Design and Performance of the Output Mode Cleaner

河邊 徑太 (Keita KAWABE)

Reference: LIGO-T04158-00-D
http://www.ligo-wa.caltech.edu/~kawabe/OMC/

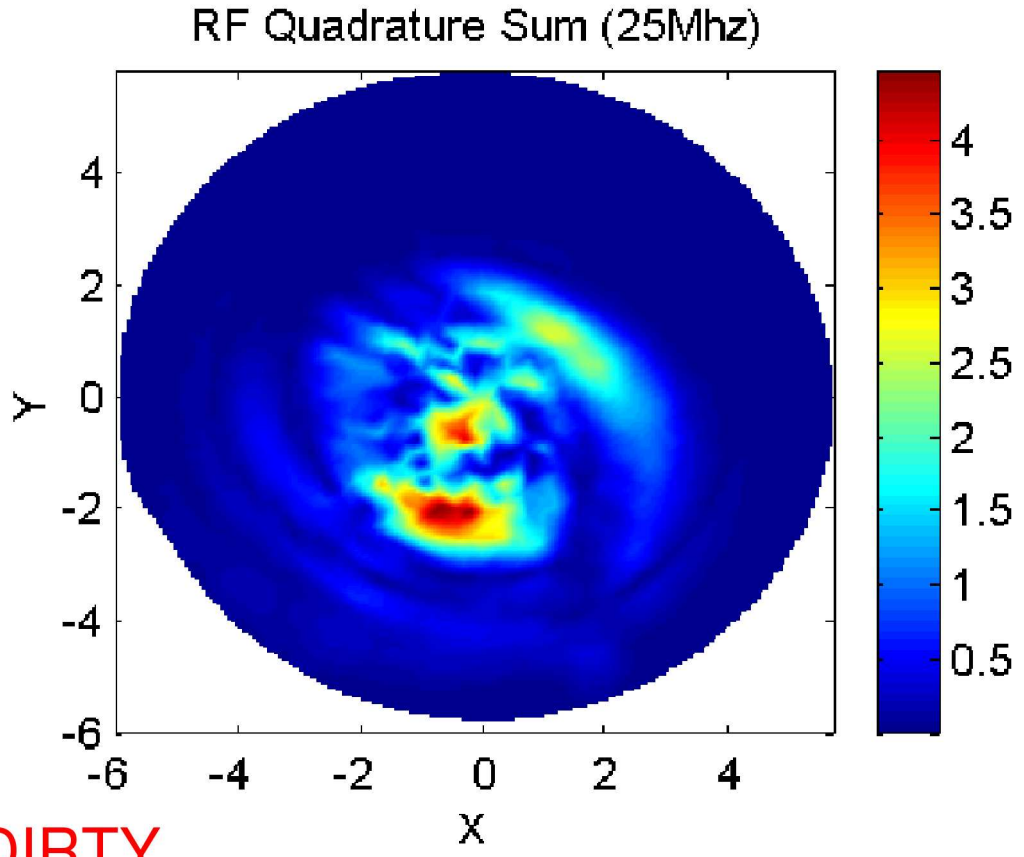
TOC

1. Why OMC
2. GEO OMC in H1
3. Excess Noise Mechanism
4. New Design Principle
5. OMC in the (near? far?) Future
6. Other Things to Consider

1. Why OMC?

AS port:

Video image (DC) and Phasecamera (25MHz)



DIRTY

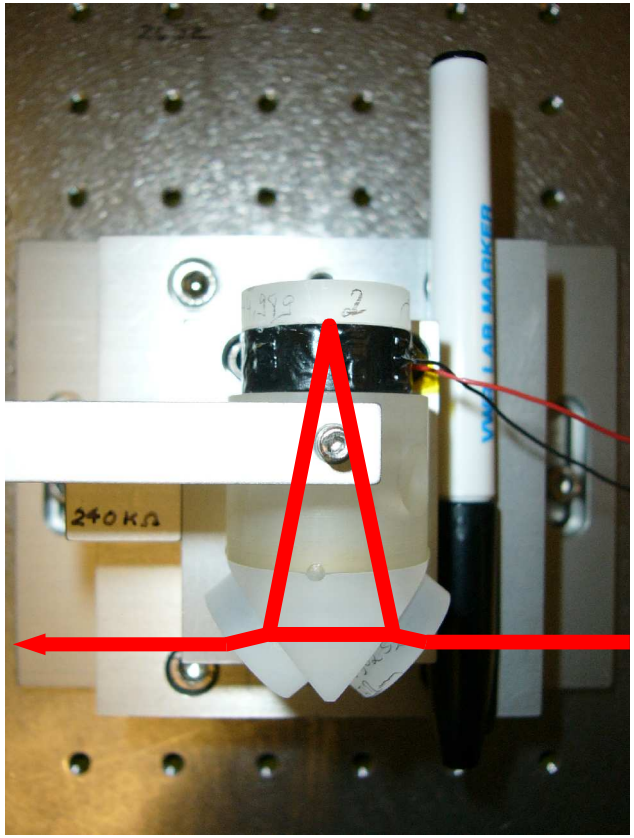
Now it's almost obvious...

"Dirty" field should be rejected

- to achieve shot noise limited sensitivity
- to stay away from potentially nasty interference of higher order modes

→ Use a discriminator: OMC

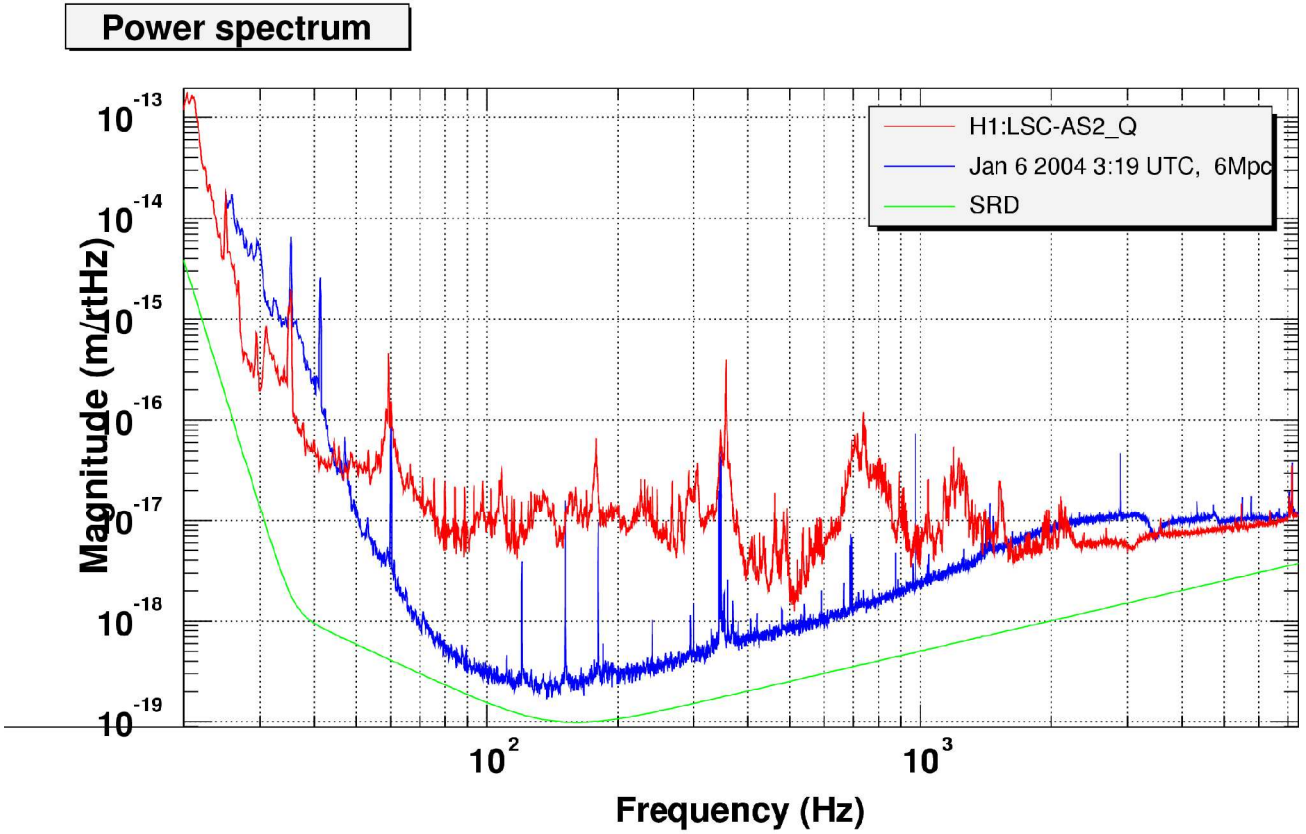
2. The GEO OMC in H1



- Triangular cavity
- Round trip 10cm, FSR 3GHz
- TMS = 0.305FSR
- Finesse 30, fc=50MHz
- Waist radius 0.1mm
- “Borrowed” from GEO
  - Thanks GEO!

Performance

Huge excess noise with the OMC



PeterF and Stefan, May 11

And What's This?

