Homodyne (DC) detection experiment at the 40 meter lab

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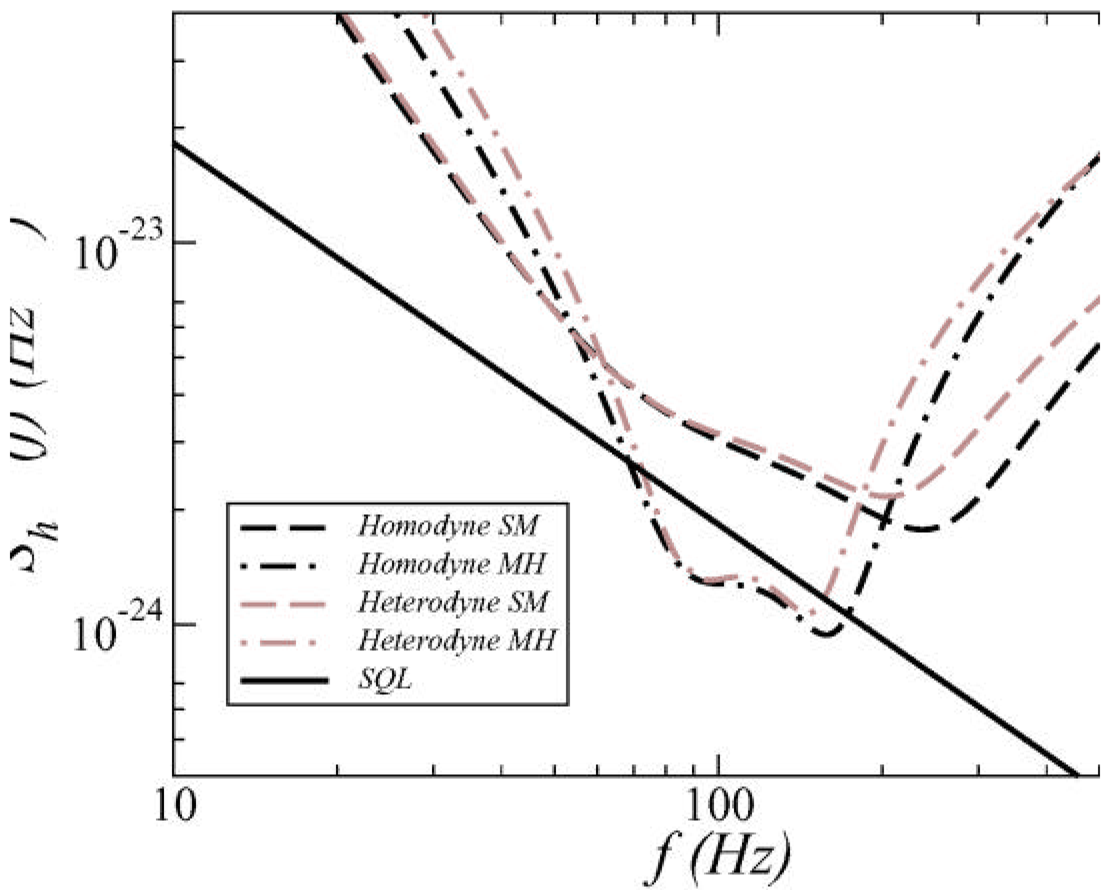
Homodyne Detection for AdLIGO

- LIGO-1-like sensing, based on beats between RF sidebands (LO) and carrier, is subject to considerable noise from the LO, which is not arm-filtered and which has additional oscillator phase noise.
- Baseline optical configuration for AdLIGO is a Fabry-Perot Michelson with both power- and signal-recycling; the signal cavity will be detuned to produce enhanced sensitivity at some GW frequency > 0
    - The detuned signal cavity means that the RF sidebands will be unbalanced; RF LO noise couplings will be worse
- Using arm-filtered carrier light as the LO in AdLIGO (DC or homodyne detection) *may* result in improved noise due to less noisy LO (if implemented well).
- Also slightly improved quantum noise (see next slide, from Buonanno and Chen).
- AdLIGO will want an output mode cleaner (OMC) to reject junk light (not containing GW signal information; due to Michelson contrast defect, mode mismatching, etc) at the asymmetric port (AP).
- This OMC can also reject the noisy RF sidebands, leaving only arm-filtered carrier and GW signal sidebands. An OMC which passes the RF sidebands is more complex.
- DC detection requires seismic and acoustic isolation of the OMC and DC photodetector.
- A pickoff before the OMC will permit standard RF detection as well, to aid in lock acquisition and to provide a backup for DARM control and GW signal extraction.

