Results of 40m prototype

LSC meeting at LHO

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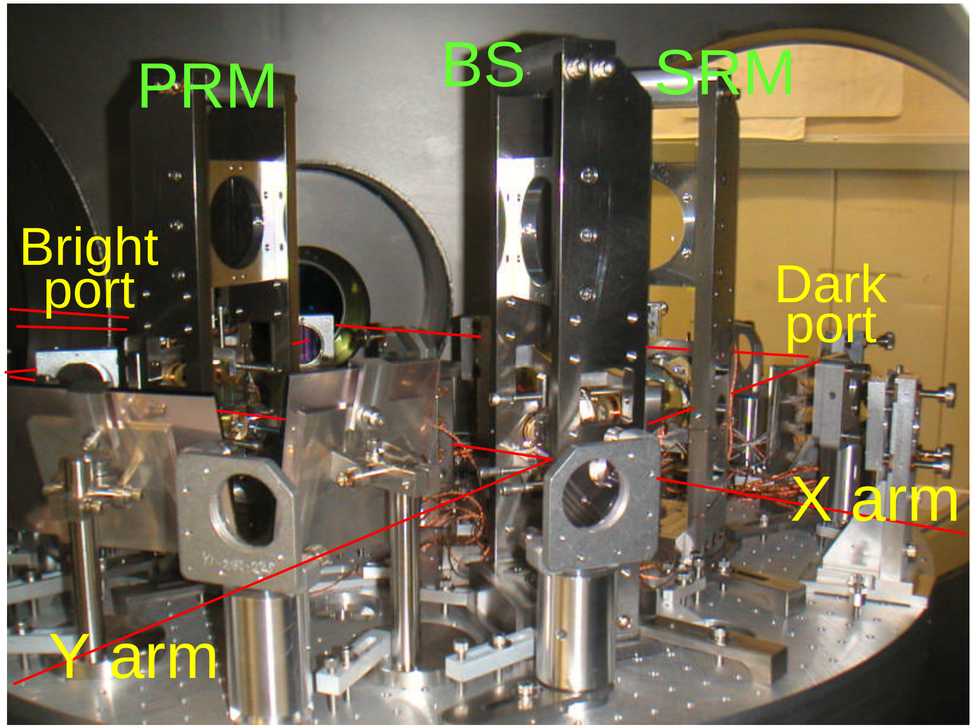
Caltech 40 meter prototype interferometer

We succeeded in locking a suspended-mass detuned RSE interferometer with power recycling.

- **Arm cavity finesse at 40m chosen to be = to AdvLIGO (= 1235)**
  - » **Storage time is x100 shorter.**
- **33/166 MHz Control RF sidebands**
- **LIGO-I 10-watt laser, negligible thermal effects**
  - » **180W laser will be used in AdvLIGO.**
- **LIGO-I single pendulum suspensions**



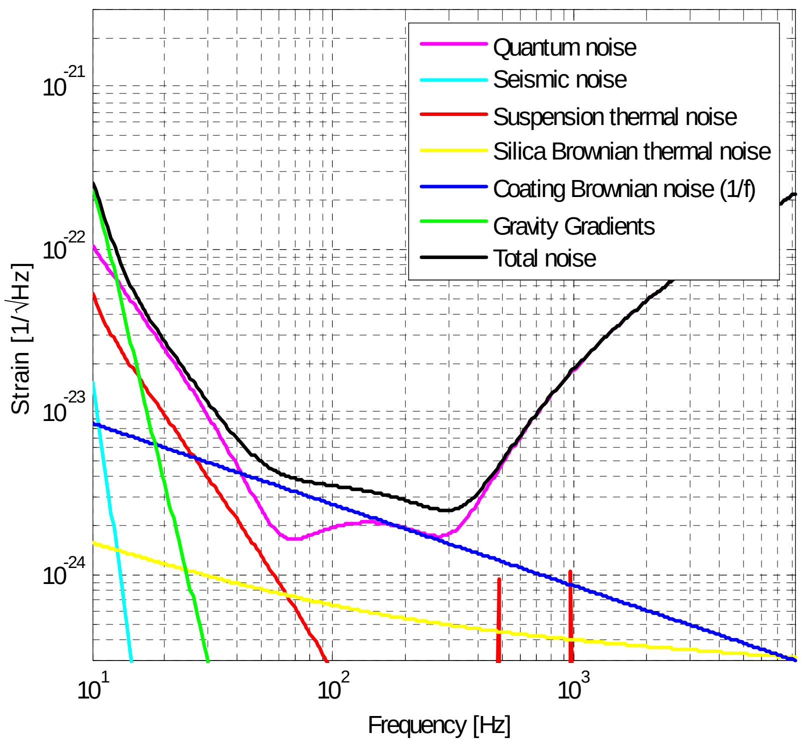
Prototyping will yield crucial information about how to build and run AdLIGO.

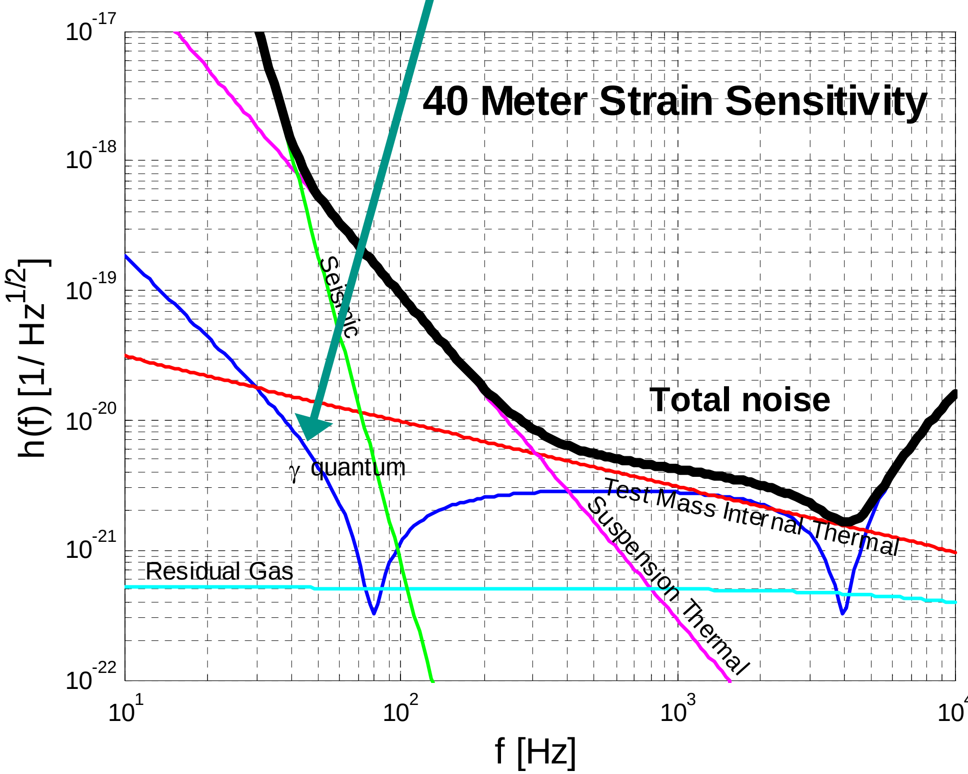
AdLIGO vs. 40m noise curve

Fight the Fundamental Noise Sources:

1) Seismic
2) Thermal
3) Quantum

Not very likely that we'll actually detect any gravitational waves here,
but hopefully we'll learn some things about operating interferometers,
especially about the quantum noise.