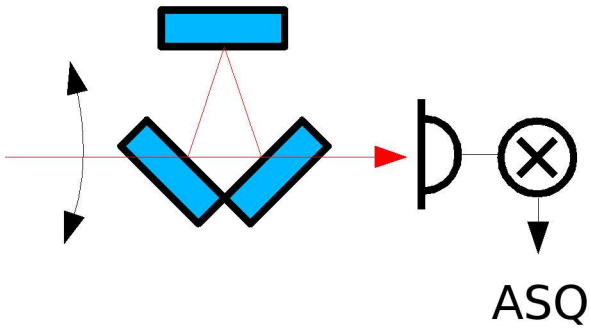
- Seemed to be of acoustic origin
- Large jitter-to-error coupling
  - Seemed to be bi-linear
  - Nobody killed the linear term, though
  - DC pointing stabilization didn't help much
  - Horizontal coupling always larger
    - → (Indicates some modal mechanism)

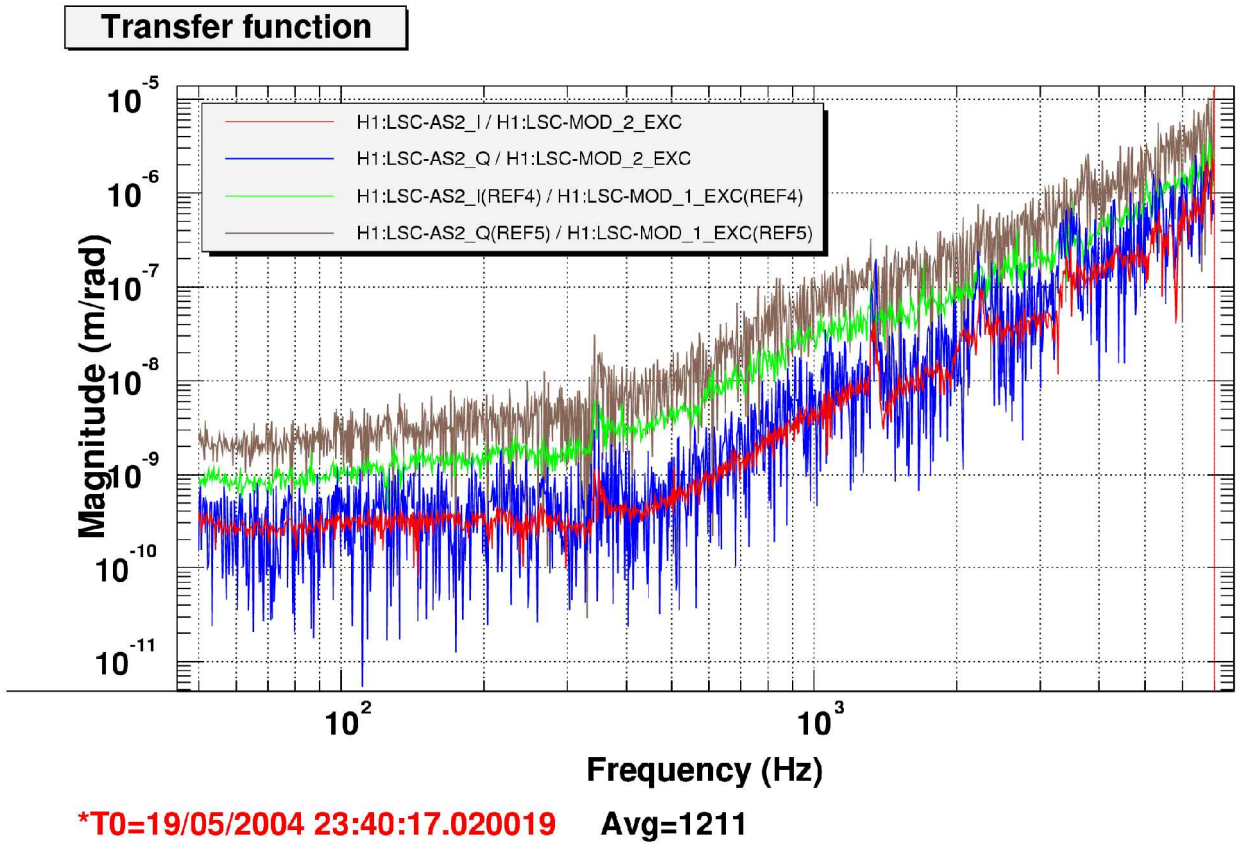
Jitter-Error Coupling

Coupling was huge (so huge that even the small jitter that cannot be measured by QPD would generate the measured excess noise):

$$ASQ/\Delta a_{Yaw} = 6 \times 10^{-9}$$

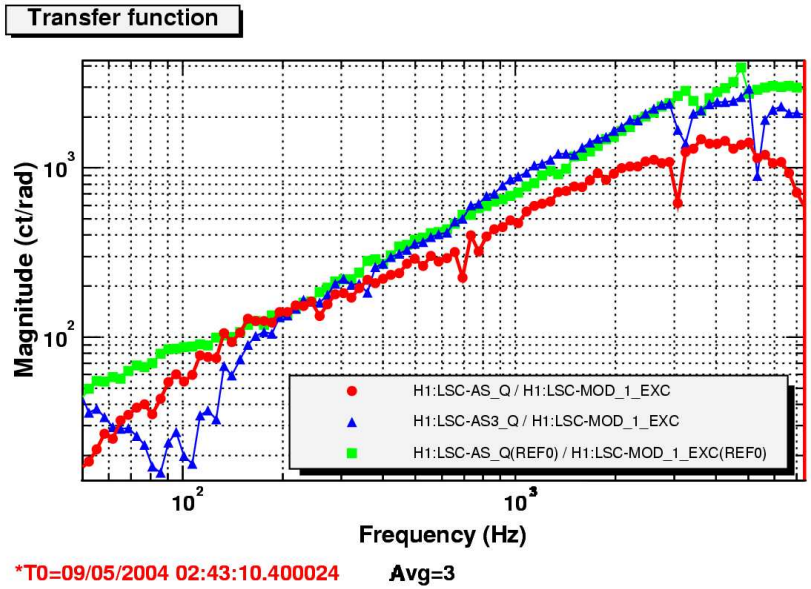
$$ASQ/\Delta a_{Pit} = 9 \times 10^{-10}$$





Stefan and Nergis, May 19

(But Don't Forget Several Things That were Actually Good)



PeterF and Stefan, Sun May 9

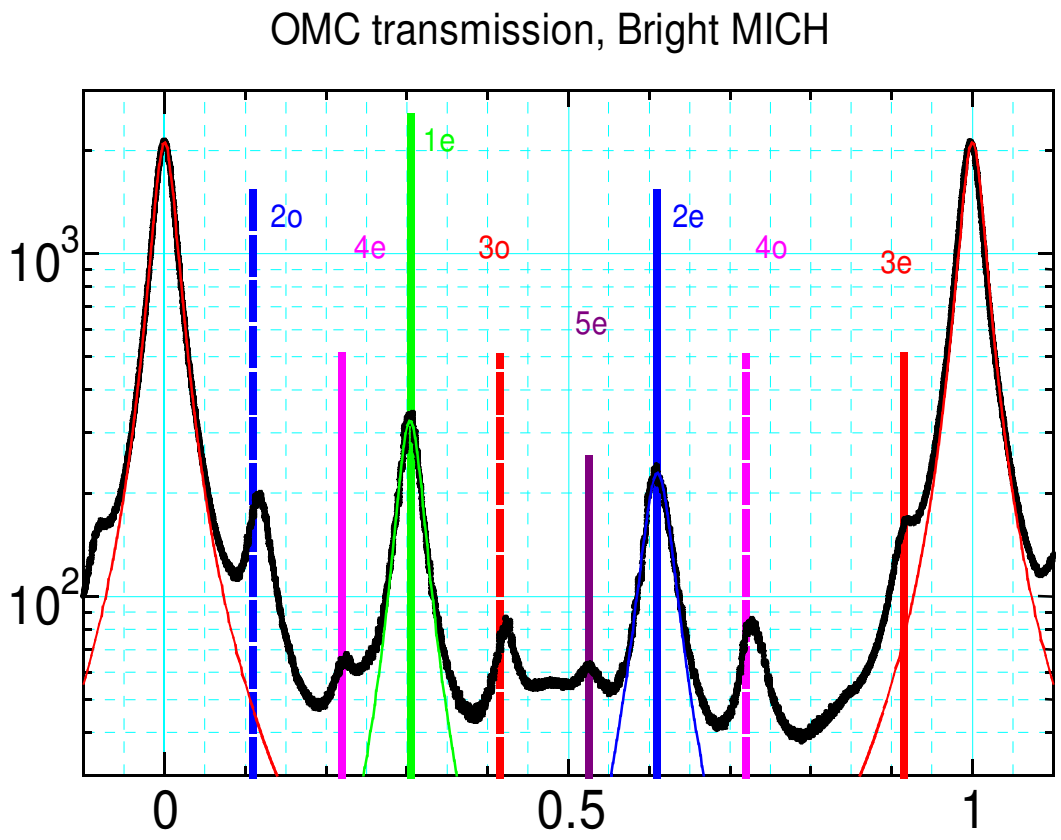
- Smaller OSC PN Coupling
- Better balance in SBs
- Smaller AM
- ... and so on