Quantum noise comparison

Buonanno &Chen:
Quantum noise + thermal noise



- ***parameters optimized for NS-NS binaries***
- ***single optimal demod phase chosen for RF***
- ***SNR for homodyne higher than heterodyne by***
    - ***5% for spherical mirrors***
    - ***10% for mexican hat mirrors***

Goals for 40m

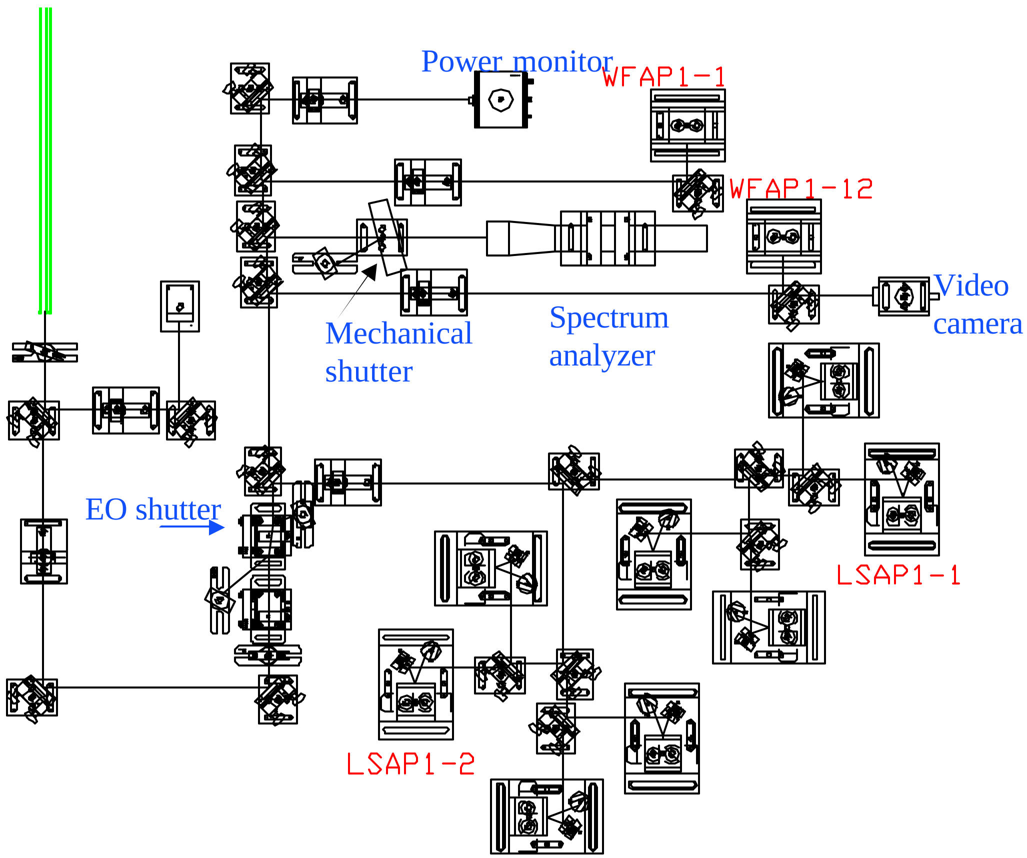
- The 40m is developing a full engineering prototype of the AdLIGO optical configuration.
- We expect to lock the full DRFPMI in the next few months, and establish a reliable lock acquisition procedure for AdLIGO.
- Then, establish expected response to large-amplitude GWs. Then, study noise.
- This is a good time, and place, to test homodyne detection.
- Initial goal is to implement a DC detection optical beamline, sensing and control electronics.
  - This can be done on existing seismic stack in (small) vacuum chamber, already in place for this purpose.
  - Then, establish expected response to large-amplitude GWs, and first look at noise.
- Establishing low-noise sensing is another matter.
  - As everyone knows, finding and eliminating technical noise sources to the point where only fundamental noise sources remain, is a long, difficult, open-ended task.
  - Initial goal for 40m DRFPMI prototype with RF detection includes only an initial look at noise sources, not an exhaustive battle with them.
  - It is not clear how much can be learned about limits to noise in homodyne detection, in the 40 meter environment.