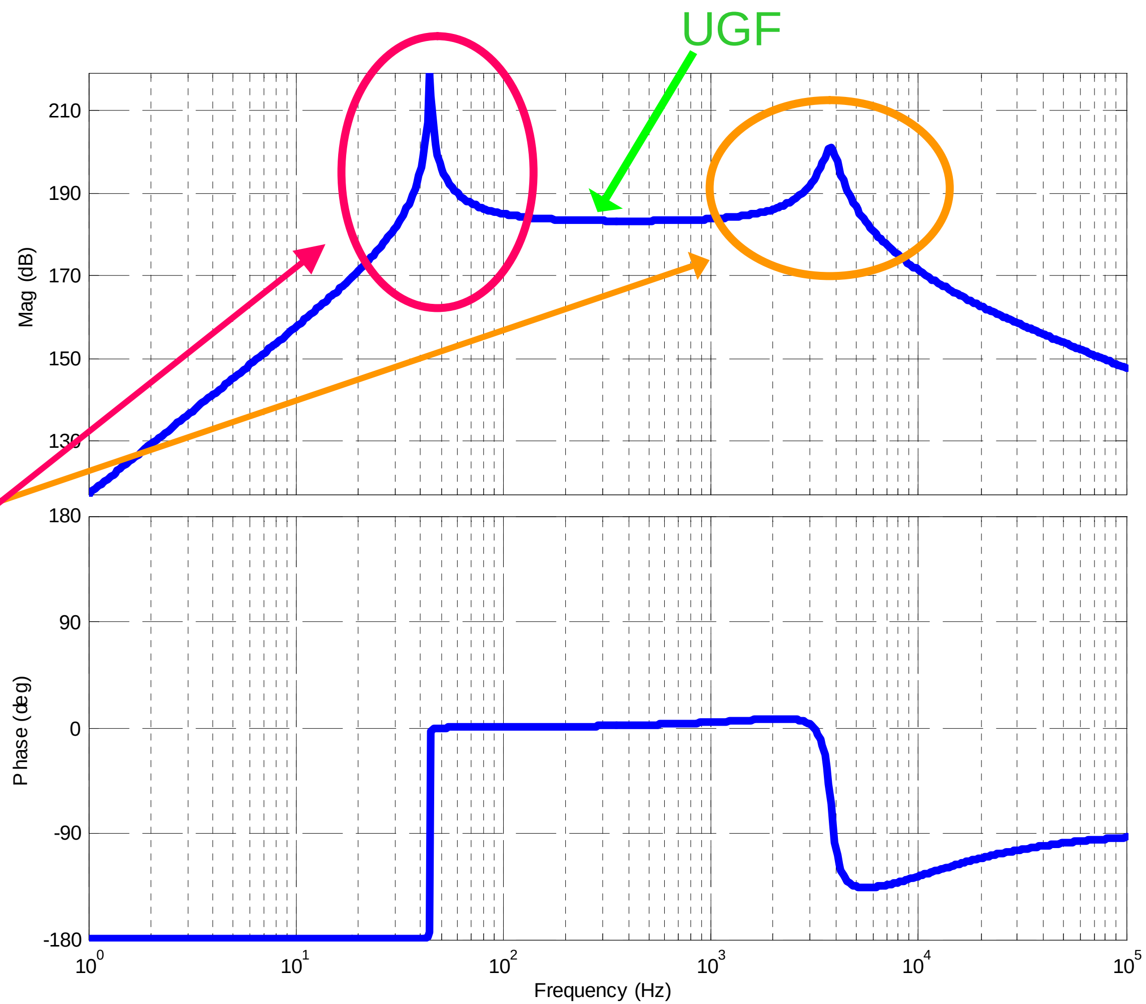




40m DARM Optical Response

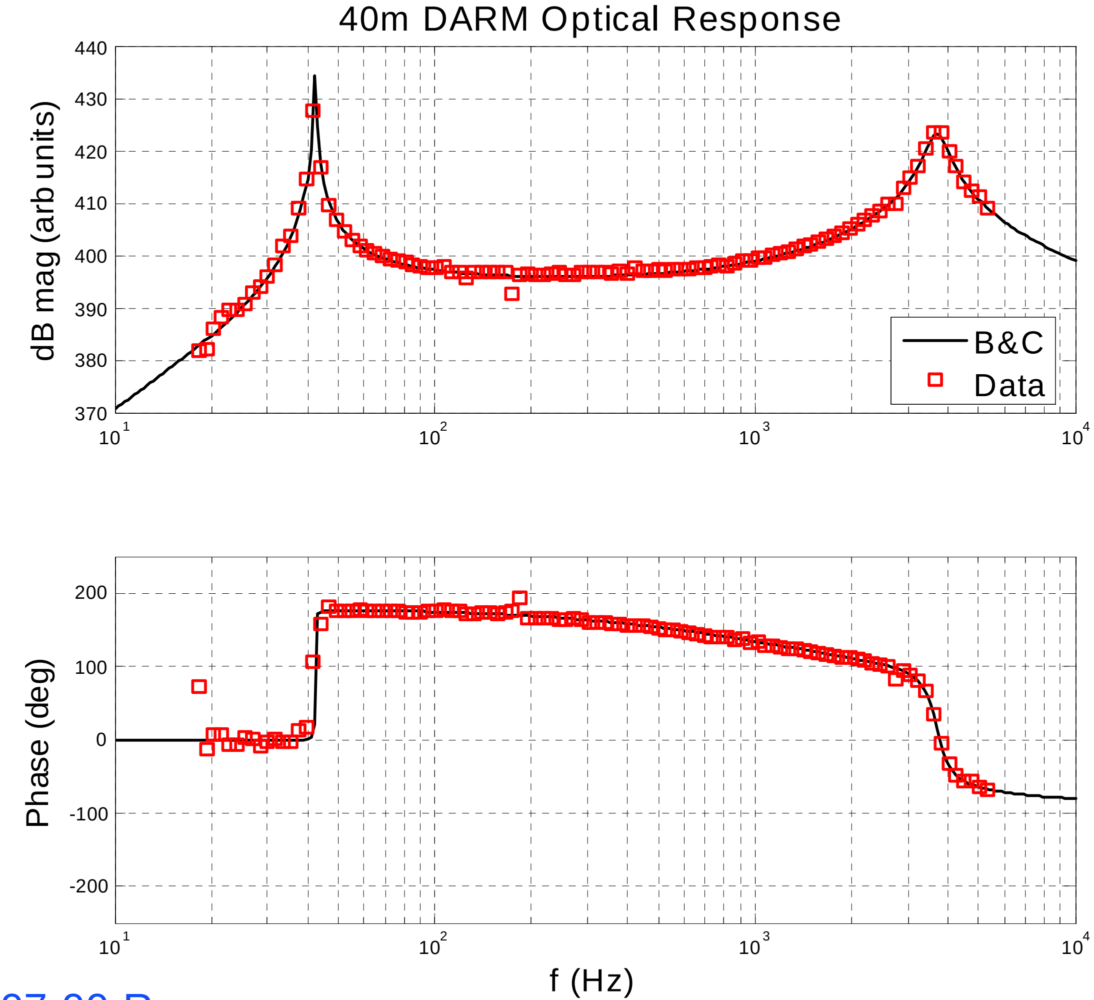
The 40m operates in a
detuned **RSE**
configuration, which
gives rise to **two**
peaks in the DARM
transfer function:

1) Optical Resonance
2) Optical Spring



DARM Optical response
with fit to A.Buonanno & Y.Chen formula

Optical spring and optical resonance of detuned RSE were measured and fitted to ABYC formula.



DARM_in1 / DARM_out

XARM_in1 / XARM_out

times arm cavity pole.

Yields optical response, taking out pendulum, analog & digital filtering, etc.

