 17 [Hz] => R_V = 57.3395 +/- 0.0011 [m]

Motivation

Importance to know mode spacings of cavities

- Precise modelling of optical configurations
- Precise diagnosis of existing optical systems

- Longitudinal mode spacing
    - o Precise adjustment of an optical system according to a design
    - o Characterizing phase shift of laser light in a coupled cavity system

- Transverse mode spacing
    - o Characterizing structures of higher order modes
    - o Diagnoses of metrological qualities of optics

Motivation

Typical application in interferometer GW detectors

- To determine how much suspensions should be moved in terms of the optical design

- To know how much phase shift modulation sidebands acquire at a non-resonant reflection by a cavity

- To avoid higer-order mode resonance at the carrier frequency

- To measure polishing quality

- To measure thermal lensing effect

Requirement

- **Method for the mode spacings of 1~100-m scale cavities**
  => mode spacings of about 1~100MHz

  - For shorter cavity (~10cm)
  cavity scanning would give a good measurement

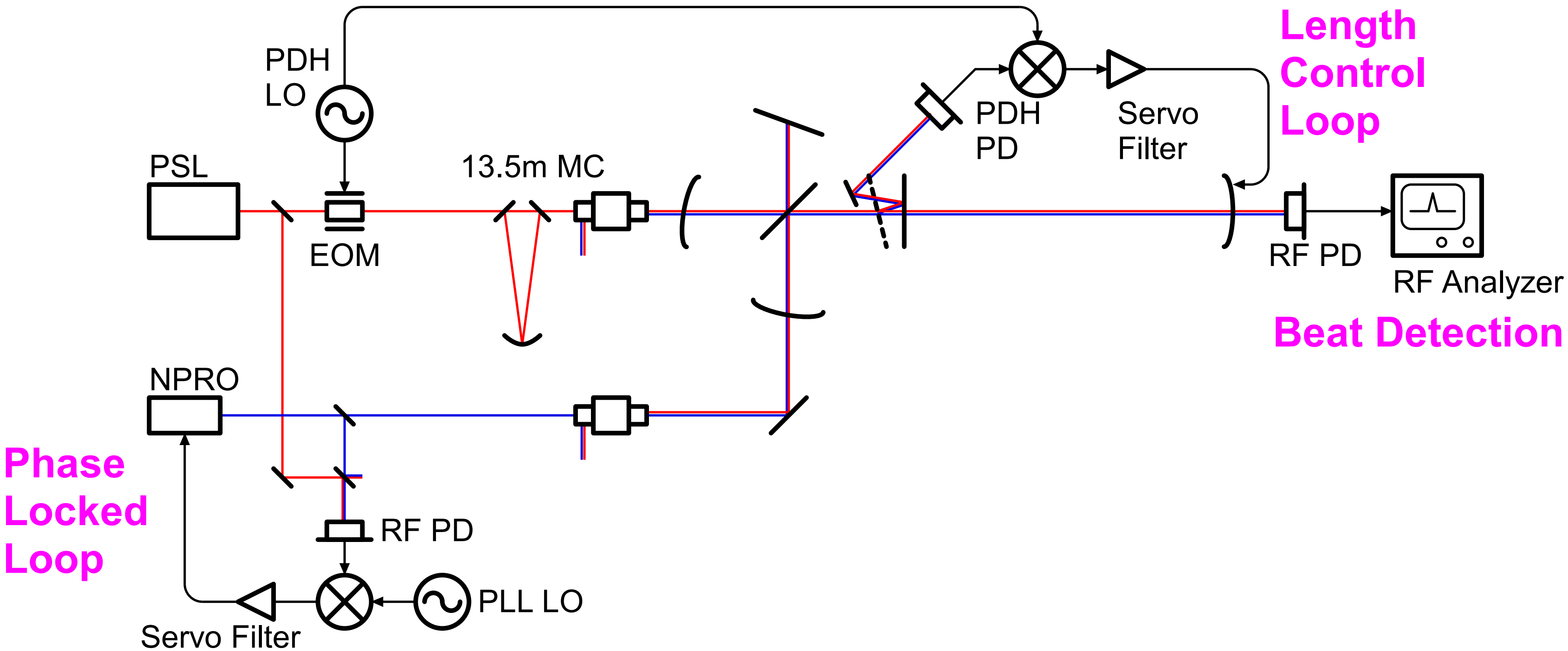
  - For longer cavity (100m~)
  frequency modulation (even through a mode cleaner)
  would provide a measurement of the cavity response

- **Precision of better than 10^{-4}**
  => Cavity length / radius of curvature in ~1mm
  => mode spacings with precision of ~100Hz

- **Applicable for an existing complex optical system**
  => Testing at the LIGO 40m interfeormeter
  => Preffered to be comptible with the LIGO 4km/2km interferometers

Method

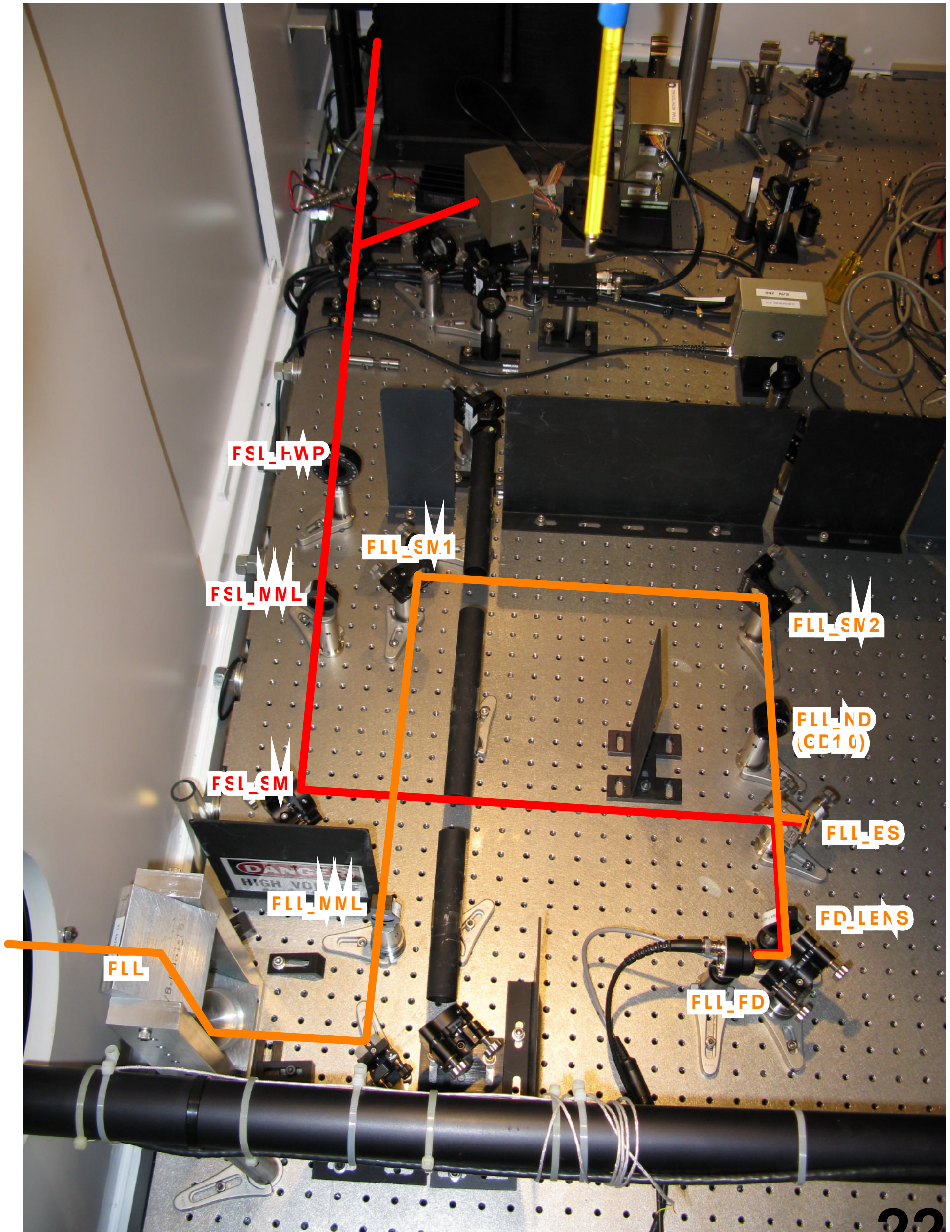
- **Resonate two laser beams to the cavity simultaneously**
  - **- Main beam and the aux. beam injected from the dark port**
  - **- Frequency difference of the two beams:** stabilized by PLL servo
  - **- Beating appears at the cavity transmission**
    only at the resonance of the aux. beam
  - **- The mode spacings are directly read**
    from the LO freq. of the PLL at the max transmission of the mode