Elements of DC detection beamline

- Currently, light exiting the signal mirror goes straight out of the vacuum chamber and into an RF detection beamline (AP1) on a nearby optical table (mech shutter, EOS, HFRFPD, DDRFPD, QPD, CCD camera; see next slide).
- Plan is to pick off some/most of that light, and send it into DC detection system.
- In-vac, seismically-isolated beamline (AP2):
  - Mode matching telescope (very short, off-axis mirrors, remote control focus)
  - Two steering mirrors (PZT, servo-controlled)
  - Output mode cleaner (3- or 4-mirror, fixed spacer, PZT-mounted mirror)
  - DC detection photodiode (in a pressurized can?) with baffling.
- OMC reflected beamline (on optical table in air):
  - IF the OMC is to be locked using reflected sidebands, eg, 166 MHz, then we need the usual: Mech shutter, electro-optic shutter and power PD, LSC RFPD, QPD, WFSs, CCD camera…
  - If the OMC is to be locked using dither locking, need DC PD instead, either in reflection or transmission.

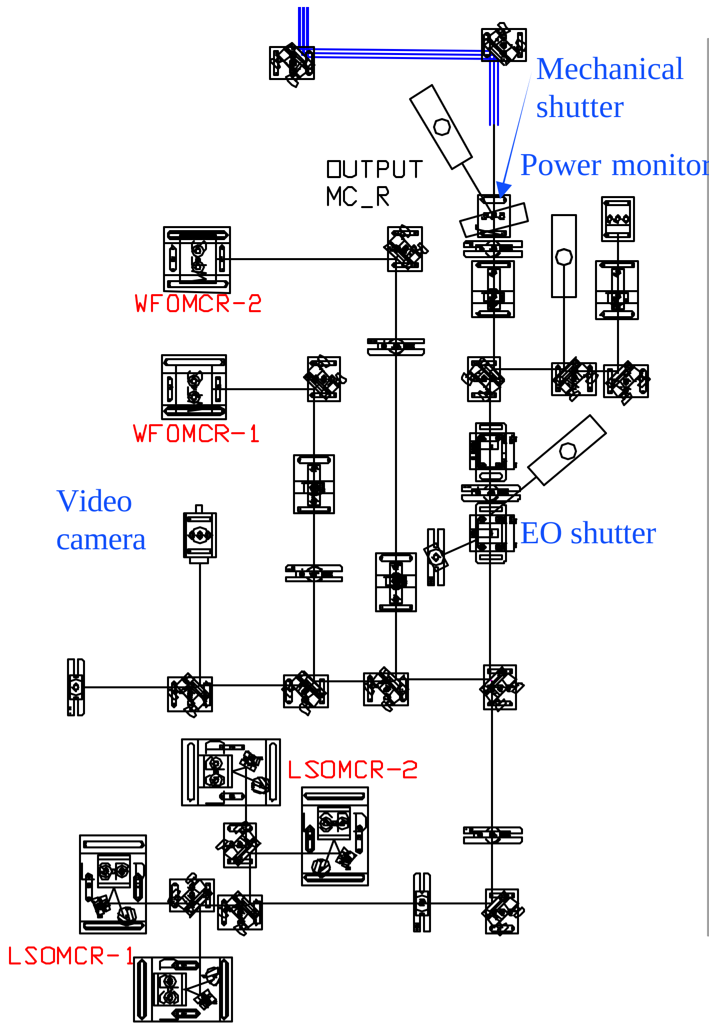
AP1 ISC System

Mike Smith 2001 “straw man” design; implemented system is different!
Only two LSC RFPDs; no WFSs.