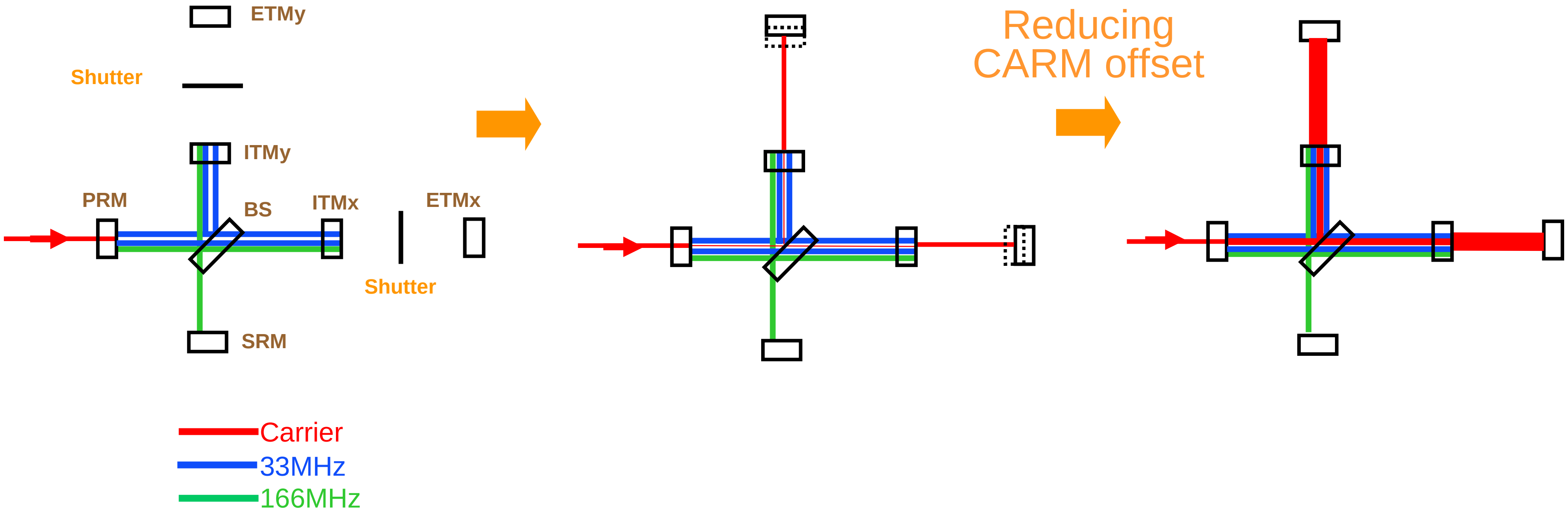
Description of data, fit: P060007-00-R.
http://www.ligo.caltech.edu/~cit40m/Docs/40mTF_060207.pdf

The way to full RSE

Oct. 2004
Detuned dual recycled Michelson

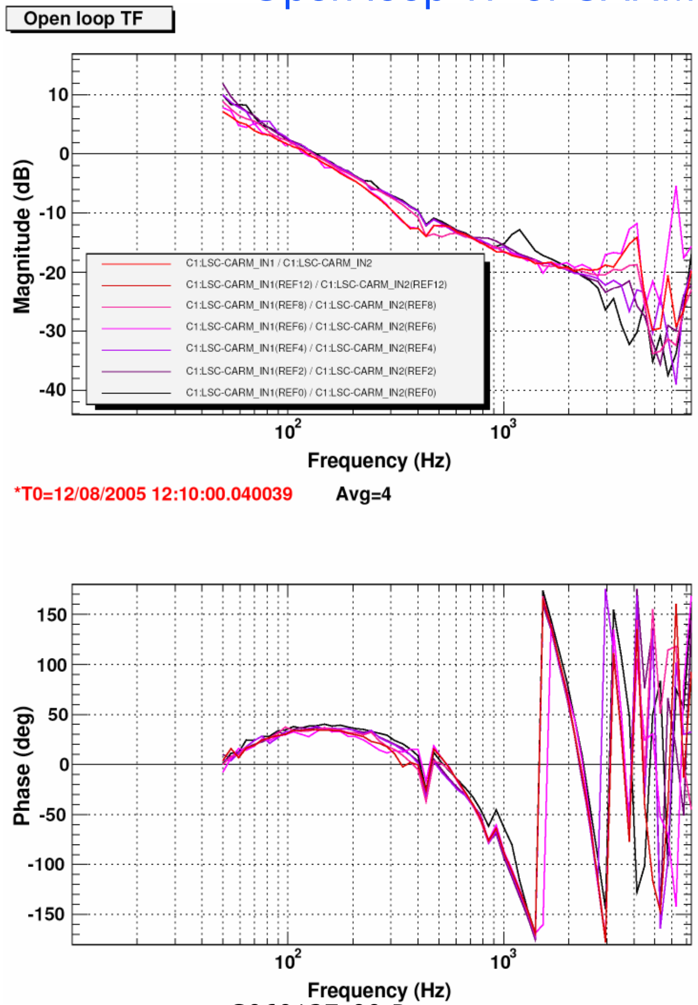
Nov. 2004
5 DOF lock with offset in CARM