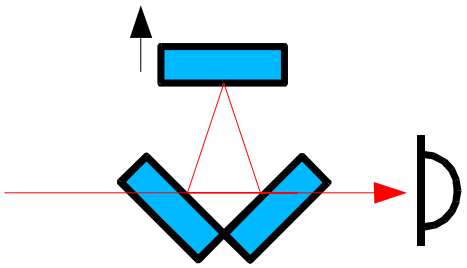
3. Excess Noise Mechanism

- Cavity parameters
- Higher-order mode coupling model

Cavity Parameters

OMC scan in Bright MICH

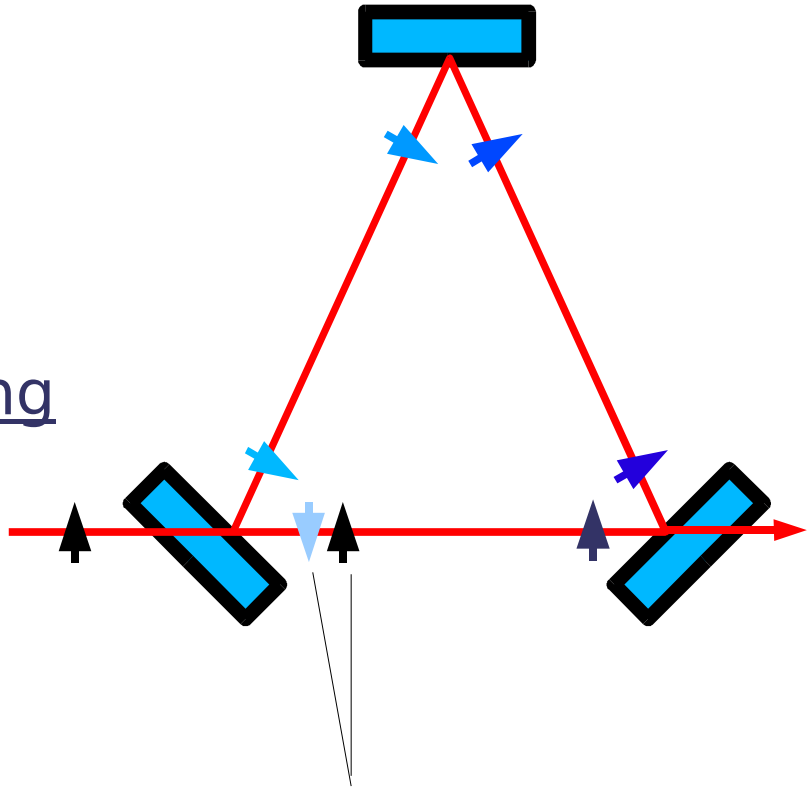




- TMS=0.305FSR
- F=30

3-mirror Oddity

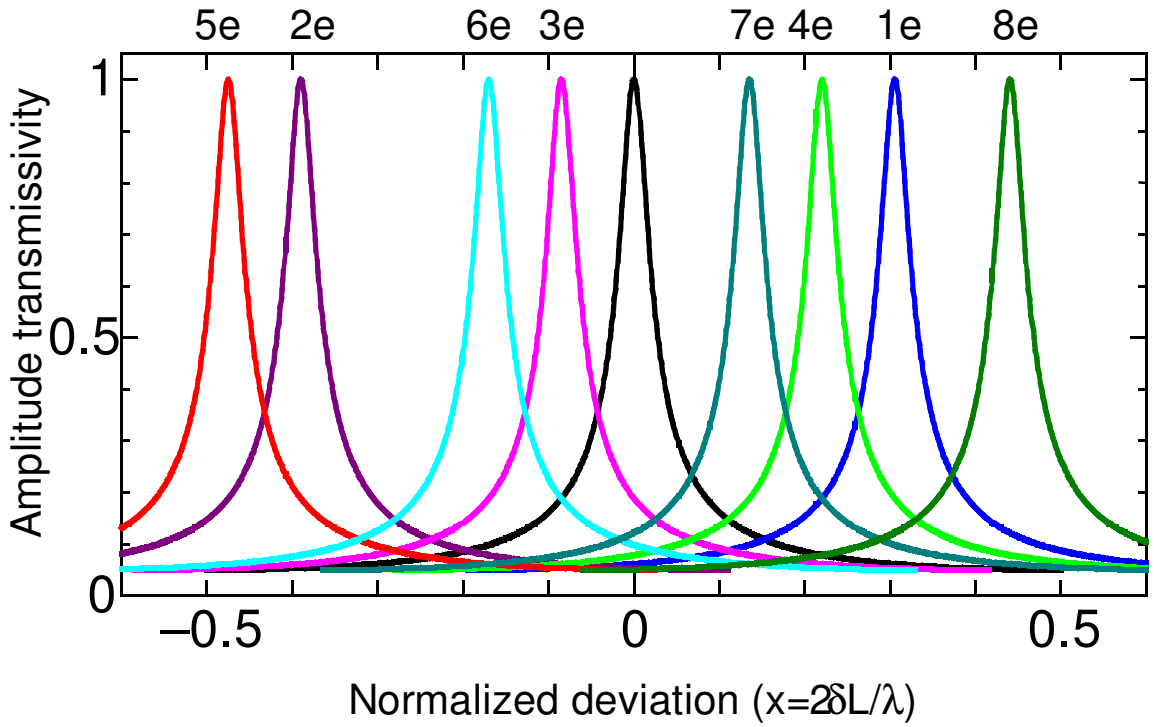
What used to form a set of same order degenerate modes in linear cavity (e.g. {U20, U11 and U02}) are split into two groups depending on the horizontal symmetry (e.g. {U20, U02} and {U11}) (you can clearly see this in the OMC scan data).



180deg phase flip!