OMC Reflected Beam Sensing System

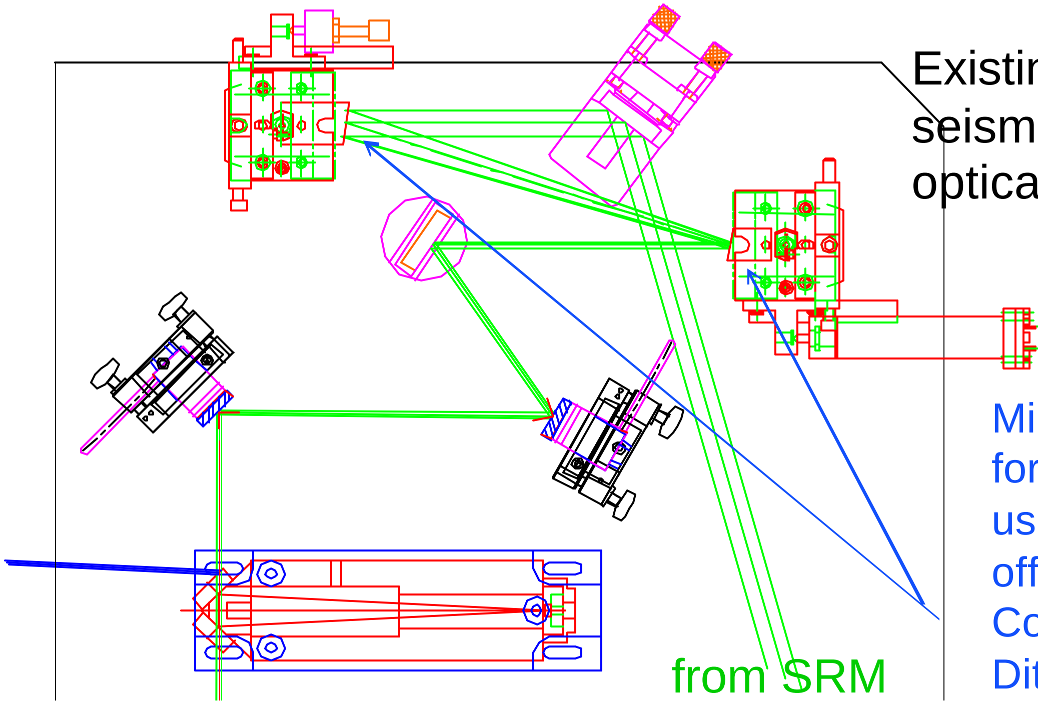
Mike Smith 2001 “straw man” design; not implemented.



Parameter	Requirement	Actual
Wavefront distortion	< 1 wave @ 1064 nm	< 0.3 wave @ 1064 nm
Main beam sample fraction	0.01	0.01
WFS1, Guoy phase 1	Quad photodiode, 177.3 MHz	QPD, 177.3 MHz
WFS2, Guoy phase 2	Quad photodiode, 177.3 MHz	QPD, 177.3 MHz
LS, RF photodiode	177.3 MHz	177.3 MHz
Fast beam shutter	Yes	EO shutter
Mechanical beam block	Yes	Uniblitz
Video camera	Yes	Watek
Reflected power monitor photodiode	yes	

OMC Beam Steering

Mike Smith 2001 “straw man” design; not implemented yet.