Oct. 2005
RSE

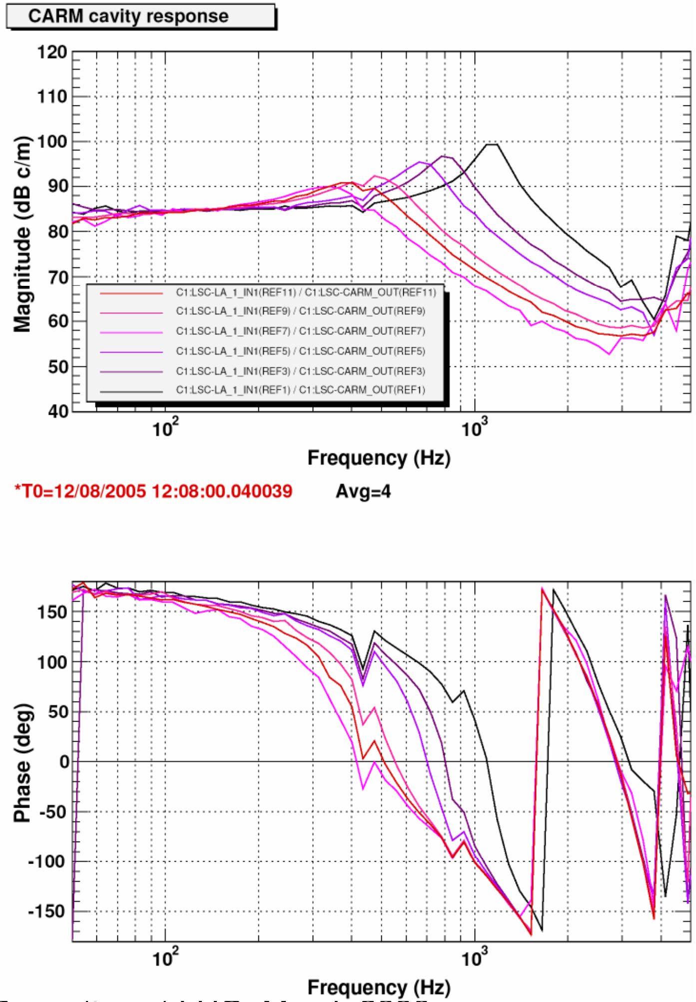


CARM optical resonance and Dynamic compensative filter

Open loop TF of CARM

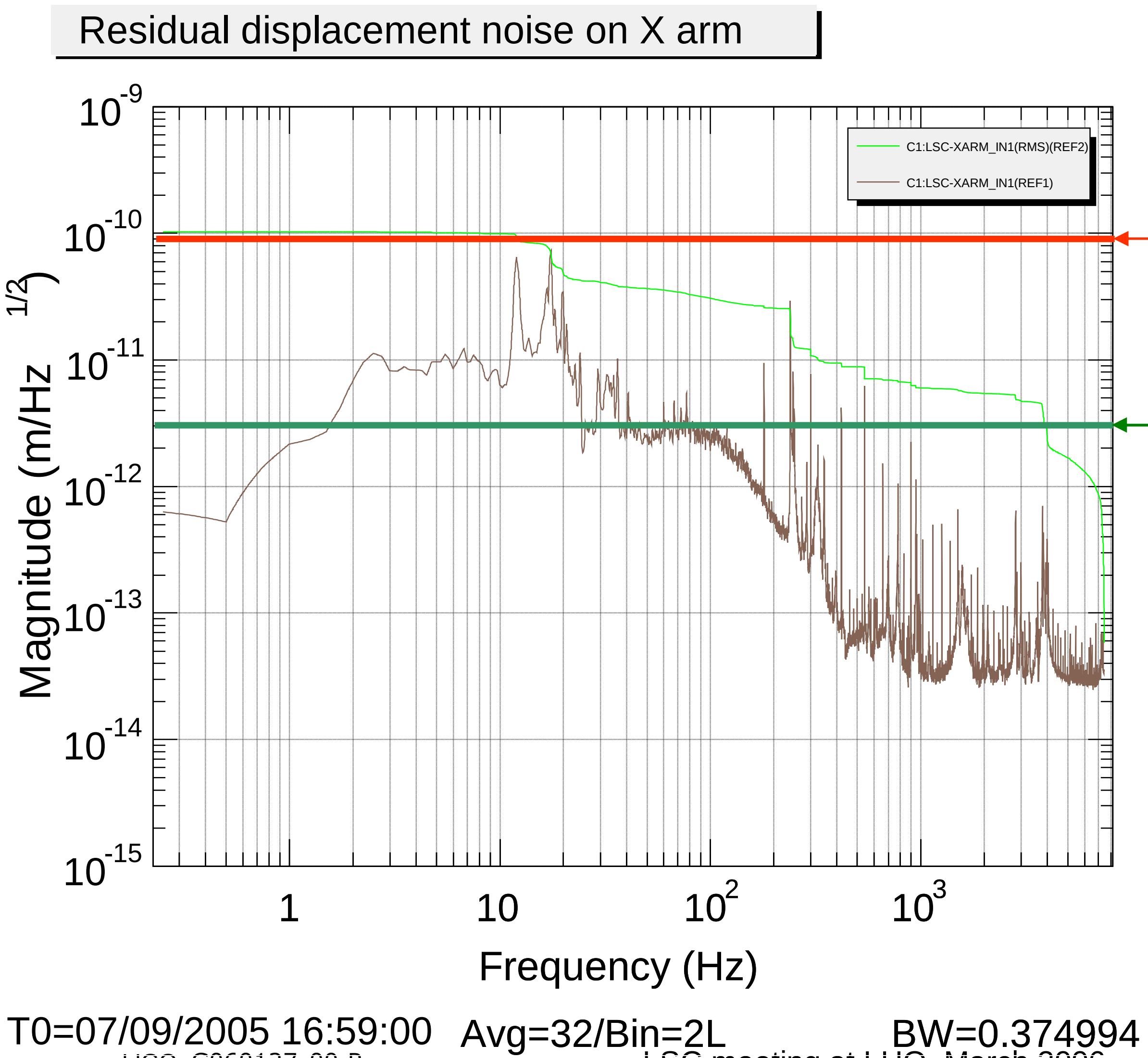


Optical gain of CARM



- Optical gain (normalized by transmitted power) shows moving peaks due to reducing CARM offset.
- We have a dynamic compensative filter having an exactly the same shape as optical gain except for upside down.
- Open loop transfer function has no phase delay in all CARM offset.

Residual displacement noise on arm



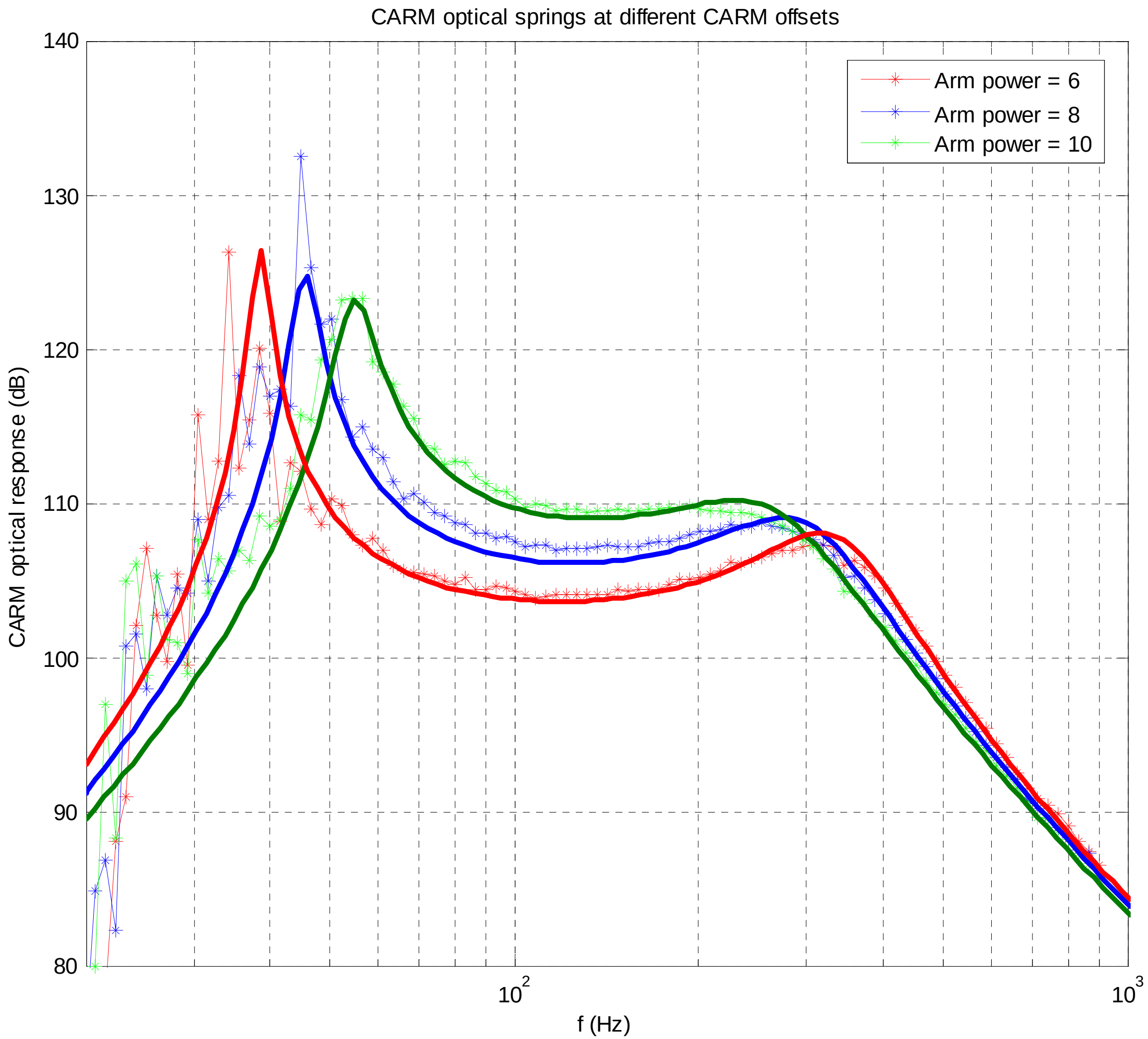
Requirement of RMS noise for offset lock (10% of FWHM of offset lock on CARM)

Requirement of RMS noise for full lock (10% of FWHM of RSE)

- RMS residual displacement noise was 30 times larger than the requirement.