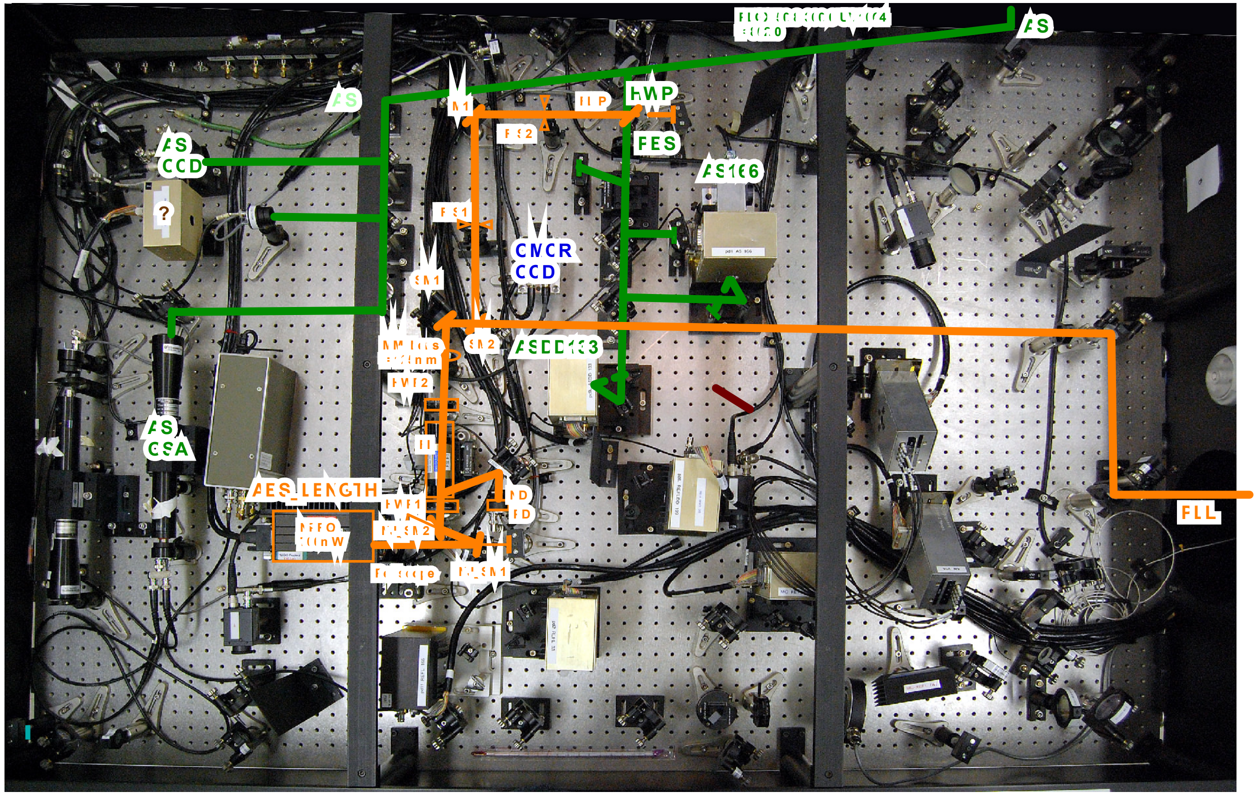
Experimental Setup

- Optical setup

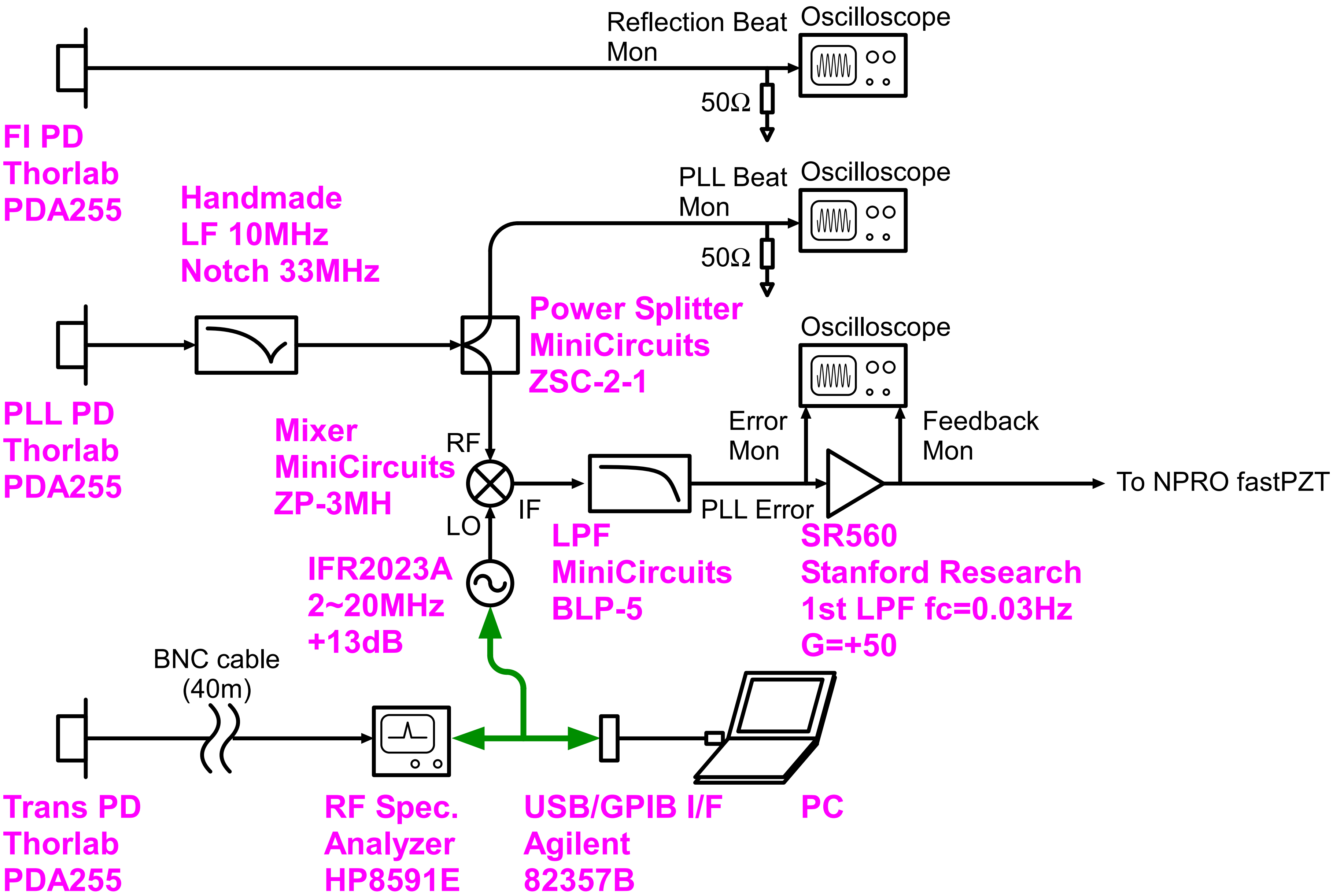
On the PSL table



On the AP table



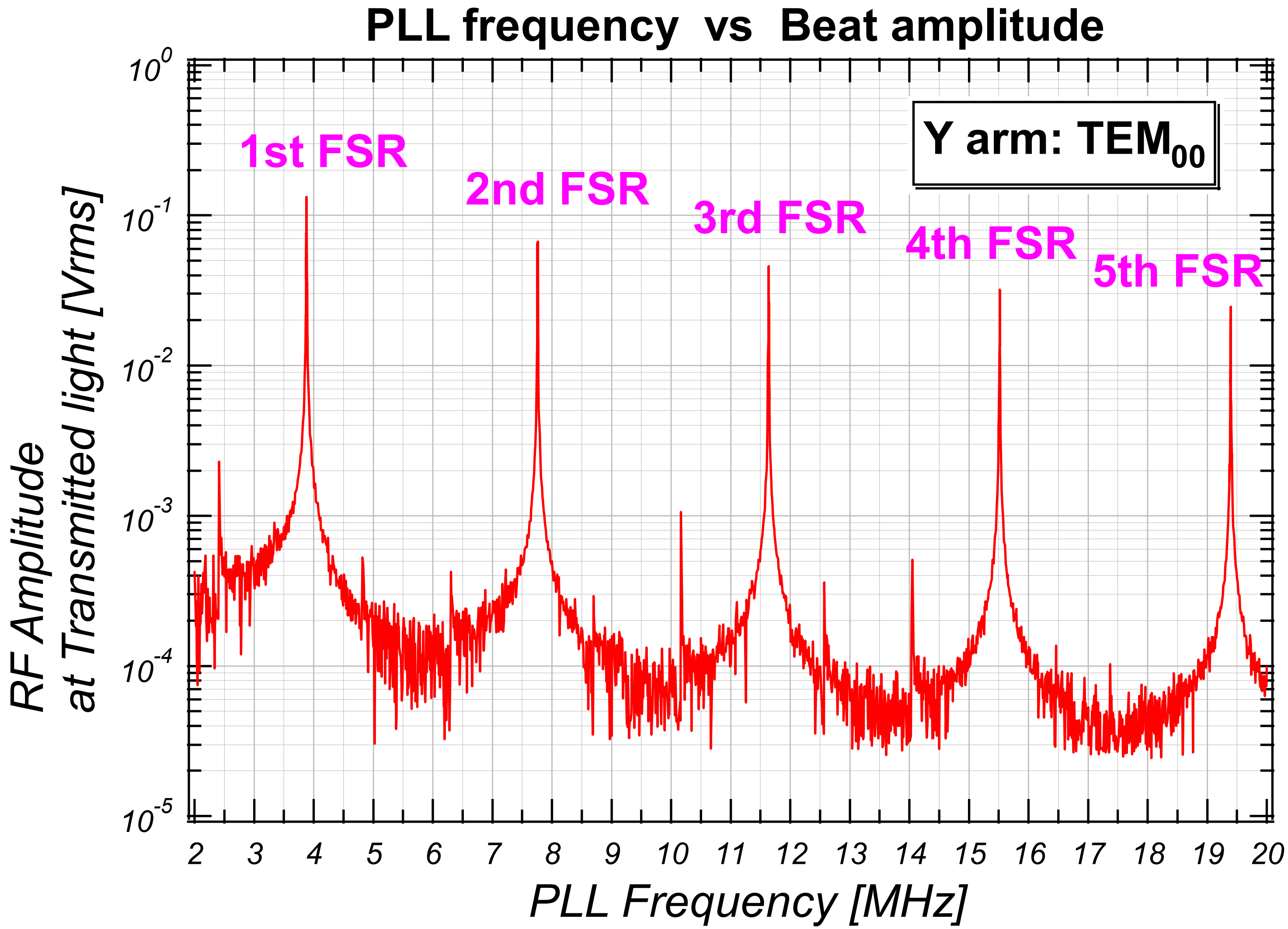
Detection setup



Results ~ londitudinal mode

- **PLL LO frequency scanning from 2MHz to 20MHz**

=> Record an RF amplitude at each frequency



Equispaced peaks for TEM00 modes are clearly observed

Results ~ londitudinal mode

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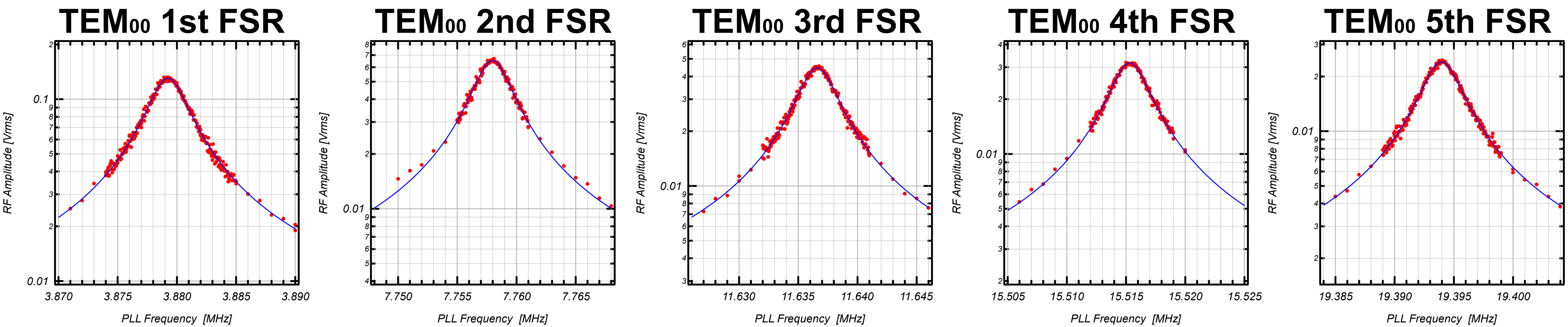
● Detailed plot and fitting of each peak

Each of the five peaks are fitted by the following formula:

$V(f) = A / \mathrm{Sqrt}[1 - (f-f_0)^2/f_c^2]$ f: variable A, f0, fc: parameters



The table of the center frequency f_0:

f1:	3879251.9 Hz +/- 8.8 Hz