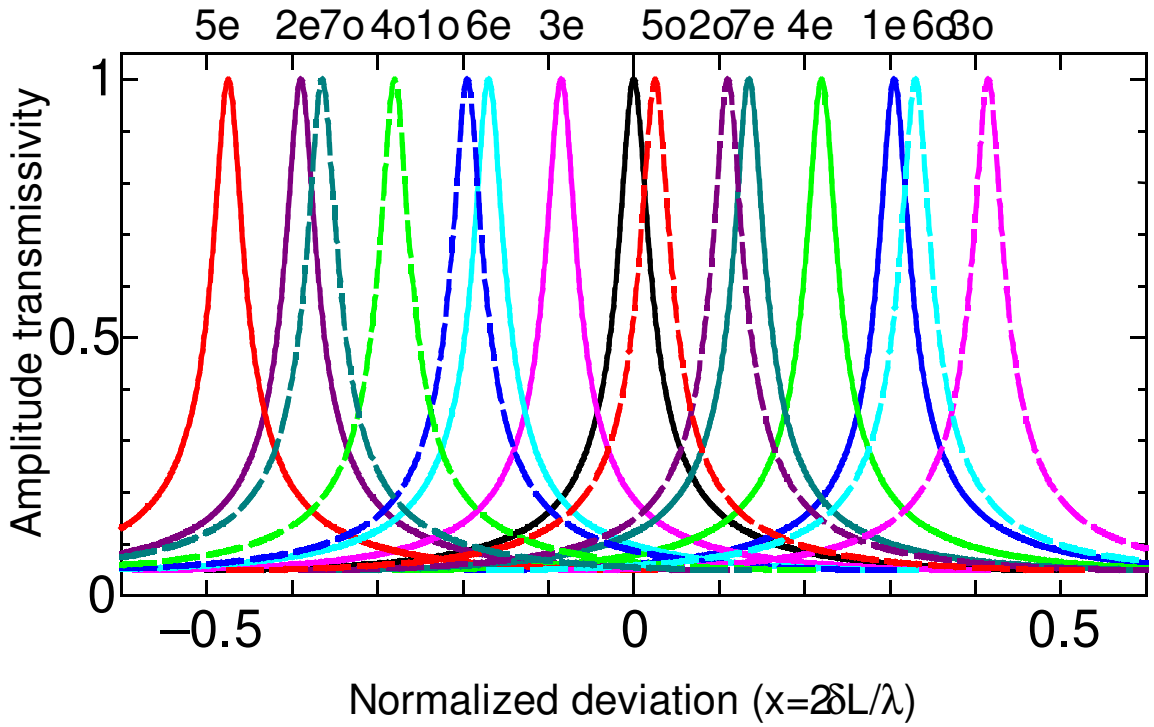
If it were a Linear Cavity,

Things would have looked reasonable

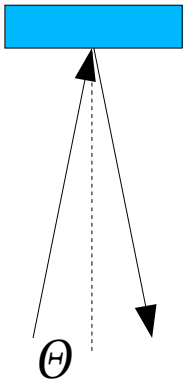


Due to the Split by 3-mirror Configuration,

n+m=5 with n=odd comes close to the resonance

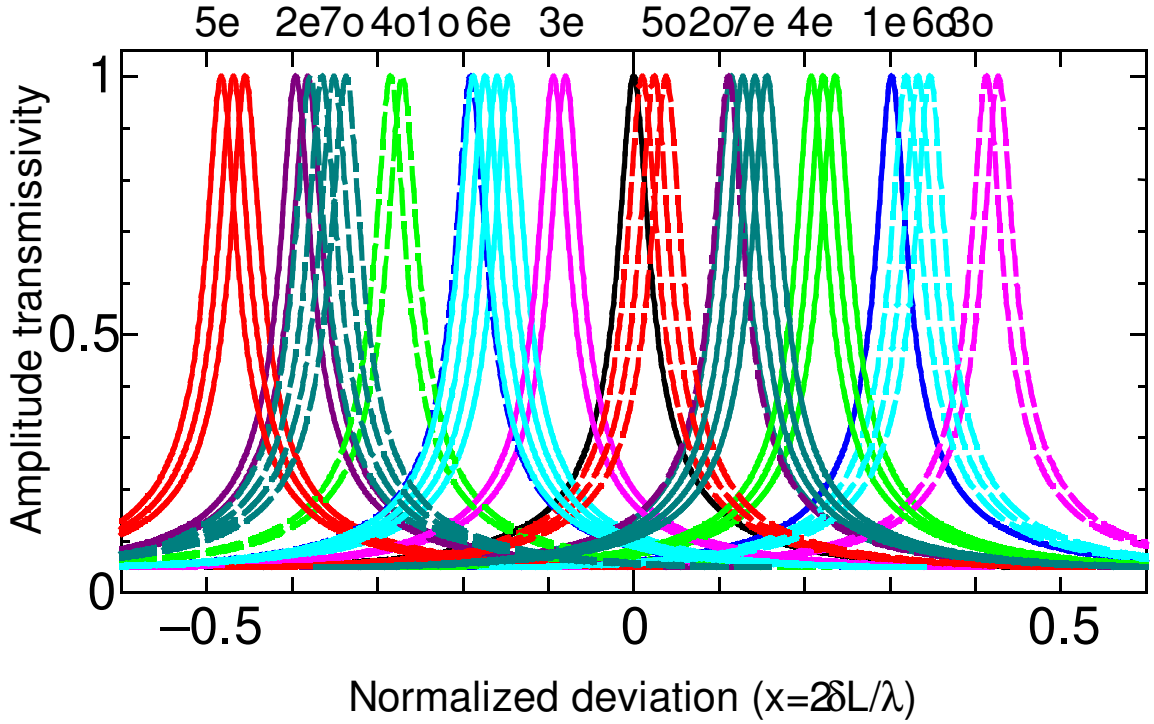


Split Due to Gouy Shift Difference



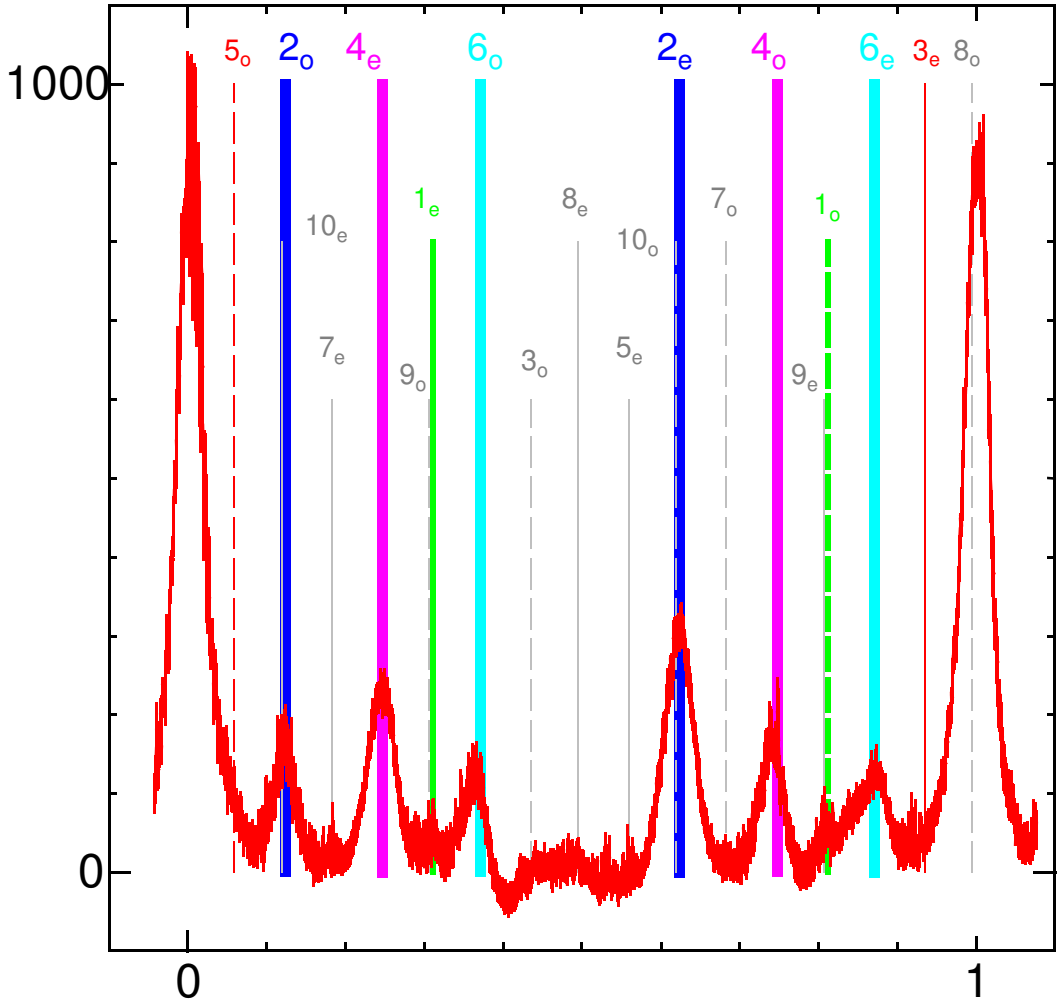
$$R_x = R\cos(\Theta)$$

$$R_y = R/\cos(\Theta)$$



“5o” in AS Field?

OMC Scan using Detect AS field

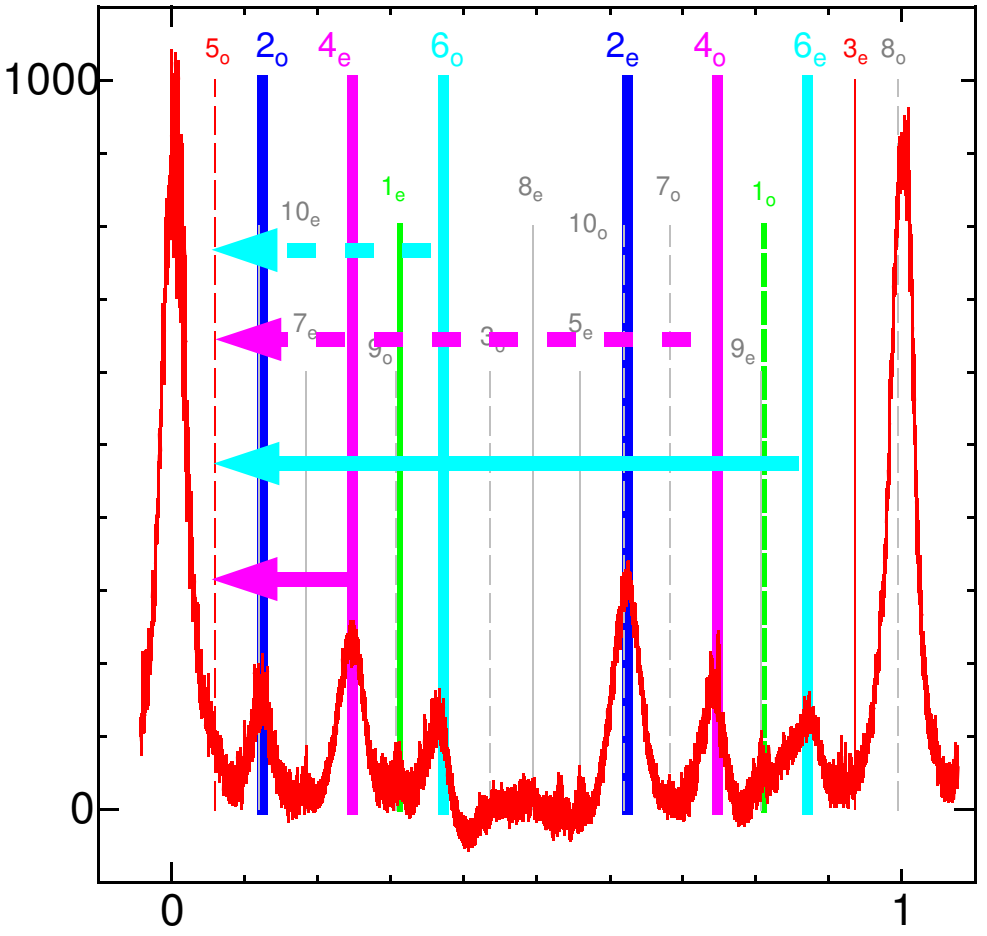


TEM00:	43%
“2e” (20+02):	14%
“2o” (11):	9%
"4e":	11%
"4o":	10%
"6e":	6.7%
"6o":	6.7%