CARM optical springs

- •Solid lines are from TCST
- •Stars are 40m data
- •Max Arm Power is ~80

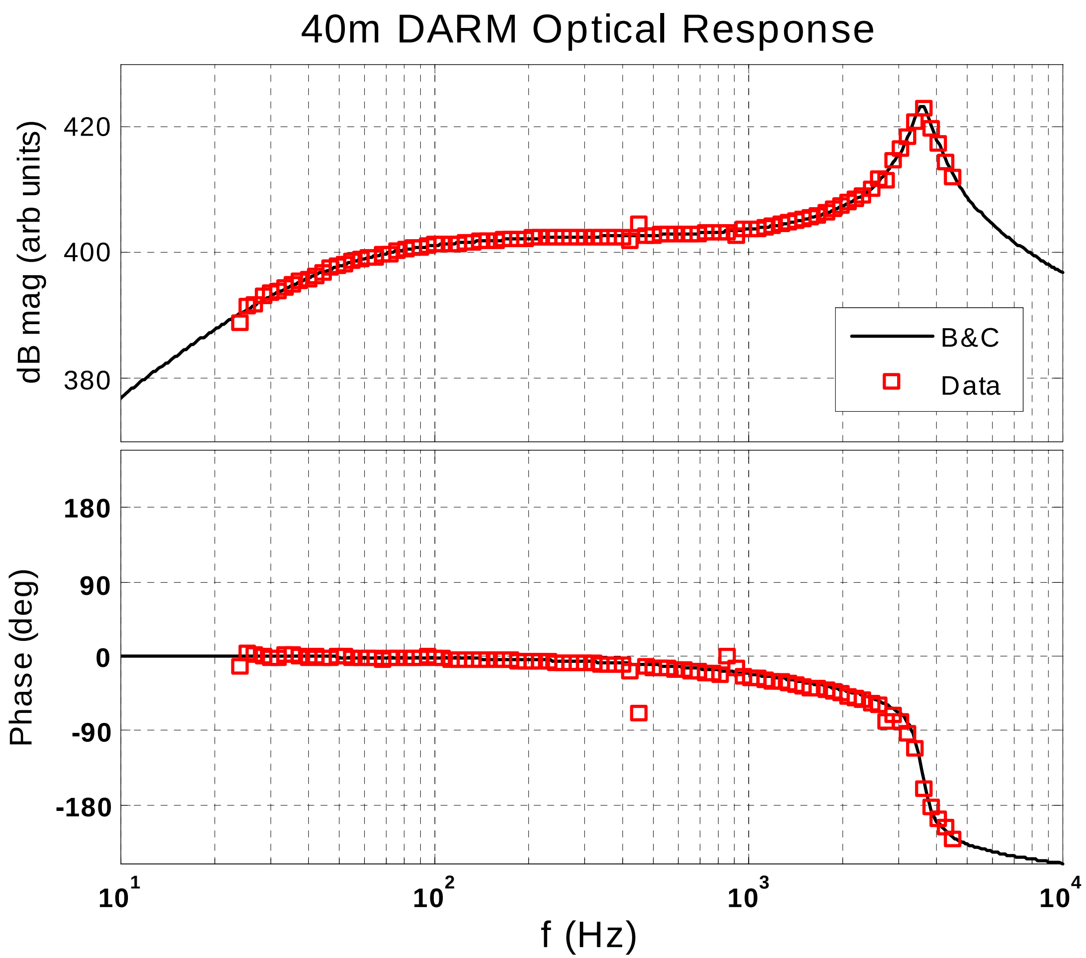


Loss control for high finesse cavity

	Design	Measured(estimated)
Loss in each mirror	35ppm	100ppm
Cavity reflectivity	93%	85%(X arm 84%, Yarm 86%)
PRM reflectivity	93%	92.2%
Loss in PRC	0%	2.3%
Achievable PRG	14.5	5.0
Coupling of PRC	Over coupled	Under coupled
Input power	0.1W	1W
Power in one arm	560W	1900W
Optical spring	23Hz	41Hz

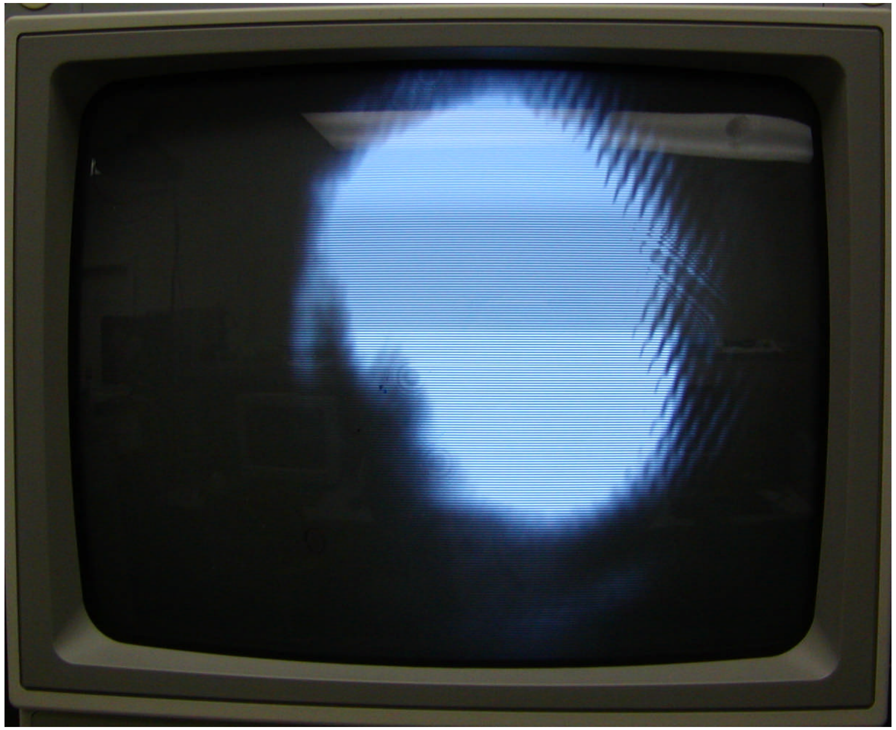
The DARM anti-spring

- With SRM detuned in the wrong direction, will see an anti-spring in DARM
- This is equivalent to resonating the –f2 RF sideband in SRC.
- Oddly, this is also easier to lock
- True for both full IFO and just the DRMI (though less noticeable on DRMI)



Why is the correct SRM position harder to lock?