f2:	7757968.1 Hz +/- 10.8 Hz
f3:	11636612.9 Hz +/- 10.2 Hz
f4:	15515308.1 Hz +/- 8.7 Hz
f5:	19393968.7 Hz +/- 8.4 Hz

Each peak frequency was measured by precision of 10Hz (= 0.4ppm ~ 2ppm)

Results ~ londitudinal mode

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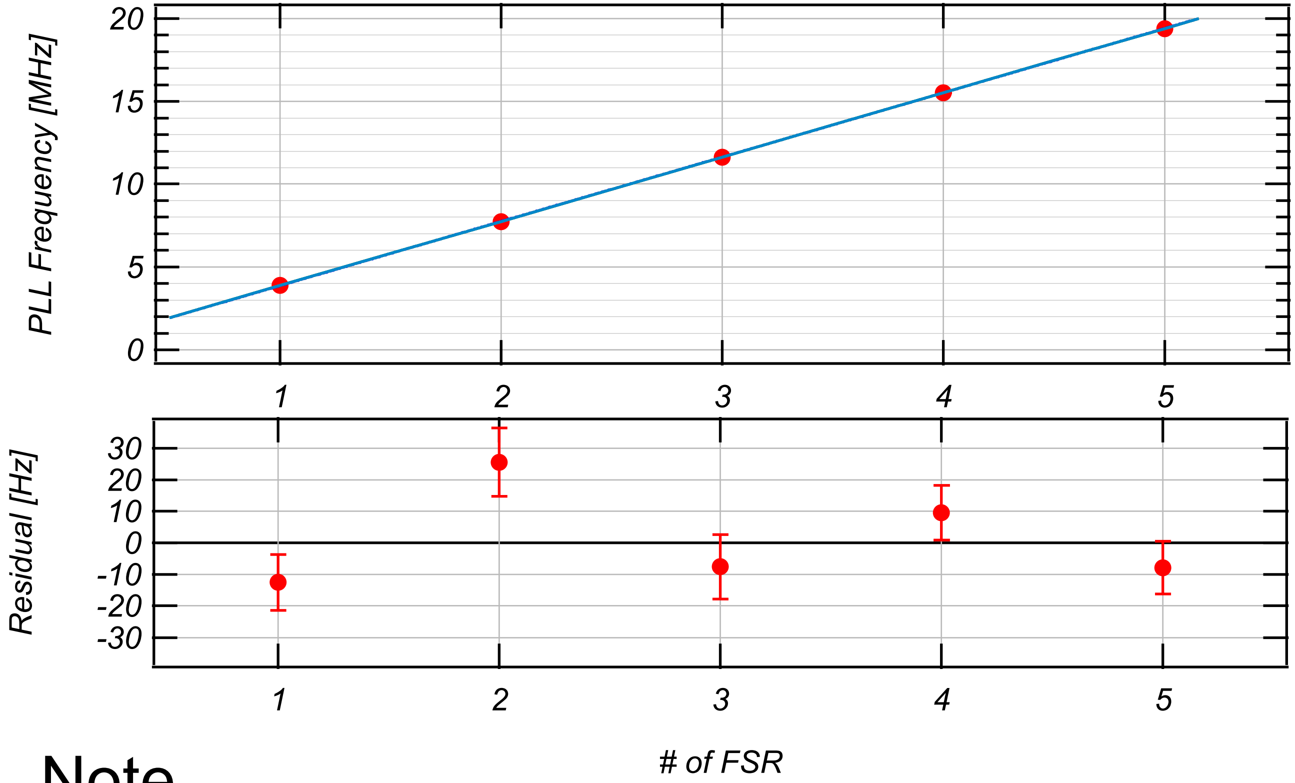
● Analysis of the peak frequencies

The five peaks frequencies are on a linear line.



$f_n = 586.4 + 3878678\ n$

Londitudinal mode spacing (FSR)
3878678 Hz

The lock of the carrier
had detuning of 586 Hz

Note

- o After the measurement the alignment was adjusted. This reduced the carrier lock detuning by 500Hz.
- o Fluctuation of FSR was less than 30Hz. This includes statistical error, fluctuation of FSR, and that of the carrirt lock detuning

(8ppm)