But NO visible "5o" field

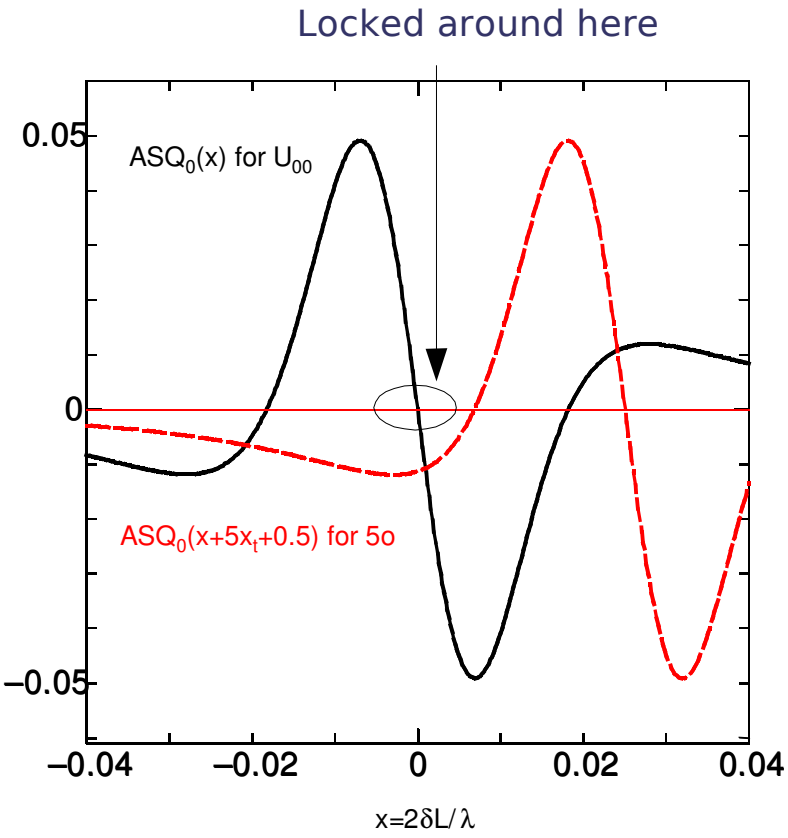
Misalignment “scatters” harmless modes to “5o” via misalignment

- (m,n) mode is “scattered" to (m+-1, n) by misalignment in yaw, and to (m, n+-1) by pitch.
  - e.g. U40 -> U50 and U30 by yaw
- "4e" and "6e" are scattered to "5o" by yaw, while “4o” and “6o” are to the same “5o” by pitch.



Each Transmissive Mode Makes PDH-like Signal in ASQ

Without misalignment, only TEM00 makes its PDH-like signal, but this is OK as the OMC is locked to TEM00 C resonance.



With misalignment, "4" and "6" modes couple to "5o" that is so close to (but not completely on) resonance, creating some non-negligible error signal proportional to the power of "5o" mode.

$$Excess\ Noise \approx ASQ_0(5x_t + 0.5) \times \left(\frac{\delta a}{w_0}\right)^2$$

The Model Seems to be Consistent with the Observation

- Coupling is quadratic
- a/w=1/4 (6.3% power loss) would give the coupling of 6x10^{-9} (the measured value).
- Coupling is dependent on modal composition
  - → Yaw and pitch sensitivity can be different
- Beam pointing stabilization cannot mitigate the effect caused by the IFO misalignment, even in DC

OMC Excess Noise Summary

We seem to be suffering because:

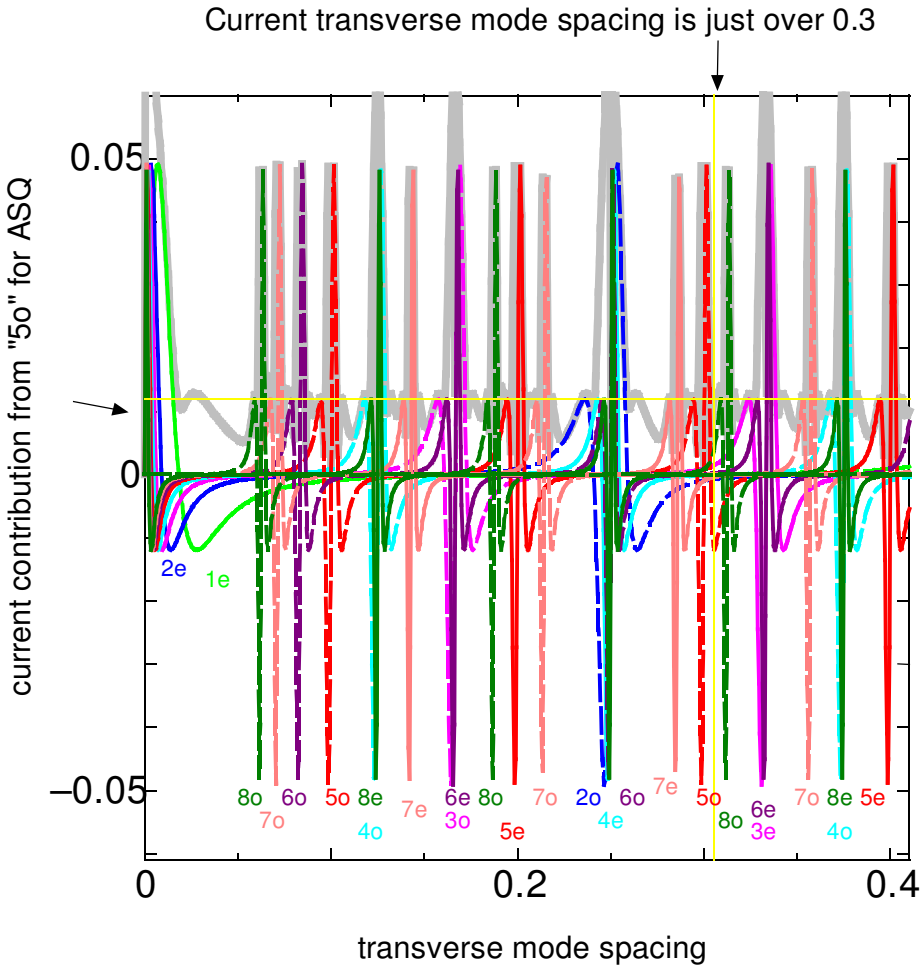
- The OMC is half transmissive for "5o" because of the triangular configuration
- The OMC has some sensitivity to length change (because the SB are not completely resonant)
- The AS field has a large “4” and “6” modal component that would couple to "5o" via misalignment.

4. New Design Principle

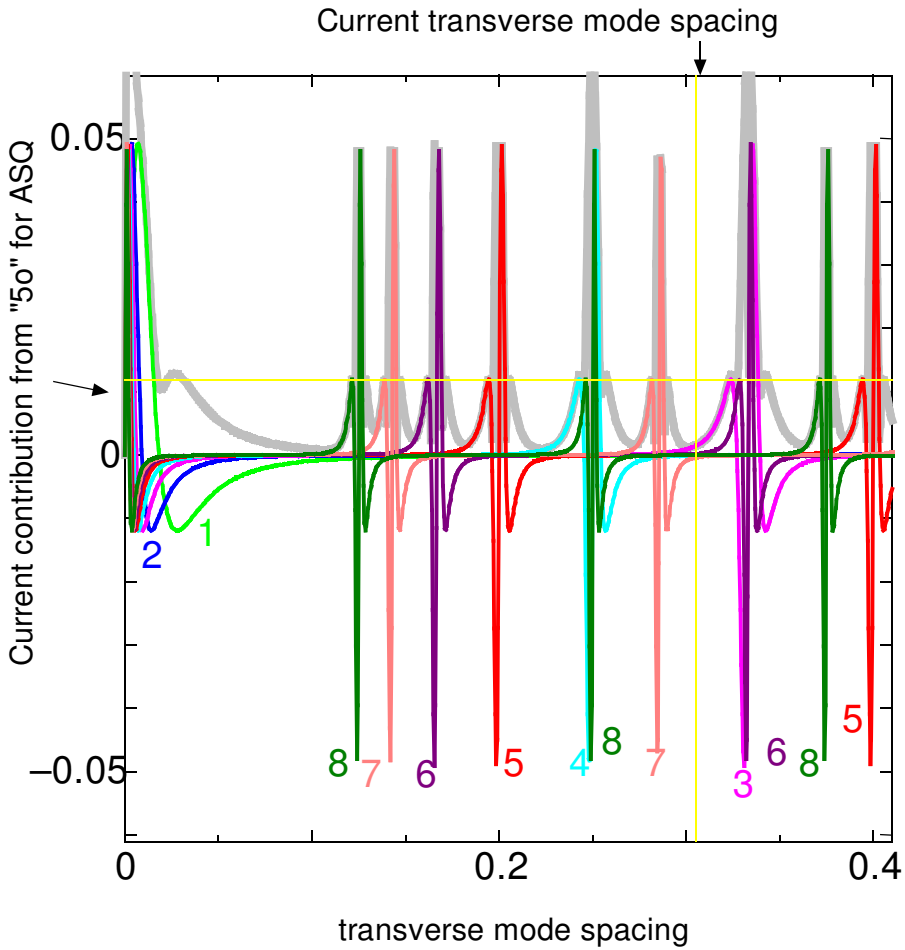
- Higher discrimination for higher order modes
  - Better degeneracy for higher order modes
    - Even number of mirrors (instead of 3)
    - Equalizing the Gouy shift for H and V
  - Higher finesse (be careful, though)
- Make the cavity less sensitive to the length fluctuation
  - Shorter Length (or LOOOONGER)