Mode healing/injuring at Dark Port



Negative spring constant with optical spring

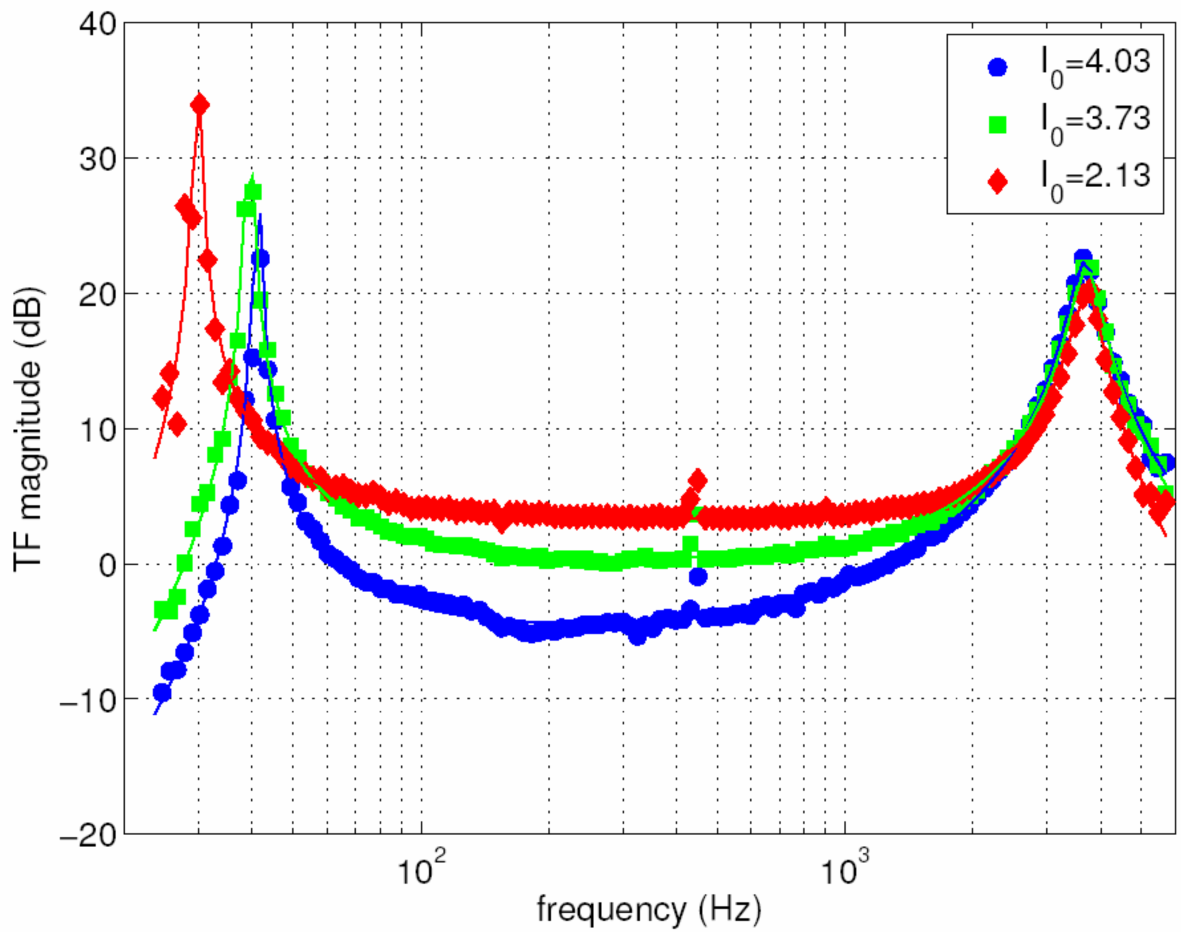
Carrier power at DP is 10x smaller

Positive spring constant with anti spring

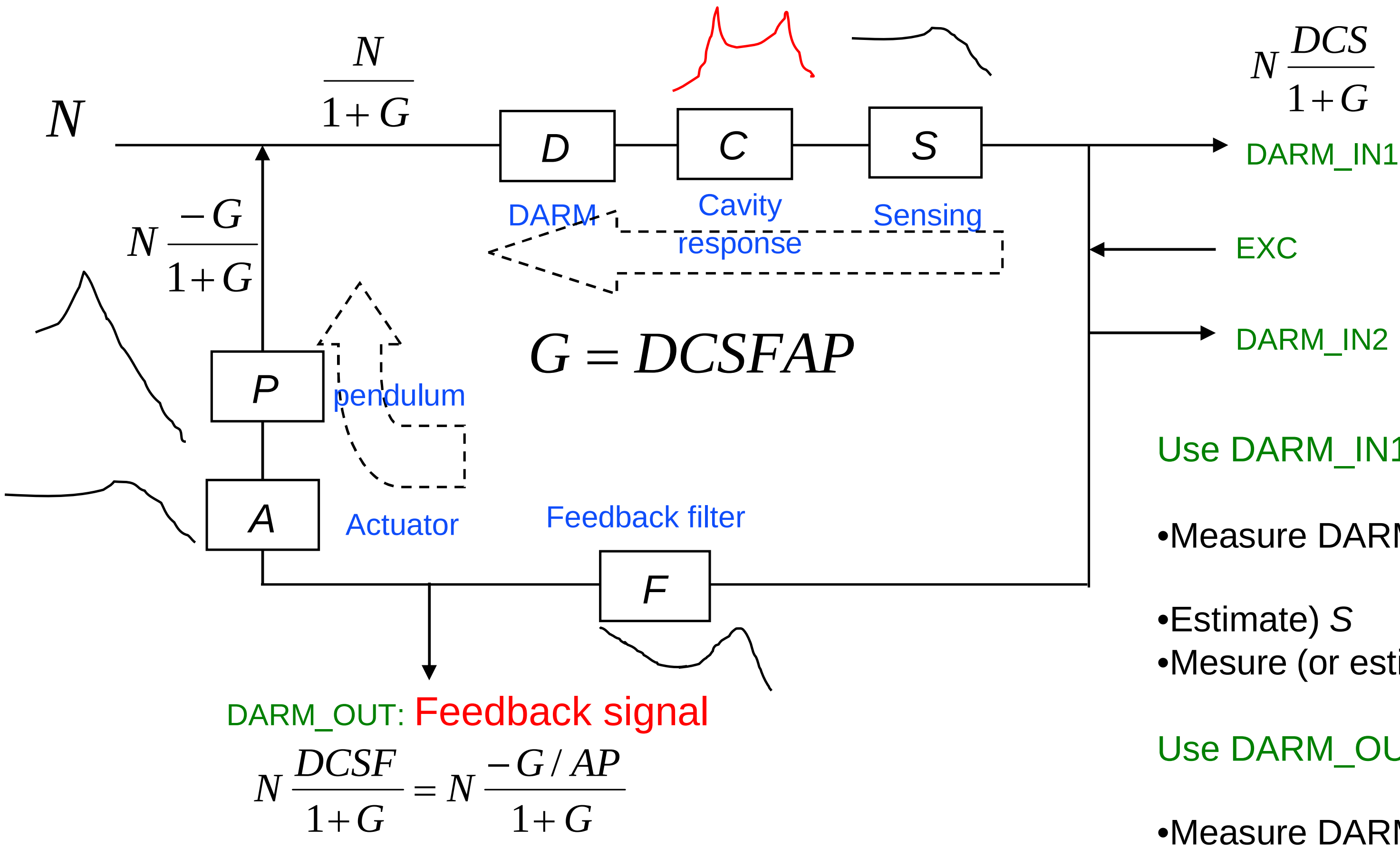
- Repeatable
- The same alignment quality

Changing the DARM quadrature

- Squares are data, solid lines are from Optickle.
- Optickle results are generated by measuring response in a single quadrature while changing the CARM offset.
- This should be analogous to how the data was taken (reducing the CARM offset while always measuring with the same RF demod phase).



Calibration for DARM loop



Use DARM_IN1

- Measure DARM_IN2/EXC= $\frac{1}{1+G}$
- Estimate) *S*
- Mesure (or estimate) *C*

Use DARM_OUT

- Measure DARM_IN1/EXC= $\frac{G}{1+G}$
- Estimate *A*
- Estimate *P*

Summary of 40m work and suggestions for AdLIGO

- We succeeded in locking 5DOF of detuned RSE interferometer.
- We measured optical resonance and optical spring fitted to ABYC formula.