f_{FSR} = 3878678 Hz +/- 30 Hz => L_{Yarm} = 38.6462 m +/- 0.0003 m

Results ~ transverse mode

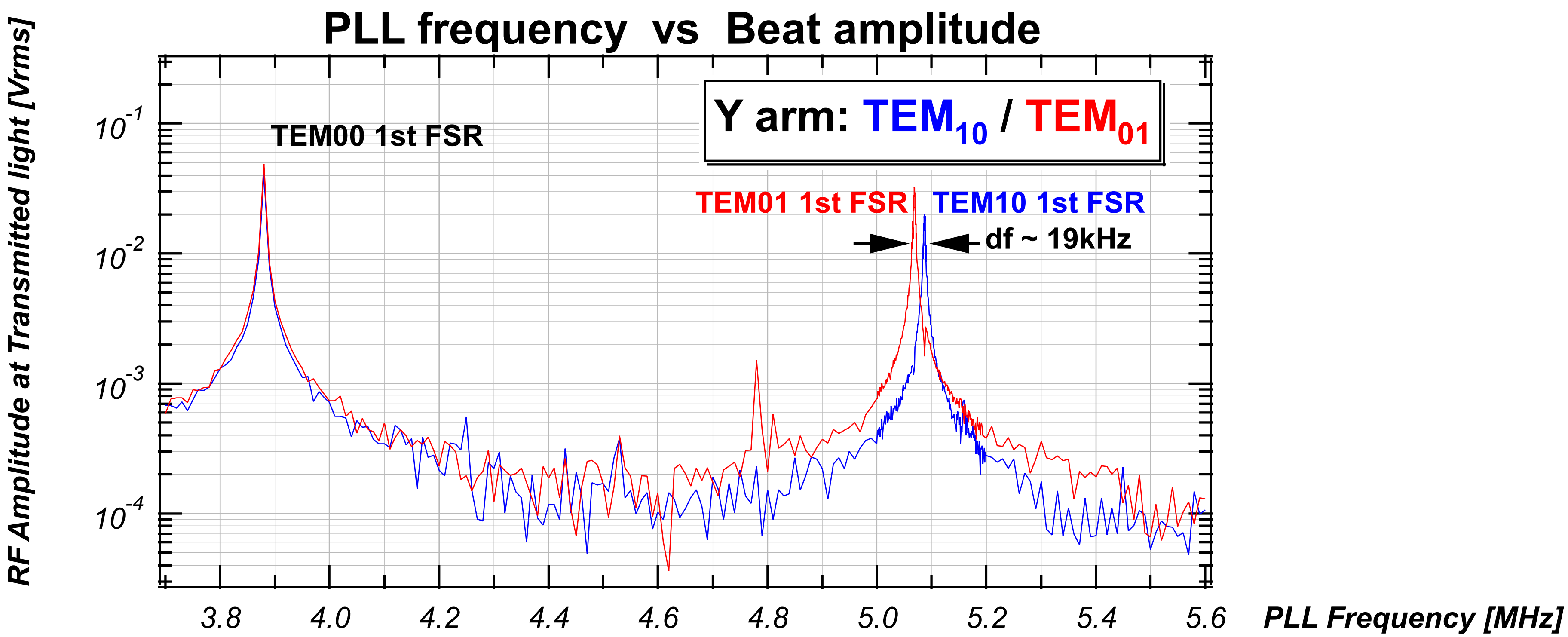
Knife edge experiment

Horiz. or Vert half of the transmitted beam were blocked by a razor blade

=> the transmitted RF PD becomes sensitive to the higher order modes

(similar to Anderson technique c.f. *Appl. Opt.* **23** (1984) 2944)

Aux beam is also misaligned to increase the amount of injected $TEM_{10 / 01}$

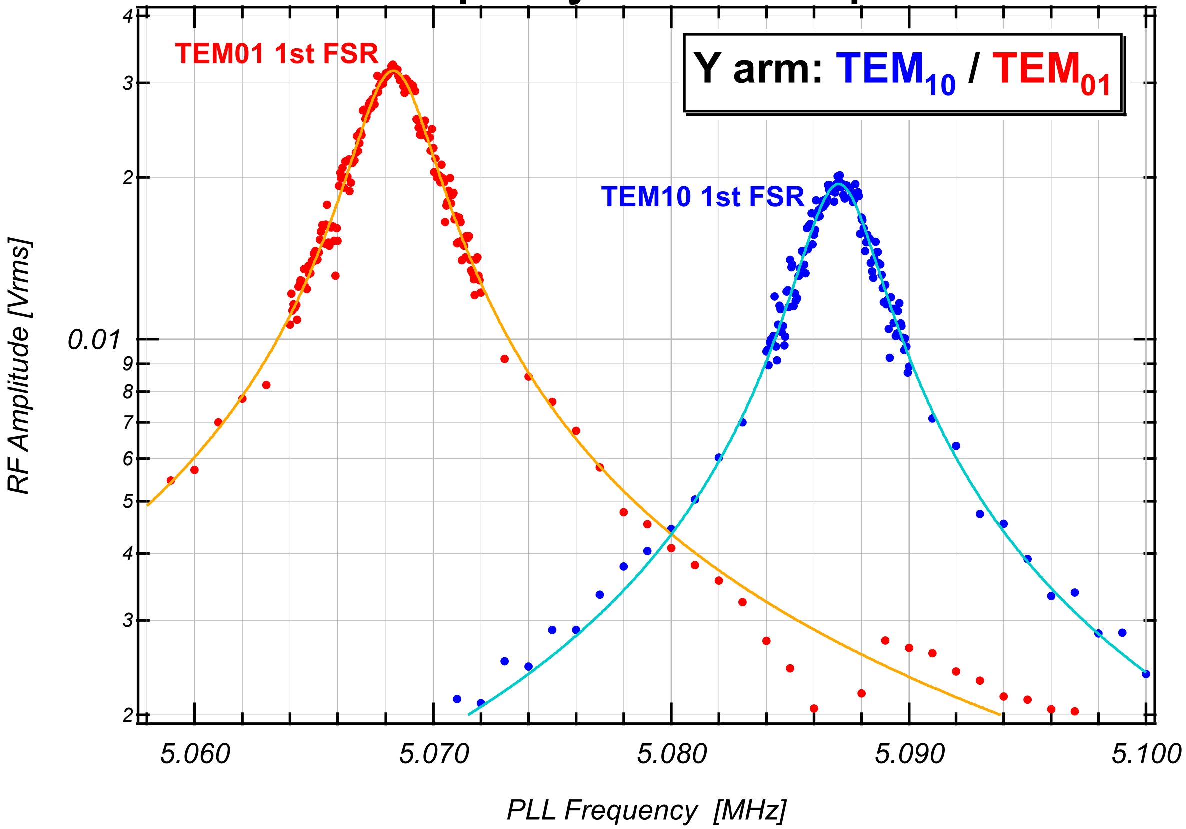


TEM10 and TEM01 peaks appeared. Split of their frequency (~19kHz) is found! =>The cavity end mirror has an astigmatism

Results ~ transverse mode

● TEM01/TEM10 resonances

PLL frequency vs Beat amplitude



o Transverse mode resonance

f_{TEM10}: 5087040 Hz +/- 20 Hz

f_{TEM01}: 5068322 Hz +/- 15 Hz

Δf = 18.7kHz.

o Using TEM_{00} results

f_{TEM00}: 3879252 Hz +/- 9 Hz
(for 1st FSR)

L_{Yarm}: 38.6462 m +/- 0.0003 m

o Those numbers give the radius of curvature of the mirror

R_H = 56.1620 +/- 0.0013 [m] (23ppm)

R_V = 57.3395 +/- 0.0011 [m] (19ppm)

Thoughts and Test for HOM

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● Result

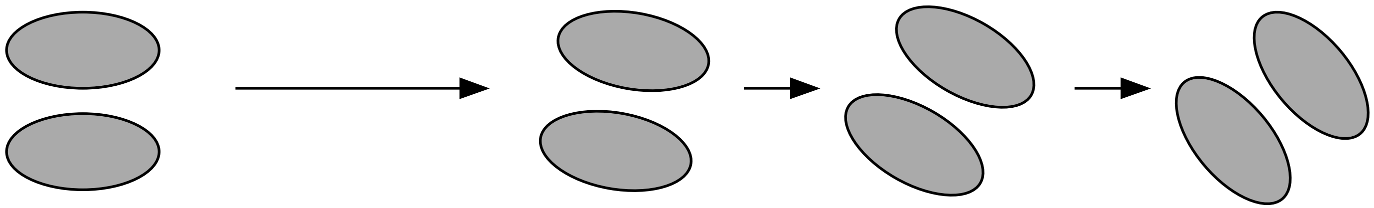
o The shape does not change. Just jumps to the other mode.
(The case above b.)

o The eigenmode looked like quite horizontal and vertical.

Conclusion: the mode really splits.

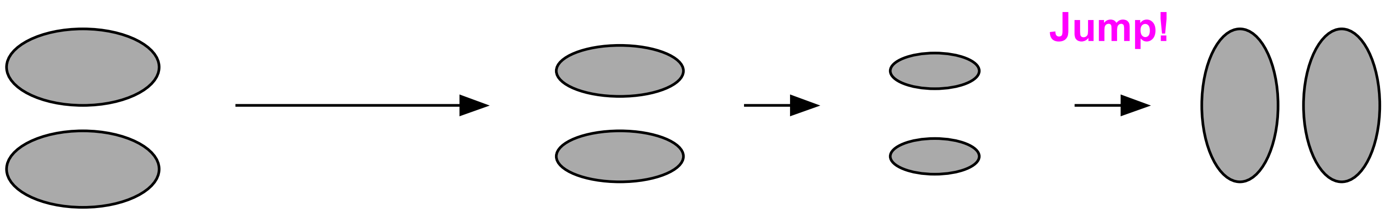
a) TEM01/TEM10 degenerated

Pitch misalign, lock TEM01 — Yaw misalign addition



b) TEM01/TEM10 split

Pitch misalign, lock TEM01 — Yaw misalign addition



Summary

- **Mode spacings of an optical cavity**
  - Useful for the design and diagnosis of the optical system.