Better Degeneracy by Using Even Number of Mirrors

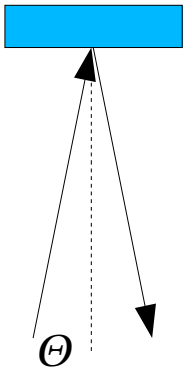
Error signal of various modes against the TMS for Triangular OMC



Same plot for 4-mirrored OMC: Less "crowded"

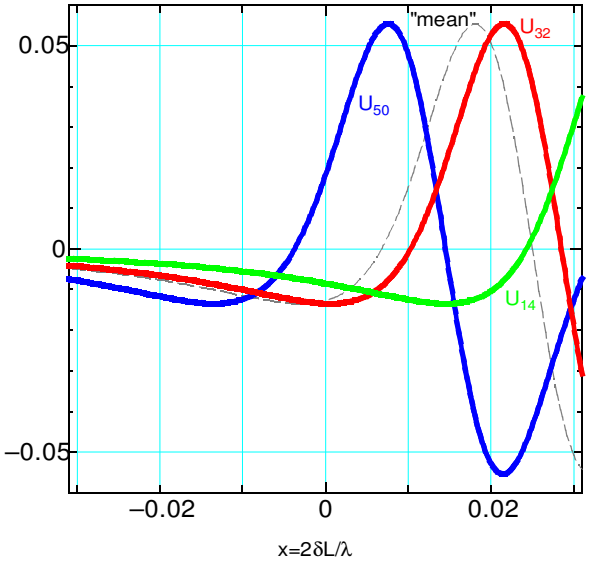


Better Degeneracy by Matching the Gouy Shift for H and V



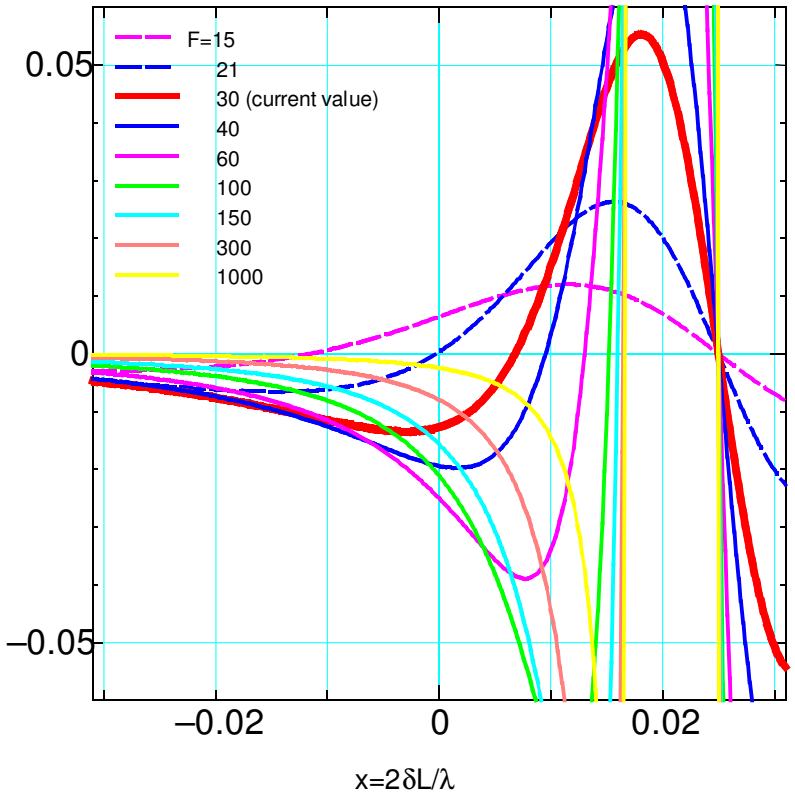
$$R_x = R\cos(\Theta)$$

$$R_y = R/\cos(\Theta)$$



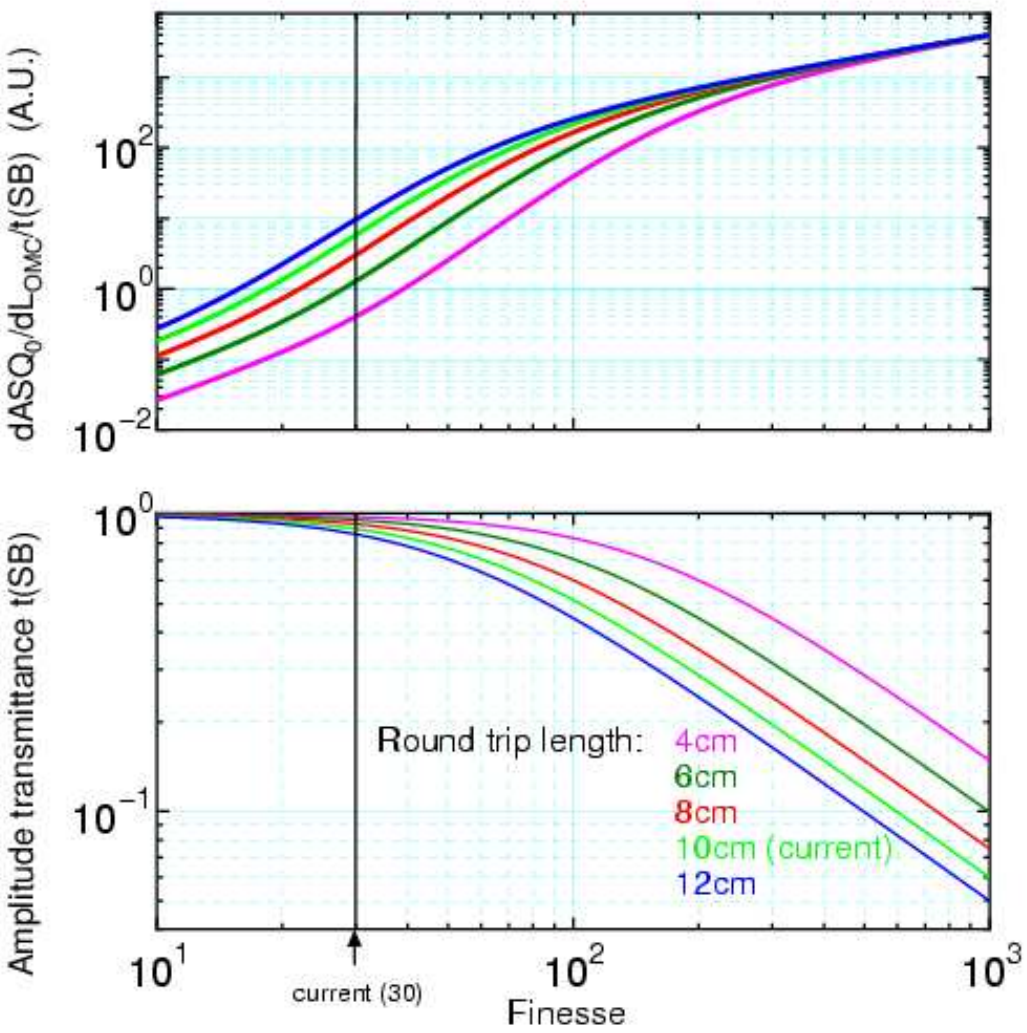
- Finite incident angle on curved mirrors
  - ROC difference for H and V
  - → Gouy shift difference for H and V, making otherwise degenerate modes split again
- Can be eliminated/mitigated by various geometrical tricks

Higher Finesse (be careful!)



- OMC becomes more sensitive to the length while GW signal gets smaller
- If something is close to resonance, we have to make the finesse VERY high, which we don't want to do.
- Therefore higher finesse doesn't help much the triangular configuration, but it helps the 4-mirror OMC.