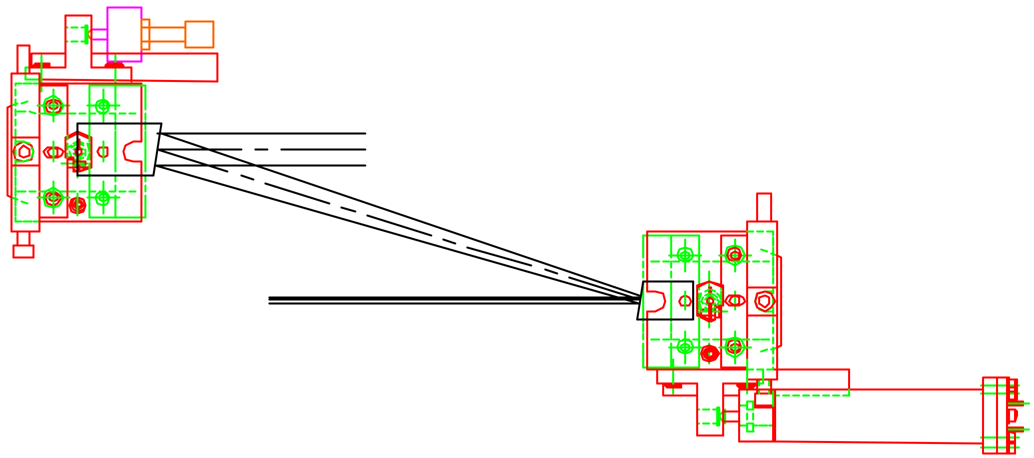
Existing in-vac seismically isolated optical table

Mike built a compact, monolithic MMT for our IMC→IFO optical train, using expensive, long-lead-time off-axis-parabolic mirrors.
Could use same design for IFO→OMC.
Ditto, for in-vac PZT steering mirrors.

Parameter	Requirement	Actual
Spot size of OMC beam	0.37 mm	
Position steering	+/-0.37 mm	+/- 0.8 mm
Divergence angle of OMC beam	0.00092 rad	
Angular steering	0.00092 rad	+/- 0.004 rad
Resonant frequency		3500 Hz
Angle sensing		Internal strain gage

OMC Mode Matching Telescope

Mike Smith 2001 “straw man” design; not implemented.