- **Londitudinal and transverse mode spacings**
  - Measured for one of the LIGO 40m arm cavities
  - Using auxiliary laser, being injected from the dark port
  - RF beating detection at the cavity transmission

- **Result**
  - Londitudinal mode spacing & cavity length:

    ν_{FSR} = 3878678 +/- 30 [Hz] => L = 38.6462 +/- 0.0003 [m]
  - Transverse mode spacing & mirror cavatures (flat-concave cavity):

    $\delta\nu_{TEM10}$ = 1207788 +/- 22 [Hz] => R_H = 56.1620 +/- 0.0013 [m]

    $\delta\nu_{TEM01}$ = 1189070 +/- 17 [Hz] => R_V = 57.3395 +/- 0.0011 [m]

- **Future works**
  - Extending the method for the other cavities / AdvLIGO

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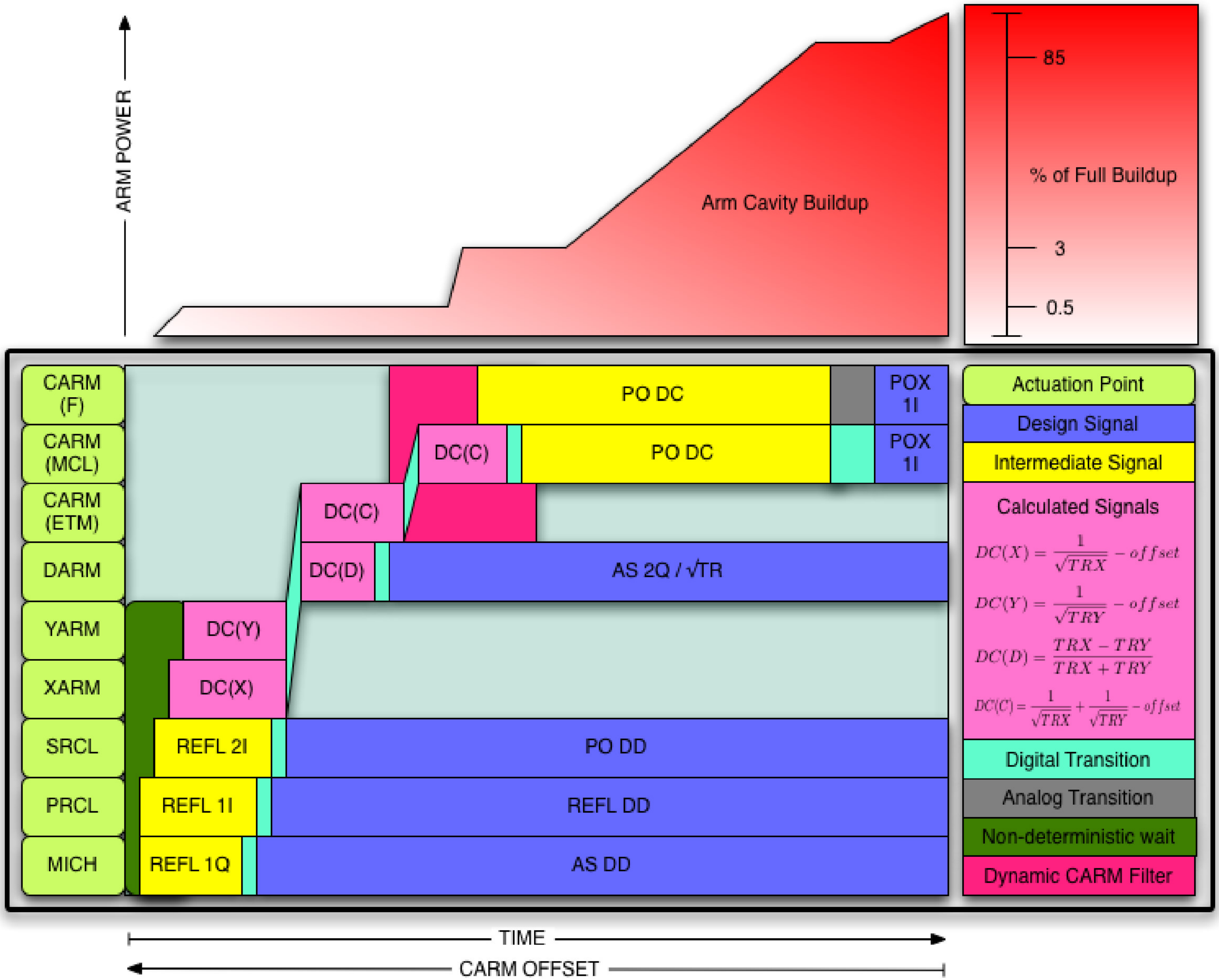
Current locking scheme

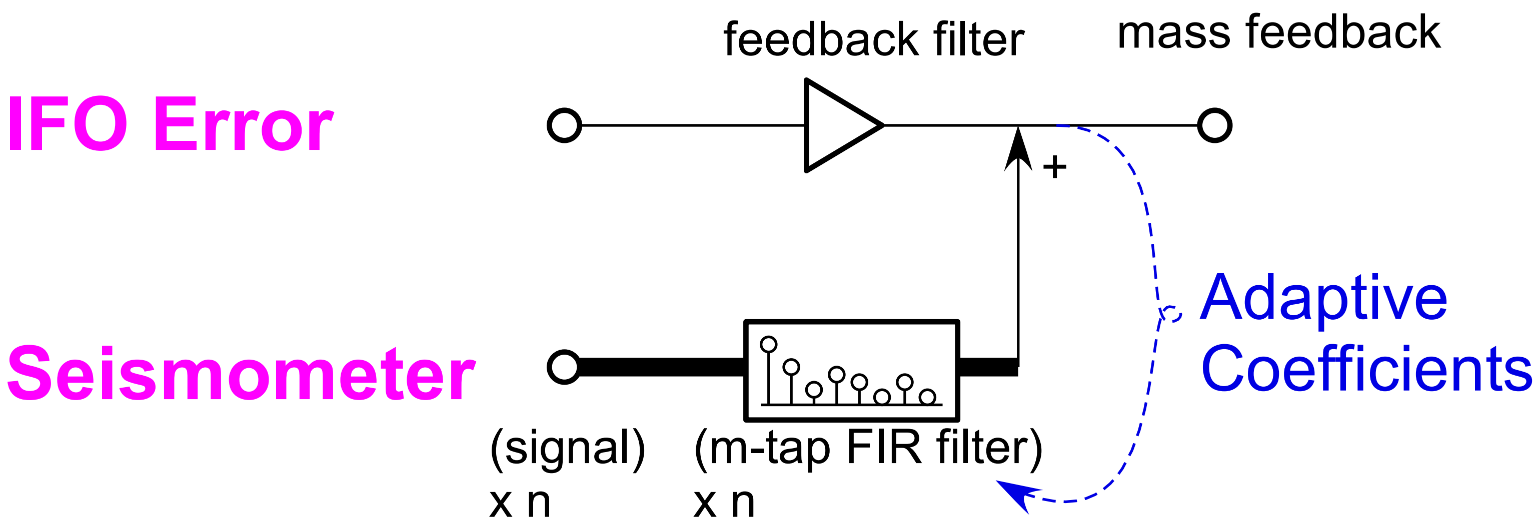


●Adaptive Feedforwarding

e.g. Adaptive Seismic Subtraction

Seismic noise ->[H(f)]-> Mirror motion
(measurable) (?) (measureable)

Why can’t we subtract the mirror motion by feedforwarding?
=> Usually H(f) is too complicated



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Adaptive Feedforwarding

Adaptive Seismic Subtraction

Mode cleaner length control

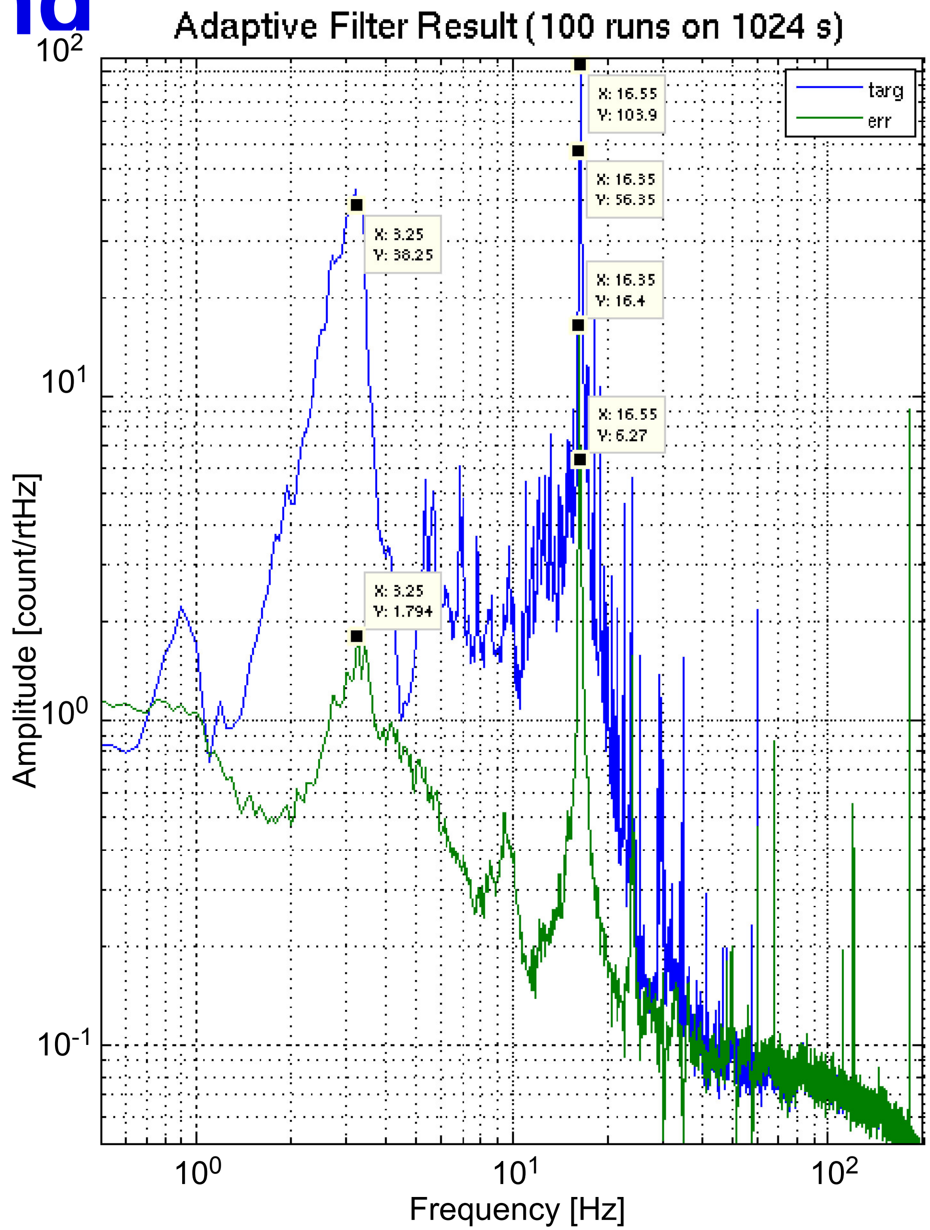
Two 3-axis seismometers

2048 tap for MISO FIR

Surprising

This is not a simulation,

but real data!