Shorter Cavity (or Longer)



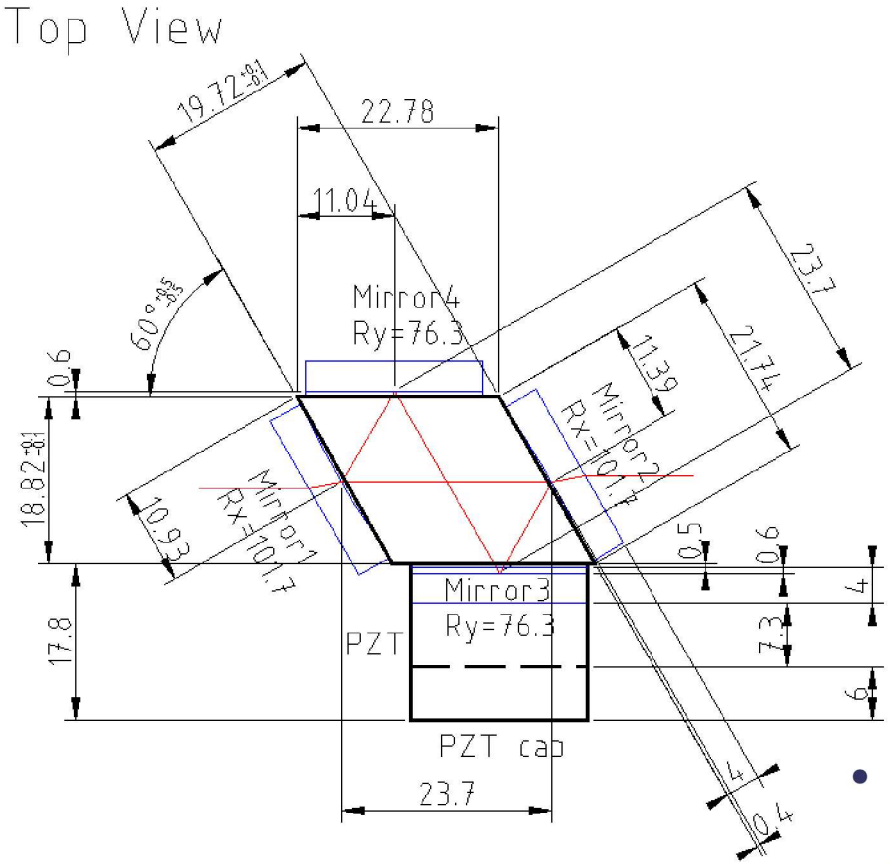
- Larger FSR
  - SB "closer" to C
  - Less sensitive to length
  - Smaller alignment coupling
- Or, FSR equal to SB (i.e. 12m roundtrip)
  - Both SB and C resonant
  - No sensitivity to length

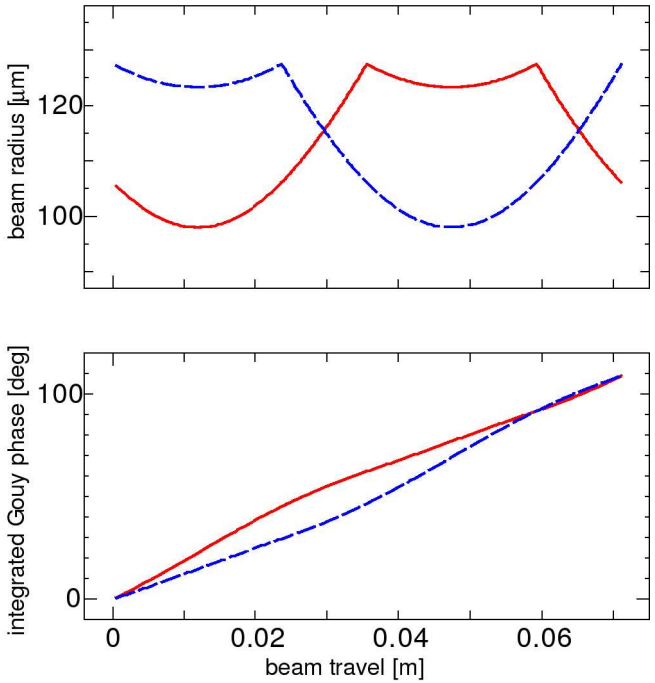
5. OMC in the Future

New OMC is on its way

- "Proof of concept" OMC to be tested in H1 (hopefully) to mitigate the effect (and confirm the validity of the model)
  - 4 mirrors instead of 3
  - Shorter (7cm round trip)
  - Cylindrical mirrors to equalize the Gouy shift for H and V
  - Higher finesse (60)
- A factor of 30 mitigation expected
- Waiting for the delivery of the mirrors (2nd week Sept.)

Geometrical Parameters





- Incident=30deg
  - → Rx/Ry=4/3
- Small difference in H and V beamsize
- Yet the Gouy shift per round trip is the same

Implication for Future Design

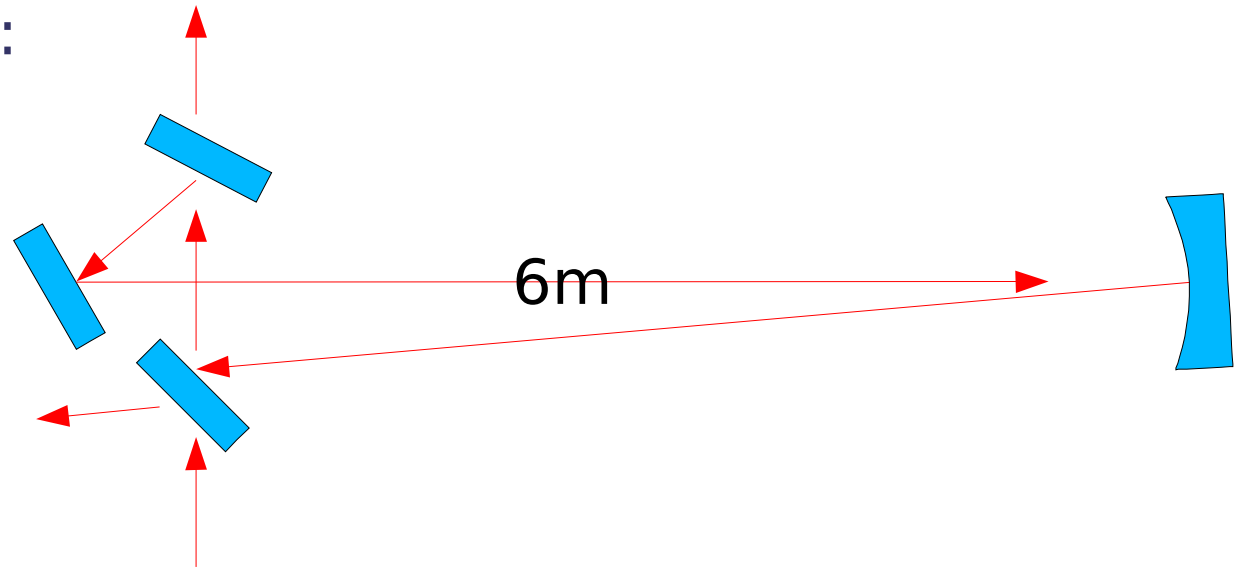
Assumption: Probably we want/need the OMC (remember the good things OMC did for H1)

- Basic idea should be "to stay on safer side"
- The followings are recommended independently of our detection method:
  - 4-mirror configuration
  - Longer roundtrip, making the incident angle small, or shorter cavity with some tricky things to equalize Gouy shift
- Everything else is dependent on the detection method, i.e. RF or DC

RF Detection (Conventional)

- FSR=f_{SB} (i.e. 12m roundtrip for 25MHz)
  - OMC becomes insensitive to length.
  - We can make finesse larger without any penalty on GW signal amplitude

example:



DC Detection (Adv-LIGO?)

- I cannot say anything as I know nothing about Adv-LIGO details (yet) (tell me references!)
- SBs (if they aren't turned off) should be rejected
  - → FSR should be different from f_{SB}
  - → FSR and TMS should carefully be chosen:

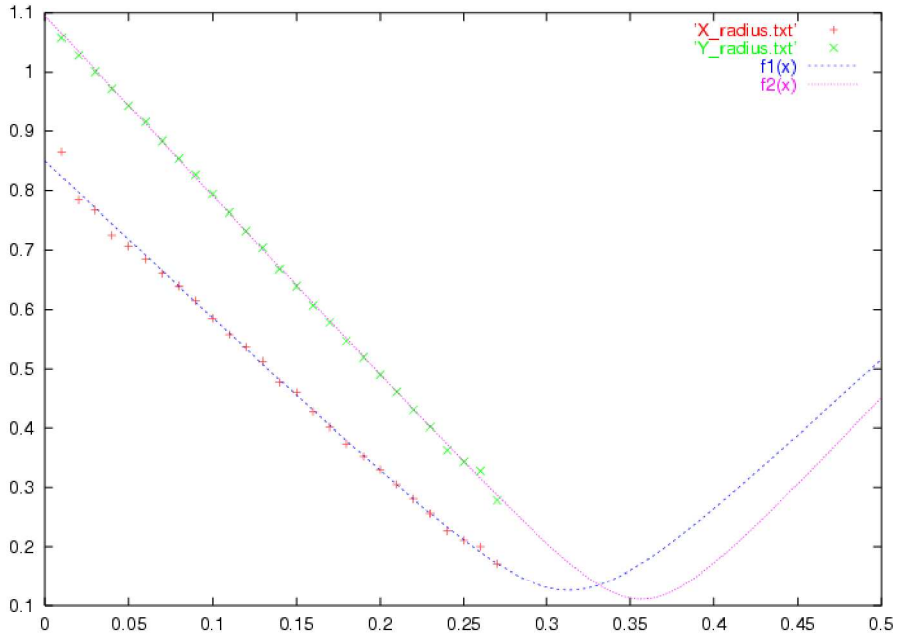
$$n f_{TMS} + m f_{SB} \neq pFSR \left(n, m, p : integer \right)$$

- OMC will always be sensitive to length
  - There's always going to be penalty for higher finesse

6. Other Things to Consider

How to improve the AS field quality?