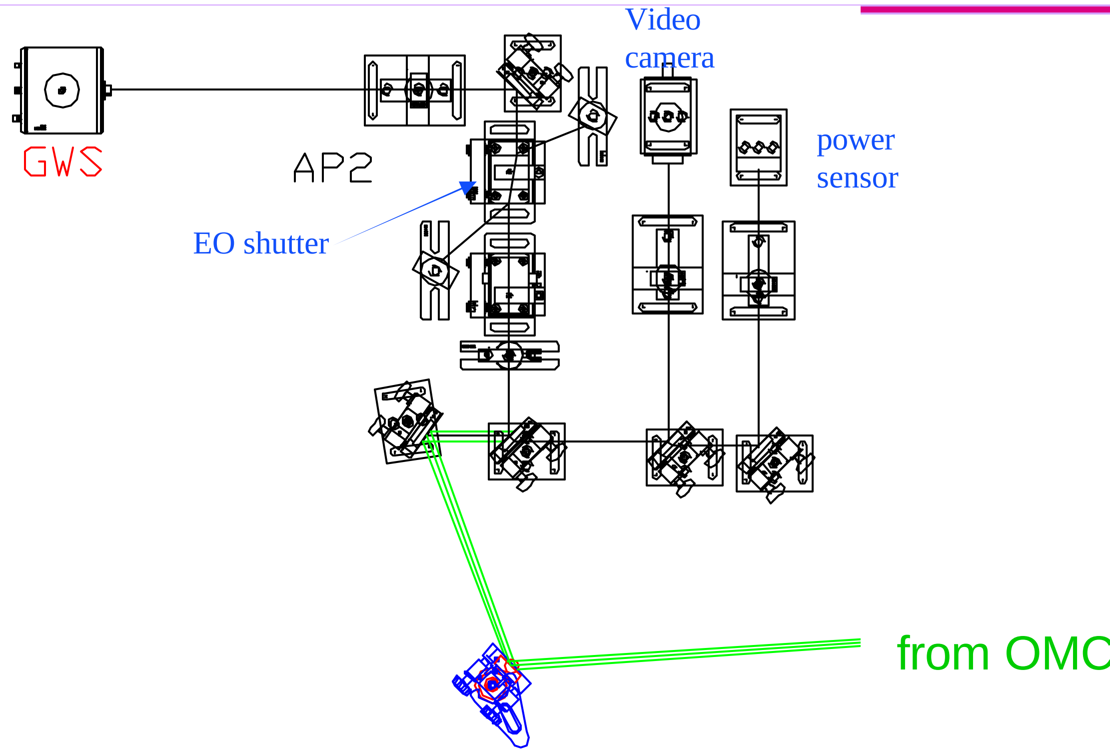


Parameter	Requirement	Actual
Clear aperture M1, mm	13	25
Clear aperture M2, mm	3	19
Input beam waist radius, mm	3.027	3.027
Output beam waist radius, mm	0.37	0.369
Power coupling error	<0.05	< 0.0001
Wavefront distortion		<0.2
Transmissivity across clear aperture		> 99.8%, ion beam coating
Magnification	0.23	0.23

AP2 ISC Optical Train

Mike Smith 2001 "straw man" design; not implemented.

GW DCPD
Will be in-vac!



Parameter	Requirement	Actual
AP2 power ratio	0.005	0.005
GWS photodetector frequency response	DC - 10 KHz	DC - 10 KHz
Seismic velocity of GWS photodetector	TBD	TBD

Many interesting questions

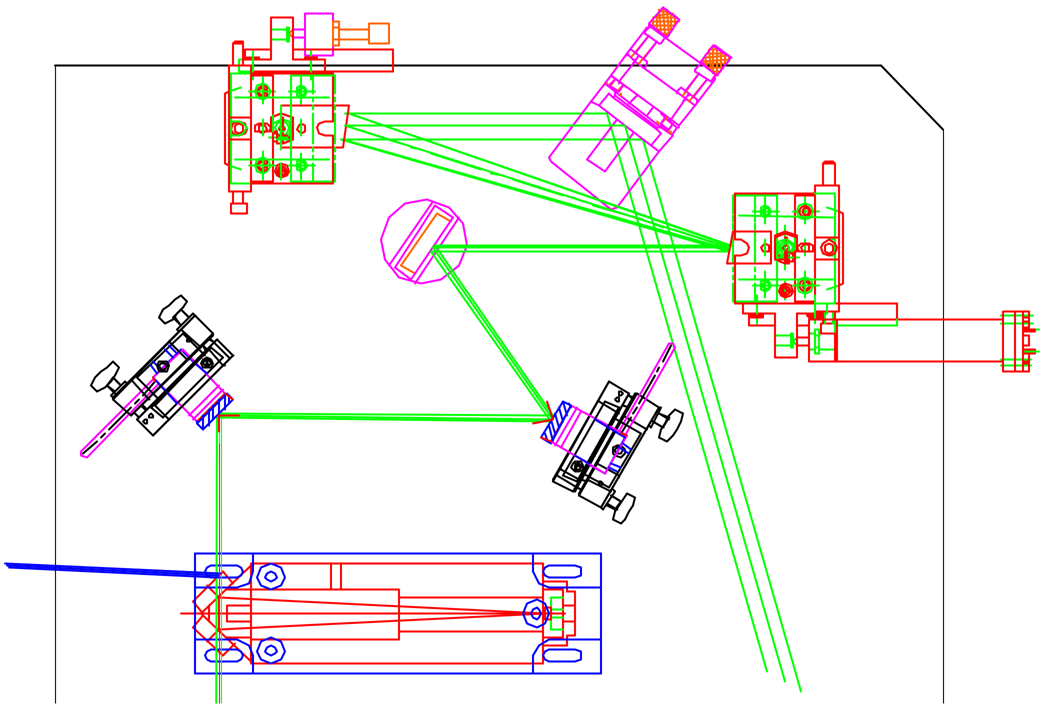
- First and foremost: given the 40m environment,
  is the entire task worth pursuing? What will we learn?
- Assuming it is worth pursuing and that we will learn a lot…
- Is the overall scheme sensible? Other/better ways?
- Predict expected noise sources / couplings:
  - laser frequency and intensity noise
  - Mach-Zehnder phase and amplitude noise
  - MICH/PRC/SRC/DARM servo offset/noise
  - OMC servo noise

  Using methods of Camp et al, Mason, Adhikari and Ballmer,…

  Kentaro Somiya accounts for full quantum noise effect, ala Buonanno&Chen.