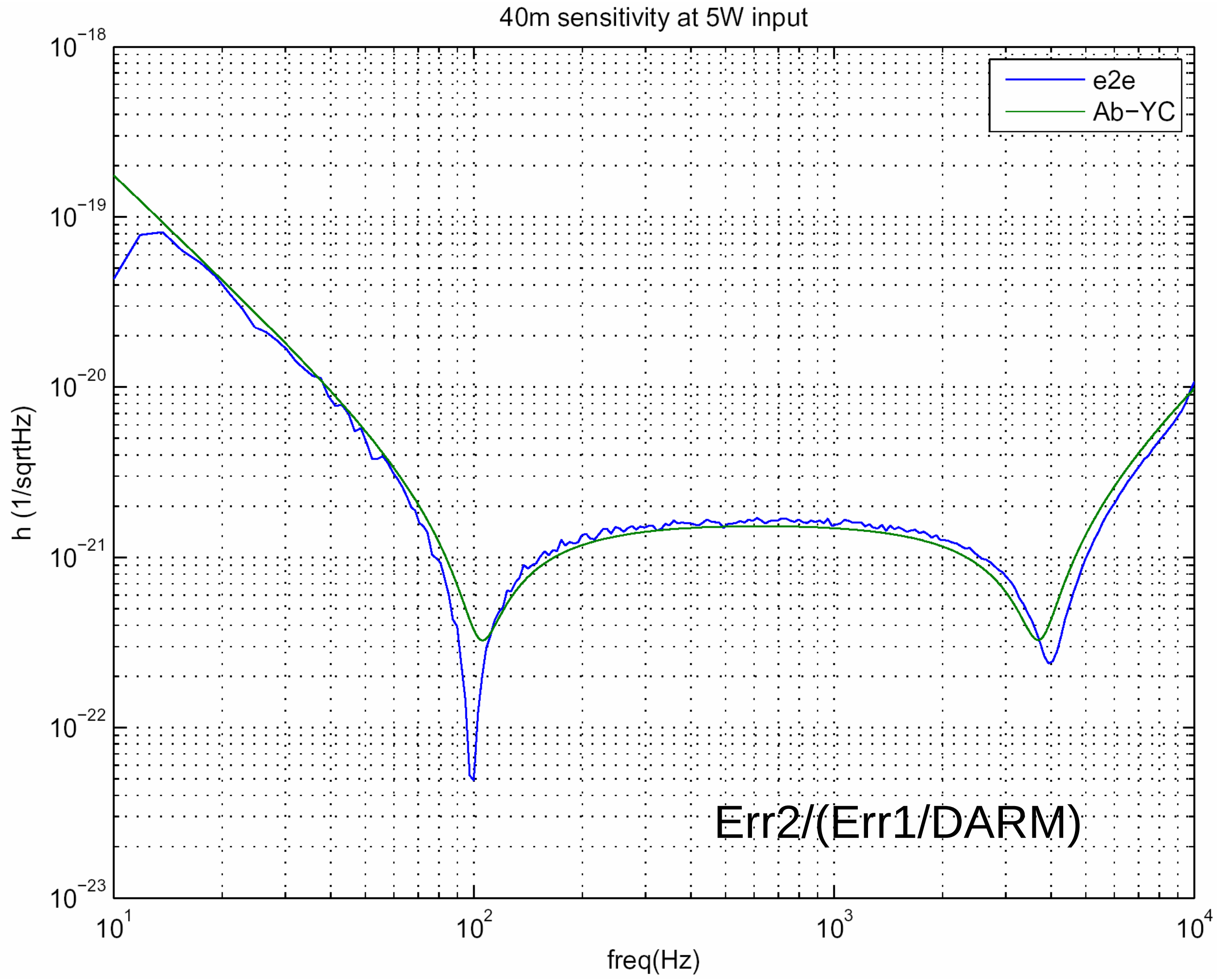
- Loss control is necessary in order to get proper power recycling gain with high (~1500) finesse cavity.
- Lock should be acquired with low input power lock, then increasing power to avoid phase delay due to optical spring in DARM and also CARM loop.
- Using analog common mode servo at very first stage to avoid less phase margin on CARM loop.
- Higher UGF for DARM (~600Hz?) with faster digital system.
- Development of a new calibration method for observation.
- Using lower RF for WFS.

Next steps

- Stable operation and noise hunting
- More lock acquisition schemes
- Modeling/E2E simulation for AdLIGO
- DC readout with Output Mode Cleaner
- Squeezed Vacuum in the Dark Port
- Active Alignment control with wave front sensors
- LF RF modulation scheme
- Alternatives to Mach-Zender
- Cleaning mirrors
- Narrow-band operation

- SQL interferometer using lighter mirror?

Optical noise of 40m in E2E



- Simple length control (UGF~100Hz)

- Err2/(Err1/DARM)

DARM: DARM excitation on mirrors
Err1: error signal with DARM excitation
Err2: error signal with optical noise

- How much further does E2E need to go? 2-photon?
- input vacuum?
- Quantum control?
- Or just classical physics + shot noise + radiation pressure noise ?

Mathematical description for optical spring in detuned RSE

ABYC equation: relation among
input vacuum **a** , output field **b**, input power and gravitational wave h

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \frac{1}{M}\left[e^{2i\beta}\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \sqrt{2\kappa}\,\tau\, e^{i\beta}\begin{pmatrix} D_1 \\ D_2 \end{pmatrix}\frac{h}{h_{\mathrm{SQL}}} \right]$$

a :input vacuum
b :output field
M^2: $C_{11}C_{22}$-$C_{12}C_{21}$
h :gravitational wave

h_{SQL}:standard quantum limit
♦: transmissivity of SRM
&ʒ: input power coupling
ℌ: GW sideband phase shift in IFO

Strain sensitivity: ratio h and **a** on **b**

$$h_n(\varsigma) = \frac{h_{\mathrm{SQL}}}{\sqrt{2\kappa}\;\tau}\left[\frac{\sqrt{(C_{11}+C_{22})^2\sin\varsigma + (C_{12}+C_{21})^2\cos\varsigma}}{D_1\sin\varsigma + D_2\cos\varsigma}\right]e^{i\beta}$$

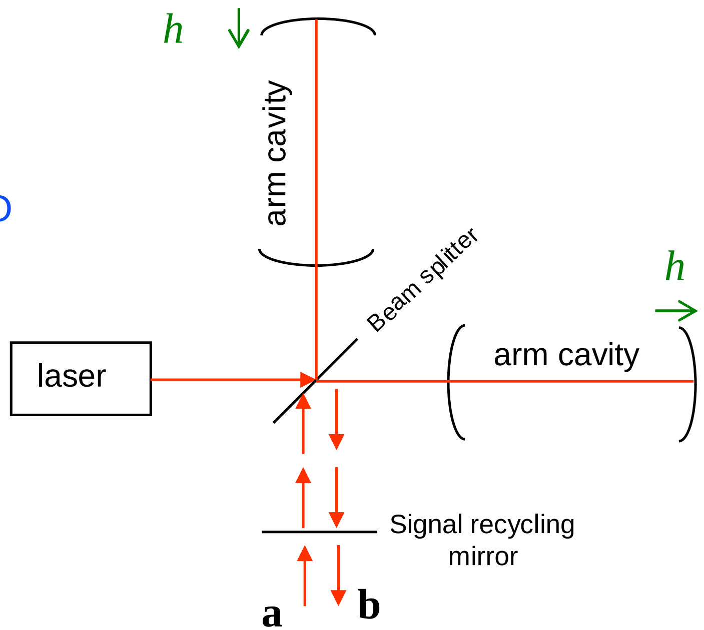
Optical noise: ratio between **a** and **b**

$$\frac{b_\varsigma}{a_\varsigma} = \frac{\sqrt{(C_{11}+C_{22})^2\sin\varsigma + (C_{12}+C_{21})^2\cos\varsigma}}{M}e^{i2\beta}$$