- Heating should help.
- HUGE Astigmatism in AS field. Why?



Waist position difference larger than Rayleigh range:
JosephB and Luca, 14 Apr

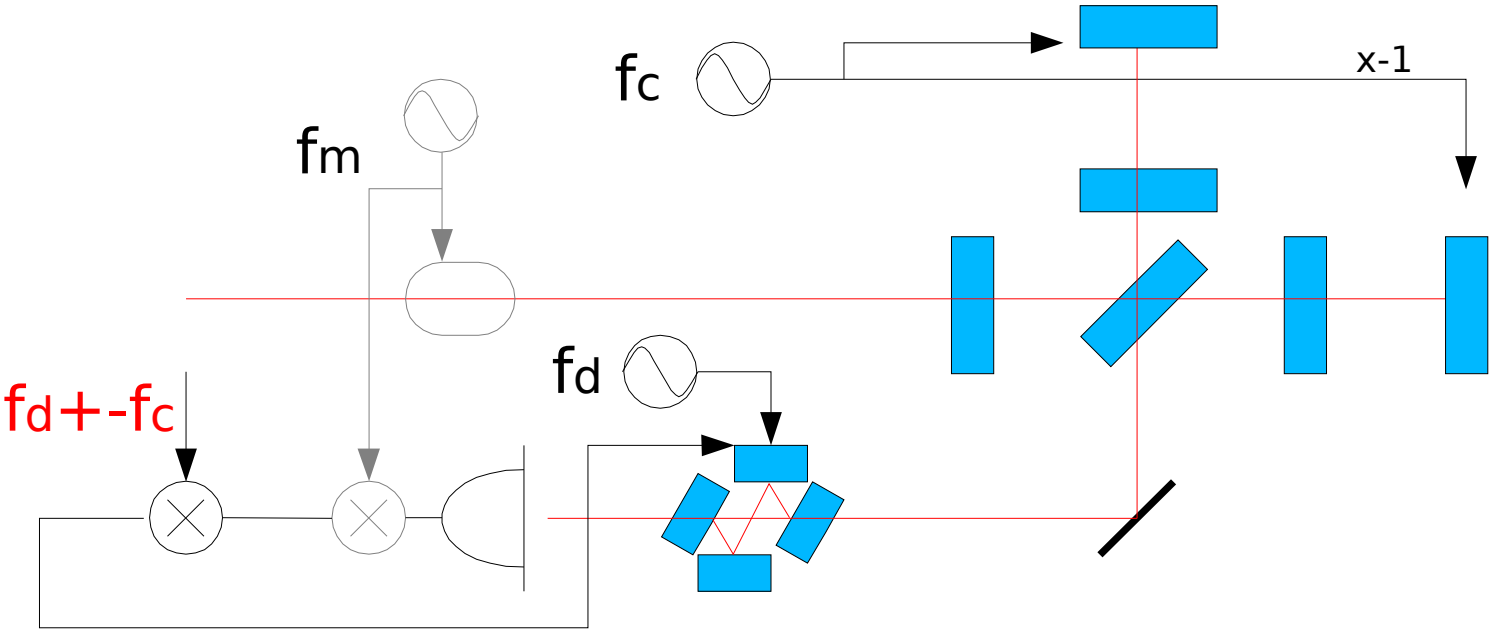
Other Things (Cont'd)

How to mode match the OMC? To What?

- ATM, it is matched to Bright MICH field and we cross fingers and hope that it is not too different from ARM field. Aren't there any better way to look into the ARM field information?
  - Matching to maximize DARM Cal in ASQ (in RF) or in AS-DC (in DC detection).
  - In RF detection, if the SB is way too dirty, we could maximize the 2^{nd} harmonics DARM cal in AS-DC.
    - Both of these techniques can also be used for locking the OMC.

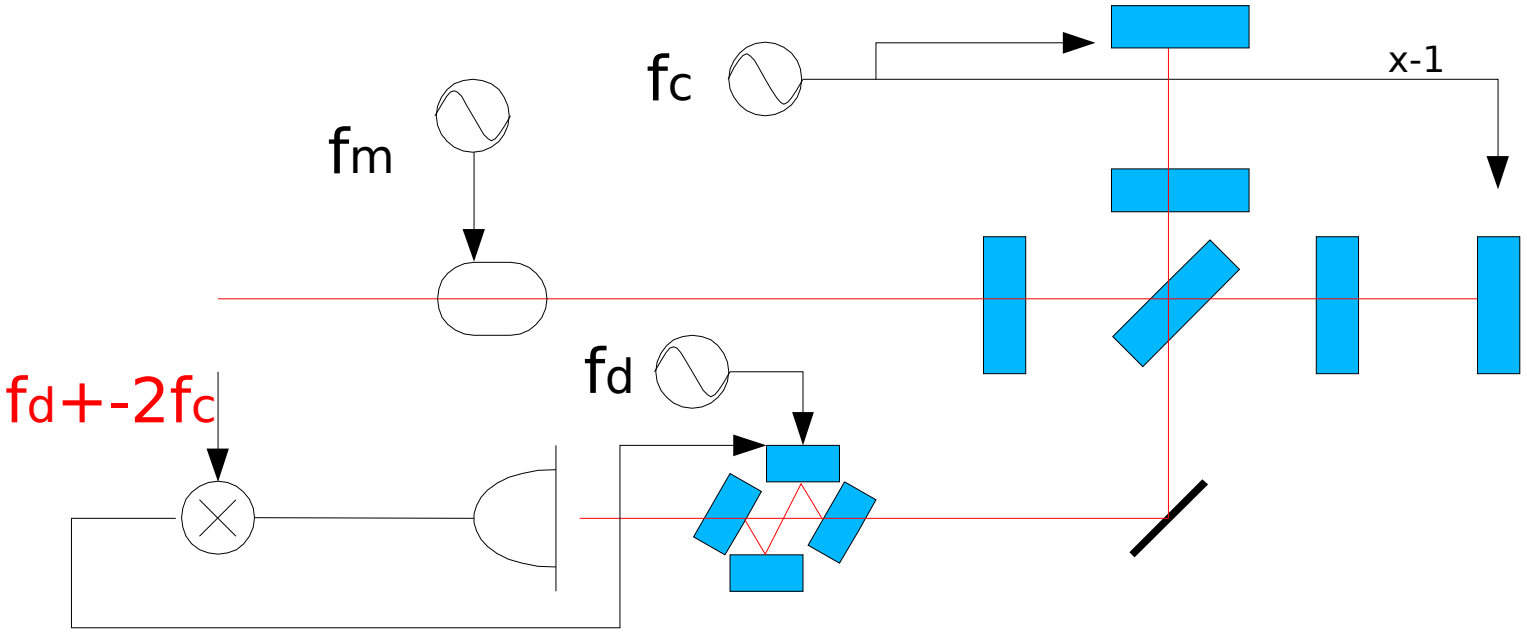
Maximization of DARM Cal in ASQ or in AS-DC

- Maximize the GW signal amplitude
- The signal is proportional to:
  f("pure" ARM carrier) x f("dirty" SB)
  f: Coupling efficiency function to the OMC TEM00
- Can be used both for DC and RF detection



Maximization of 2nd Harmonics of DARM Cal in AS-DC for RF Detection

- If the SB is spacially way too dirty, we might NOT want to use SB information for matching
- In that case, we can use the 2nd harmonics of the DARM cal in AS-DC, which only looks at the carrier that couples to the ARMs.



Locking Techniques Head to Head

- The only reasonable option tested thus far is "2-omega" RF lock, which maximizes USBxLSB, ensuring that C is centered on resonance
  - Cannot be used for DC detection nor when fSB=FSR (no signal)
- “DC" dither lock to maximize the DC throughput was considered to be evil as this gives the offset to C
  - But the offset of C becomes OK when fSB=FSR, and this can also be used in DC detection
- "ASI" lock to equalize the imbalanced SBs was considered to be evil as this gives the offset to C
  - But this becomes OK when fSB=FSR
- Two "maximize DARM Cal" variations can be used in DC detection as well as RF, and seem to be as reasonable as "2-omega" RF lock
  - → Should be studied further

Summary

- Somewhat sad story about the original OMC, but we've learnt (yes indeed a great amount)
  - → Thank you again, GEO guys!
- New design guides/principles are developed
- New OMC on the way
- New matching/locking schemes are studied
- (As always) several things are missing, and we appreciate any help
- Go to Joe's phasecamera presentation tomorrow!