END

Discussion

About the carrier (PSL) lock detuning

The large (~500Hz) offset of the carrier lock by misalignment.

- In principle, this should not happen by misalignment. ***In principle***

- By a faster measurement, the precision may be improved.(?)

Scanning of the FSR not only **higer side** of the carrier but also **lower side** ensures the offset really exists.

About phase detection

- The resonant freqs = the peak freqs => this is a power detection
- Can we improve the precision by **phase detection**?
- Probably, it will be **difficult**. Because:

  The aux beam is not enough stable owing to the low gain/bandwidth of the PLL servo. => This method is like a narrow band noise injection

  The frequency of the aux beam is locked, but the phase is not locked. The incident beam has arbitrary phase.
- Do we use phase correction? (PZT in the injection path)

Future Works

- **Measuremet for the other 40m arm**
  - For TEM_{00}, $TEM_{01}/_{10}$
- **Characterization/Improvement of the PLL servo**
  - Openloop TF, in-loop/out-of-loop signal
  - Wider bandwidth, higher gain
- **Measrement for PRC/SEC**
  - Extending the method for shorter cavities.
    - => **Wider scanning range** probably required
  - The cavities with lower finesse (or even **frequency dependent**)
    - => Modeling will be needed for predicting/understanding the result.
  - **Individual/recombined** PRC/SEC length
    - => provides a precise BS branching ratio
- **Modeling work for the 40m & AdvLIGO to know:**
  - How much the optical lengths should be adjusted
  - Requirements for the radius of curvature

Previous works

R. G. DeVoe et al, Phys. Rev. A 30 (1984) 2827-2829

"Laser-frequency division and stabilization"

Measurement of the londitudinal mode spacing for a 50-cm table top cavity, using double frequency modulation/demodulation. Observed dL/L=2×10^{-10} level fluctuation.

A. Araya et al, Applied Optics 38 (1999) 2848-2856

"Absolute-Length Determination of a Long-Baseline Fabry-Perot Cavity by Means of Resonating Modulation Sidebands"

Measurement of the londitudinal mode spacing for a 300-m suspended FP cavity, using similar technique to DeVoe's one. Observed dL/L=6×10^{-8} level fluctuation.

M. Rakhmanov et al, Meas. Sci. Technol. 10 (1999) 190-194.

"An optical vernier technique for in situ measurement of the length of long Fabry-Perot cavities"

Measurement of the londitudinal mode spacing for a 40-m suspended FP cavity, using cavity length sweeping.The obtained precision was dL/L=10^{-4}.

The VIRGO collaboration, Applied Optics 46 (2007) 3466-3484.

"Measurement of the optical parameters of the Virgo interferometerier"

Measurement of the londitudinal and transverse mode spacings for cavities including 3000-m suspended FP arms, using cavity length sweeping.The precisions for the londitudinal and the transverse were 10^{-5} and 5×10^{-3}, respectively.

Previous works

M. Rakhmanov et al, Class. Quantum Grav. 21 (2004) S487-S492
“Characterization of the LIGO 4 km Fabry.Perot cavities via their high-frequency dynamic responses length and laser frequency variations”

R. Savage et al, LSC Meeting on March 2005
LIGO document G050111-00
“Summary of recent measurements of g factor changes induced by thermal loading in theH1 interferometer”

R. Savage et al, Poster in 6th Edoardo Amaldi Conference (2006)
LIGO document G050362-00
“Measurement of thermally induced test mass surface curvature changes in a LIGO 4-km interferometer”

Measurement of the londitudinal and transverse mode spacings for LHO 4km suspended FP cavities, using transfer function measurement with injected phase modulation sidebands through the mode cleaner. The precisions for the londitudinal and the transverse were 2×10^{-8} and 7×10^{-4}, respectively. Change of the mirror curvature by the thermal effect is observed.

Practical Details 1

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● Optical layout at the AP table

Periscope:
To raise the beam elevation from 3inch to 4inch

INJ_SM1/2:
To steer the aux. beam independetly from the main beam

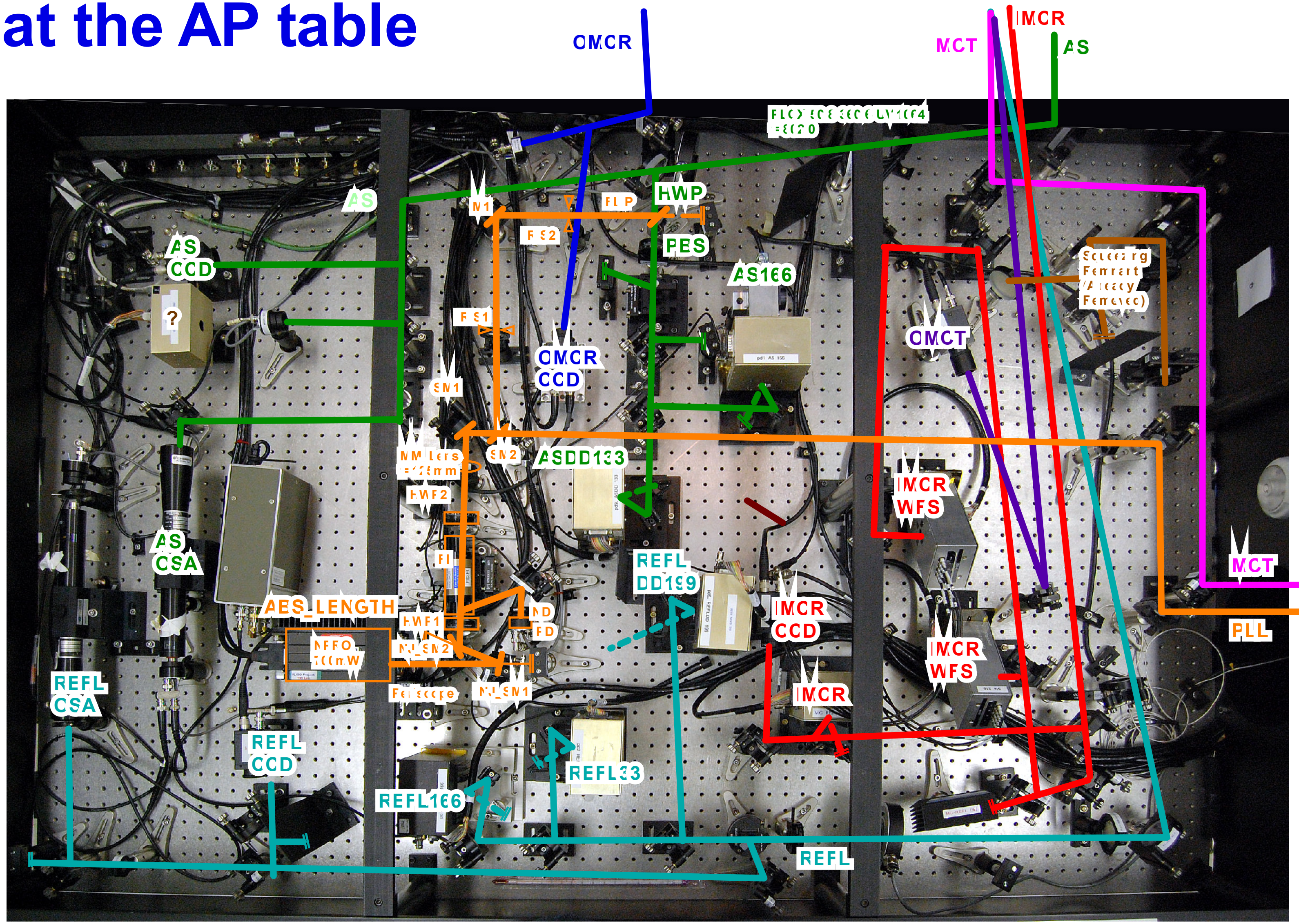
HWP1:
Half wave plate to make the beam horiz-polarized (42deg nominal)

FI:
Faraday isolator

HWP2:
To make the beam to the IFO horiz-pol (357deg nominal)

MM_Lens:
To match the NPRO mode to the IFO beam. (f=125mm)

SM1/SM2:
Steering mirrors
SM2 is a 45deg R=95% mirror so that there can be a beam to the PLL setup



IRIS1/IRIS2:
For the coarse alignment of the aux beam

FLIP:
Flipper mirror to turn on/off the aux optics.