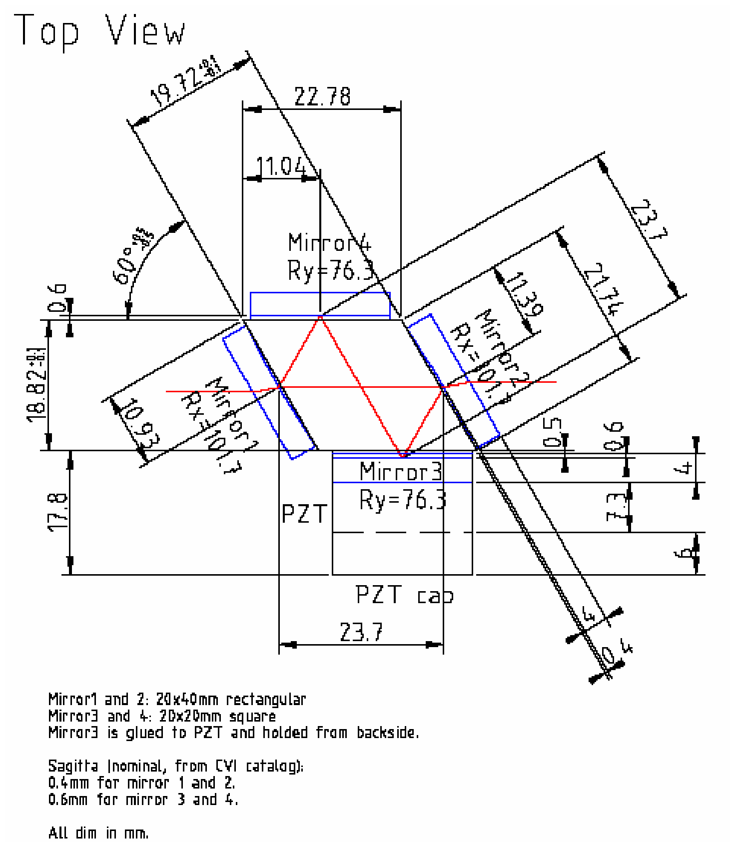
  Must pursue in parallel with design and construction of engineering prototype of homodyne detection.
- OMC: 3-mirror or 4-mirror?

OMC – 3-mirror or 4-mirror?



3-mirror PMC-like?

(incident angle ~42º,
small astigmatism)



K.KAWABE
05/Aug/2004
Ver.002

4-mirror Keita-design?

(incident angle ~30º,
larger astigmatism,
half as many HOM accidental resonances)

Many interesting questions / 2

- Locking the OMC: PDH reflection locking? Dither-lock?
  - Will using the RF sideband (+166 MHz) to reflection-lock imprint the very noise we are trying to get away from, onto the transmitted carrier light, thus defeating the primary purpose of homodyne detection?
  - Is dither-locking simple and straightforward? At 8192 Hz or 4096? (We routinely ditherlock our Michelson at 120 Hz).
- To get the arm-filtered DC light out the AP:
  - offset lock the arms?
  - offset-lock the MICH?

$$E_d{}^c = \frac{E_m{}^c}{2} t_r G_r{}^c \times \left[\frac{A_{cm}\left(1 + i r_f \frac{\omega}{\omega_c}\right) + i G_a k \,\mathrm{d}x_{a-} + i k \,\mathrm{d}x_{r-}}{\left(1 + \frac{i\omega}{\omega_{cc}}\right)} \right], \qquad (23)$$

From seminal paper by Camp/Yamamoto/Whitcomb/McClelland (J. Opt. Soc Am 17, 120)