Measurement of optical response: ratio h and **b**

$$\frac{b_\varsigma}{h} = \frac{\sqrt{2\kappa}\;\tau}{h_{\mathrm{SQL}}}\left[\frac{D_1\sin\varsigma + D_2\cos\varsigma}{M}\right]e^{i\beta}$$

a <<h; non-quantum measurement



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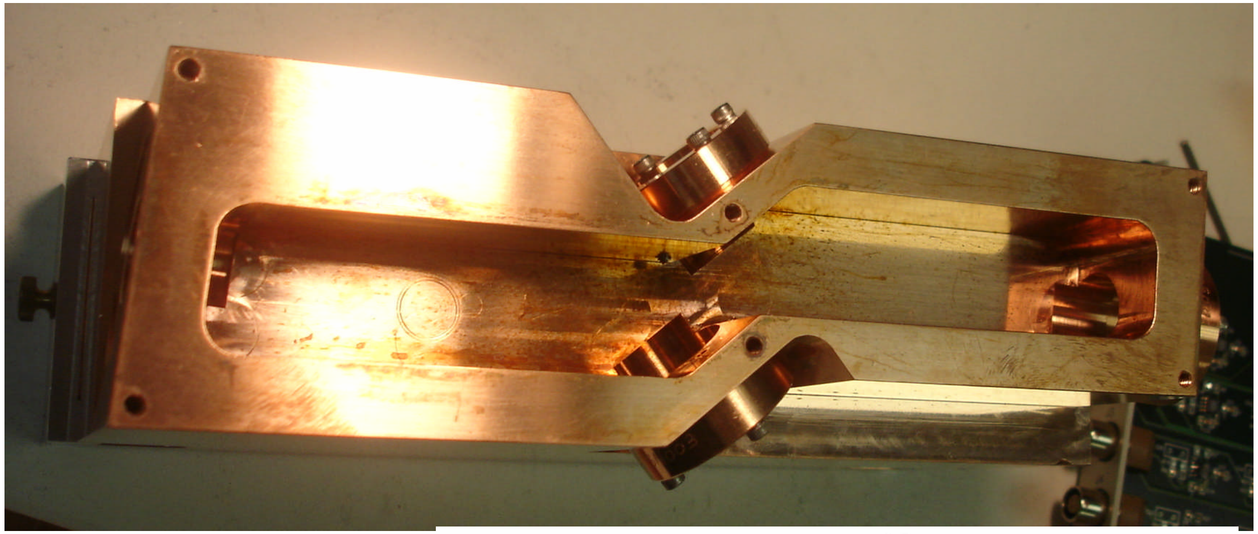
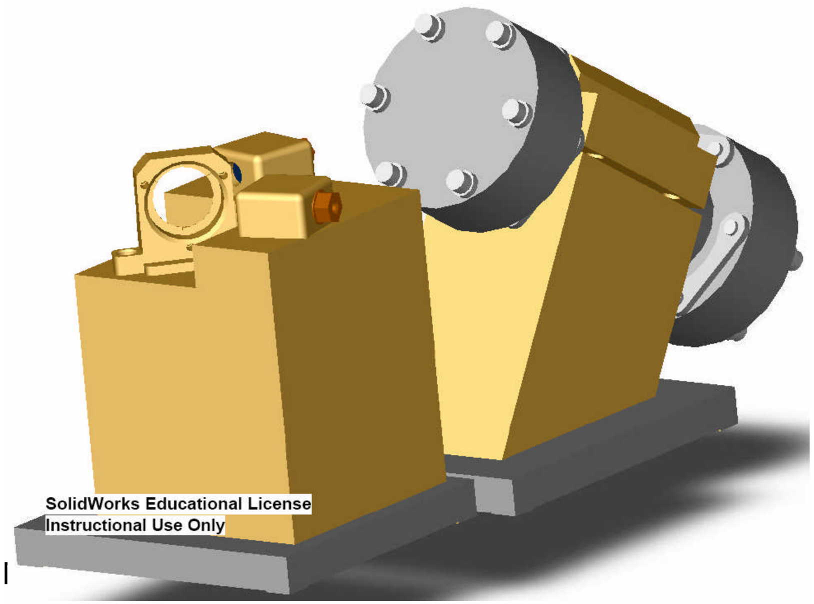
- SQL interferometer using lighter mirror?

Output mode cleaner, DC PD

OMC:
Monolithic, copper, 4-mirror design.





DCPD:
Monolithic, electronics in vacuum nipple

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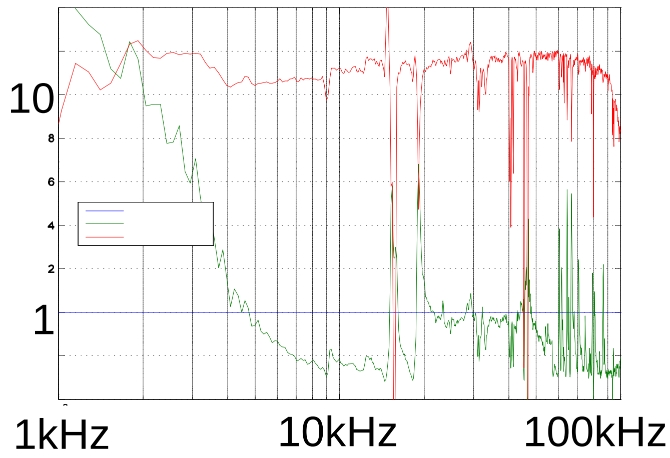
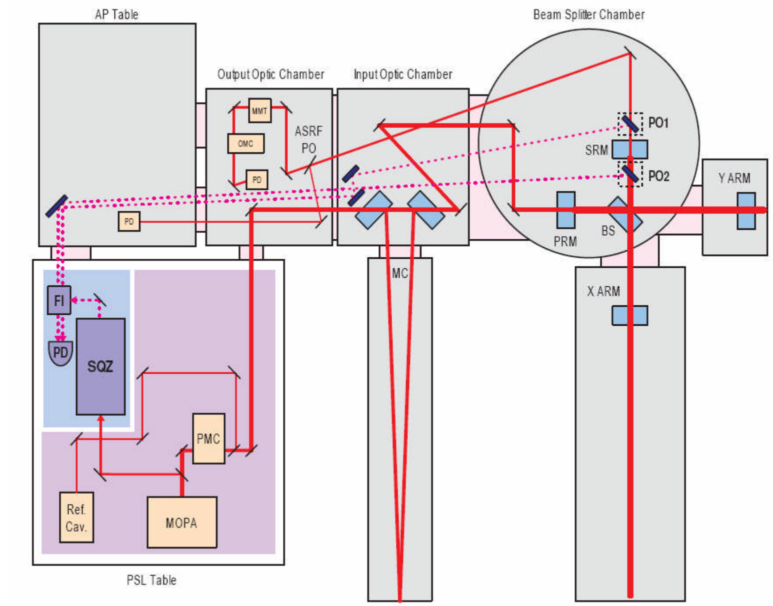
Squeezing Tests at the 40m

- Audio frequency squeezed sources now available at MIT
- Time to take steps toward eventual implementation on long baseline interferometers





» Homodyne detection along with ifo signals and noise couplings
  – Most interesting and relevant for complex ifo configurations
» A few interferometer configurations possible
  – narrow- or broadband RSE, DRMI, FPMI
» Noise coupling studies possible
» LIGO-like control systems for eventually porting squeezing technology to long baseline ifos