Practical Details 2

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● Optical layout at the PSL table

PSL_HWP:
Half wave plate to make the beam horiz-polarized

PSL_MML: (f=0.401 m)
To match the PSL beam to the aux beam at PLL_BS (zR ~ 5m)

PSL_SM:
Steering mirror for the PSL beam

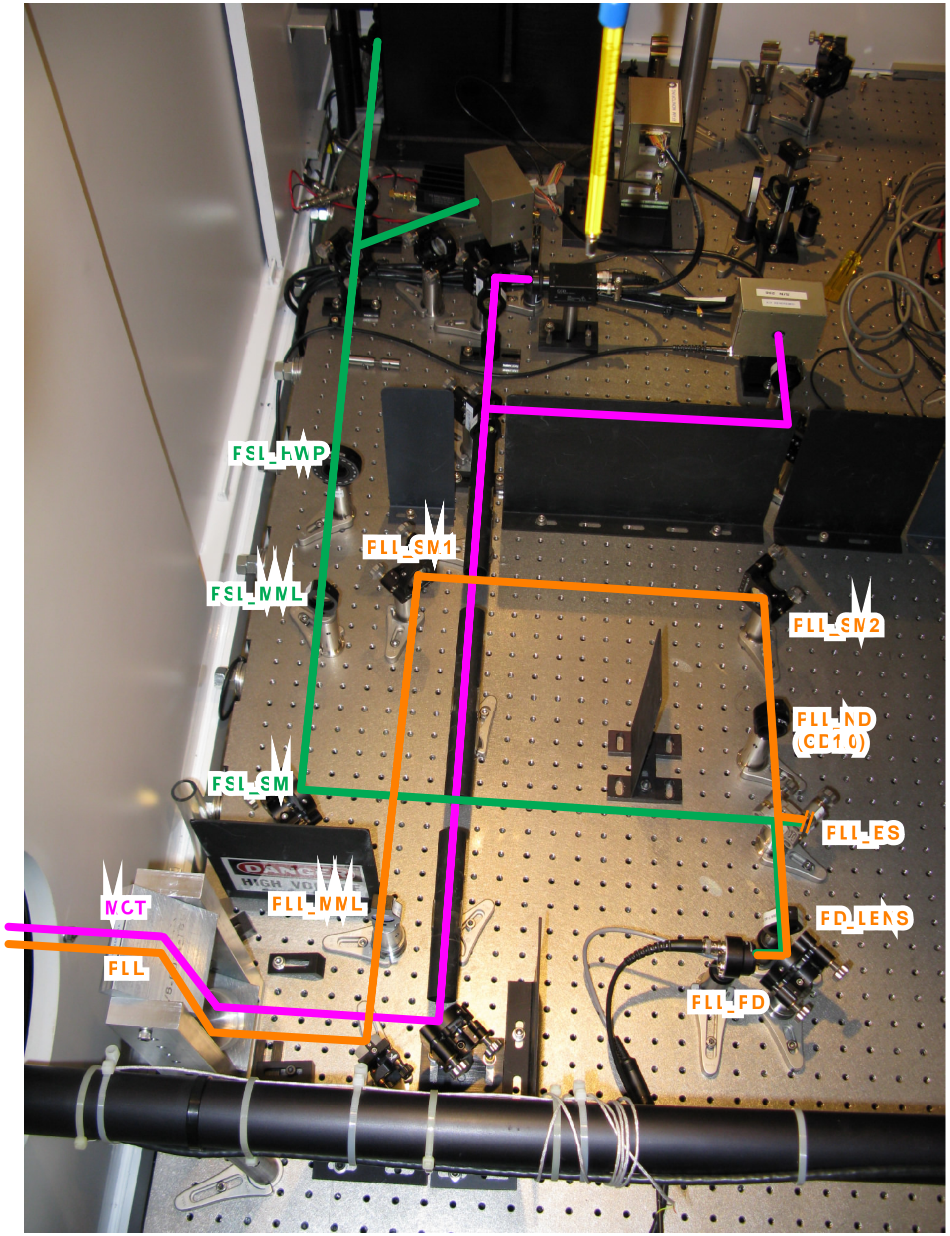
PLL_MML: (f=0.687 m)
To match the aux beam to the PSL beam at PLL_BS (zR ~ 5m)

PLL_SM1/SM2:
Steering mirrors for the aux beam

PLL_BS:
BS where the aux beam and the PSL beam recombines

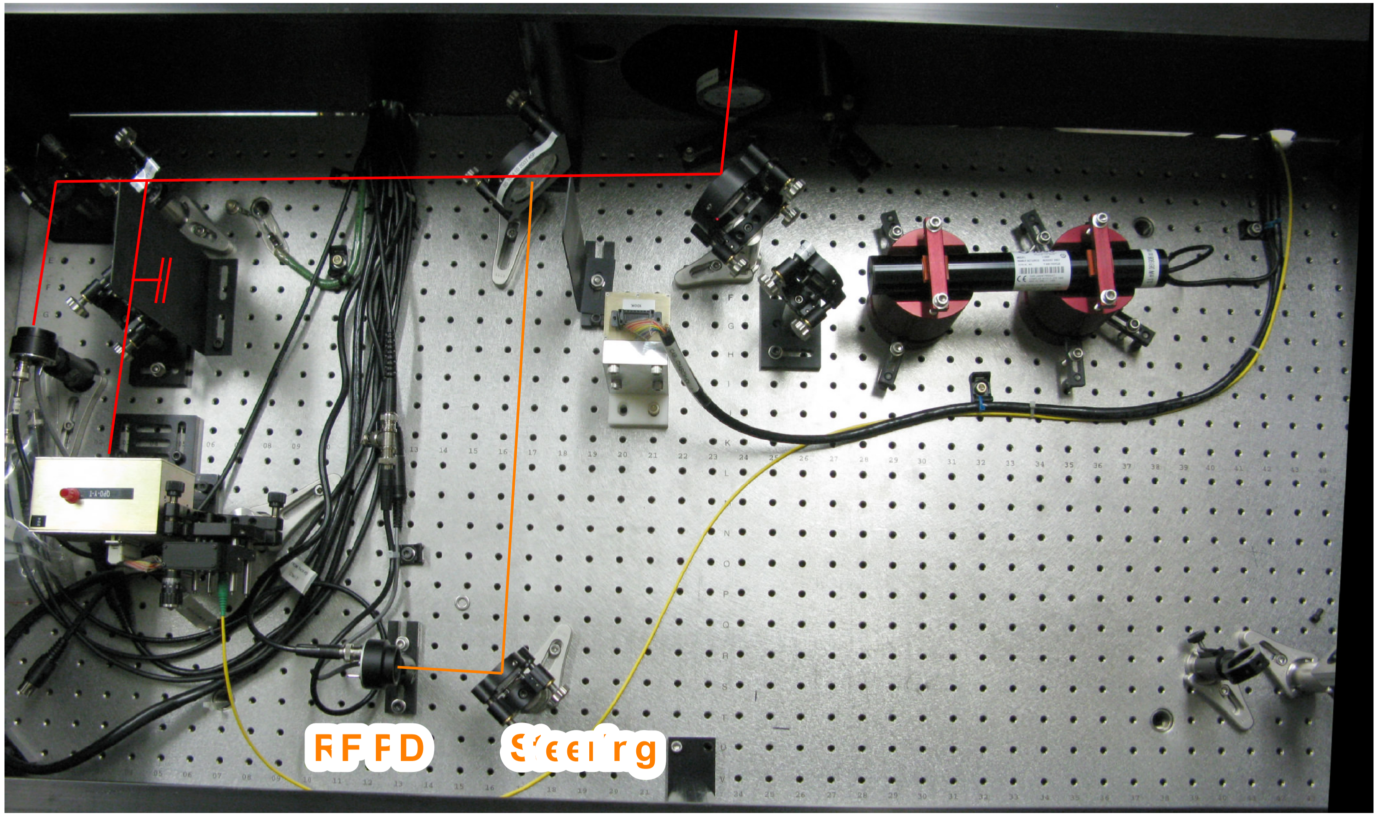
PD_LENS:
Lens to focus beam onto the PD

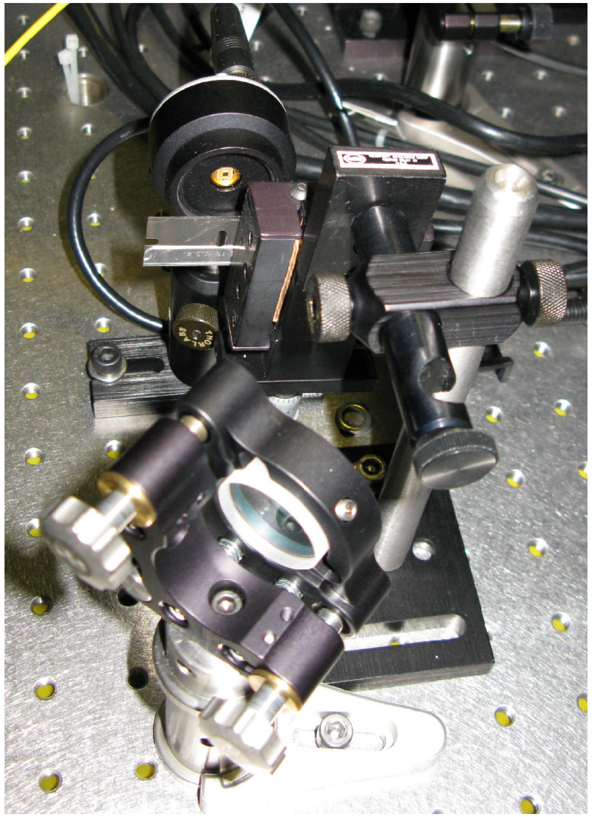
PLL_PD:
Thorlab PDA255 ~50MHz



Practical Details 3

● Optical layout at the Y End table





Steering mirror:
To steer the beam to the PD

RF PD:
Thorlab PDA255 ~50MHz
The beam is focused at the PD
because of the first lens

Knife Edge:
Placed just in front of the PD
so as to avoid diffraction

Practical Details 4

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Mode matching for the injection beam

Position[m]			
0.000	NPRO Shutter		
0.050	H Waist	radius: 0.230mm	zR: 0.156m (c.f. NPRO manual)
	V Waist	radius: 0.175mm	zR: 0.090m (c.f. NPRO manual)
0.483	Lens1 (f=0.125m)		
0.649	H Waist		zR: 0.0204m
0.656	V Waist		zR: 0.0136m
1.457	Lens2 (f=0.802m)		
10.39	H Waist		zR: 29.3m
(0.002)	V Waist (virtual)		zR: 47.0m

Actual obtained beam overlapping ~ 38%
***The actual position of Lens1 was tweaked to optimize the actual mode matching.**

Mode matching for the PLL setup

PSL beam: Beam collimated in ~1^{+} inch region => zR ~ 0.029m => w0 ~ 0.1mm
A lens with f=401mm is used so that the resulting zR ~ 5m is obtained.

Aux beam: Beam collimated in ~3 inch region => zR ~ 0.075m => w0 ~ 0.16mm
A lens with f=687mm is used so that the resulting zR ~ 5m is obtained.

Actual obtained beam overlapping ~ 29%
***The merit of using thick collimated beam:**
The tolerances to the londitudinal and transverse position of the beam are relaxed.

Practical Details 5

● Alignment Procedure

o Preparation

1) Turn on NPRO several hours before the experiment so that the laser frequency can be stable.

2) Open the shutter of NPRO.

o Initial alignment of the injection beam

3) Adjust INJ_SM1/SM2 so that the NPRO beam can go through the center of FI.

4) Turn up FLIP. Close the NPRO shutter.
   Adjust M1/FLIP so that the ifo beam can go through IRIS1/IRIS2.
   * IRIS1/2 should be in a reasonable place from the beginning.

5) Open the shutter of NPRO again. Adjust SM1/SM2 so that the NPRO beam can go through IRIS1/IRIS2. Confirm the spots on the SM1/SM2 are located at reasonable places on the mirrors.

6) Now, it is expected that the reflection of the injection beam from SRM or ITM appears at AS CCD, if either SRM or ITM is aligned.

7) Adjust INJ_SM1/INJ_SM2 so that the injection beam at AS CCD can overlap to the IFO beam.

8) Confirm the beam at the output of the FI also overlaps. Adjust the steering mirror just before the RF PD.

Practical Details 6

● Alignment Procedure 2

o Temperature scan for the beat

9) Change the ifo configuration to the X or Y arm only, if not yet done.

10) Put the RF PD output to an RF analyzer. Scan the crystal temperature of the 700mW NPRO so as to find the peak of beating. Note that the beating was found at NPRO LT~48.8deg for PSL LT=~46.5 deg.

o Precise alignment of the injection beam

11) Once the beat is found, you can adjust INJ_SM1/INJ_SM2 such that the beating amplitude is maximized.

o Precise alignment of the PLL alignment

12) Confirm all of the beam of the PLL setup is located on the proper position of the mirror. (Particularly, on the AP table)

13) Adjust PSL_SM so that the PSL beam overlaps the aux beam at PLL_BS. Adjust PLL_BS so that the beating at the PLL_PD is maximized.

15) Adjust PSL_SM and PLL_BS simultaneously so that the beating at the PLL_PD is further maximized.

o Tip for the daily alignment

Only 10)-15) are fine for the daily alignment. If the alignment had been previously adjusted, and you found a large misalignment when FLIP is popped up, it is presumably caused by the flipper. Adjust flipper so that the spot on the CCD video or the beating is optimized.

Practical Details 7

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Beating conditions on 2008-Aug-03

o How to calculate mode overlapping ratio

$E1 = \mathrm{Sqrt}(P_1) \langle TEM_{00}| \mathrm{Exp}(i\ w1\ t)$

$E2 = \mathrm{Sqrt}(\alpha\ P_2) \langle TEM_{00}| \mathrm{Exp}(i\ w_2\ t) + \mathrm{Sqrt}[(1-\alpha)\ P_2] \langle TEM_{XX}| \mathrm{Exp}(i\ w_2\ t)$

$E1\ E1^* = P_1,\ E2\ E2^* = P_2$

$P_{beat}=(E1+E2)(E1+E2)^* = P_1+P_2+2\ \mathrm{Sqrt}(\alpha\ P_1\ P_2)\ \mathrm{Cos}[i\ (w1-w2)\ t]$

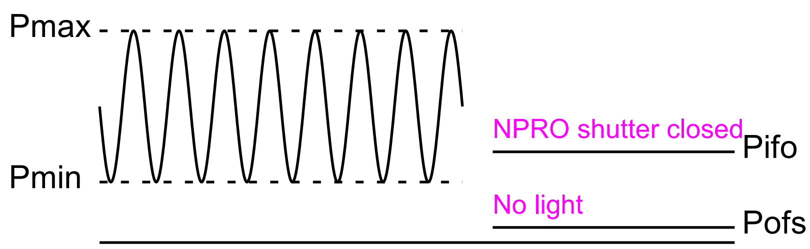
o Temperature setups

NPRO LT = 48.74 deg , PSL LT = 46.45 deg

The higher NPRO LT has lead the lower beat freq => f(NPRO) > f(PSL)

o Beating at the FI output on 2008-Aug-03

Pmax	= 398 mV	→	P1=246mV
Pmin	= 174 mV		P2=34mV
Pifo	= 252 mV		57% intenisity modulated
Pofs	= 5.80 mV		α=0.37



o Beating at the PLL PD on 2008-Aug-03

Pmax	= 420 mV	→	P1=64.8mV
Pmin	= 162 mV		P2=220mV
Pifo	= 71.2 mV		62% intenisity modulated
Pofs	= 6.40 mV		α=0.29

Practical Details 8

●ifr2023A calibration

o Calibration of the PLL LO frequency is essential for our measurement:
Because PLL LO is the frequency reference

o Calibrated by frequency counter SR620 is locked to the GPS signal.

o The frequency of the IFR2023A was scanned:
from 1MHz to 20MHz with 1MHz interval.

o The linear fit was taken. Result:

f_{freq_count} [Hz] = K0 + K1 * f_{IFR} [Hz]

K0 = 0.00 +/- 0.02
K1 = 0.999999470 +/- 0.000000001

o All of the frequencies for the measured points were converted by this formula.

Practical Details 9

GPIB commands for the PLL freq scanning

o HP = RF Spectrum Analyzer, IFR = IFR2023 function generator

o Initialization

Write to HP: "AUNITS V"	#Represent peak value in Vrms
Write to HP: "CF 3456789HZ"	#Set the center freq
Wait 1sec	
Write to HP: "SP 1MHz"	#Set freq span to 1MHz
Wait 1sec	

o In the scanning loop

Write to HP: "CF 3456789HZ"	#Set the center freq
Write to IFR: "CFRQ 3456789HZ"	#Set the carrier freq
Write to HP: "MKPK HI"	#Find highest peak in the spectrum
Wait 1sec	
Write to HP: "MKA?"	#Query for the peak amplitude
Read value from HP	#Get the peak value

Thoughts and Test for HOM

Questions

- The TEM01 and TEM10 of the Yarm were found to split with 19kHz separation. Is this true?
- In which direction the eigenmodes are?

Thoughts

- The separation of 19kHz is a kind of too big because the cavity bandwidth is several kHz.
- This means that "TEM01 and TEM10 can not resonate at the same time (by the PSL beam)".

Test

- Imagine we are just using the PSL beam and playing with an arm cavity.
- Tilt the end mirror in pitch. Resonate the TEM01 mode (8-shaped).
- Then tilt the end mirror in yaw.
- a) If the resonances are degenerated within the bandwidth of the laser, it rotates freely.
- b) If the resonances splits, the tilt in yaw does not change the shape. Then suddenly jumps to TEM10 (by an accident).

Thoughts and Test for HOM

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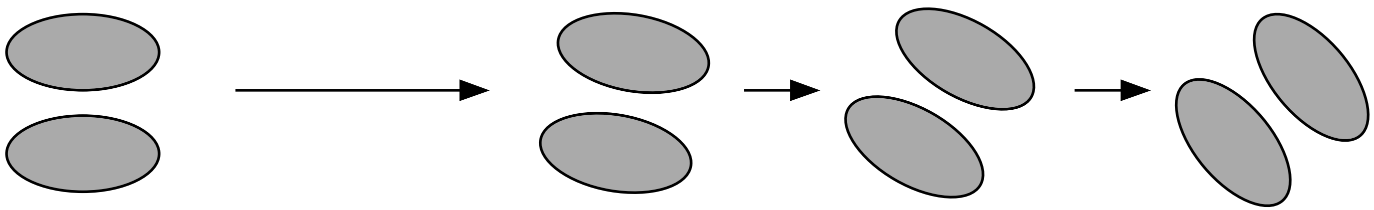
● Result

o The shape does not change. Just jumps to the other mode.
(The case above b.)
o The eigenmode looked like quite horizontal and vertical.

Conclusion: the mode really splits.

✕ **a) TEM01/TEM10 degenerated**
Pitch misalign, lock TEM01 Yaw misalign addition



○ **b) TEM01/TEM10 split**
Pitch misalign, lock TEM01 Yaw misalign addition