Demonstration of lock acquisition and optical response on Detuned RSE interferometer at Caltech 40m

GWADW-VESF meeting @ Elba

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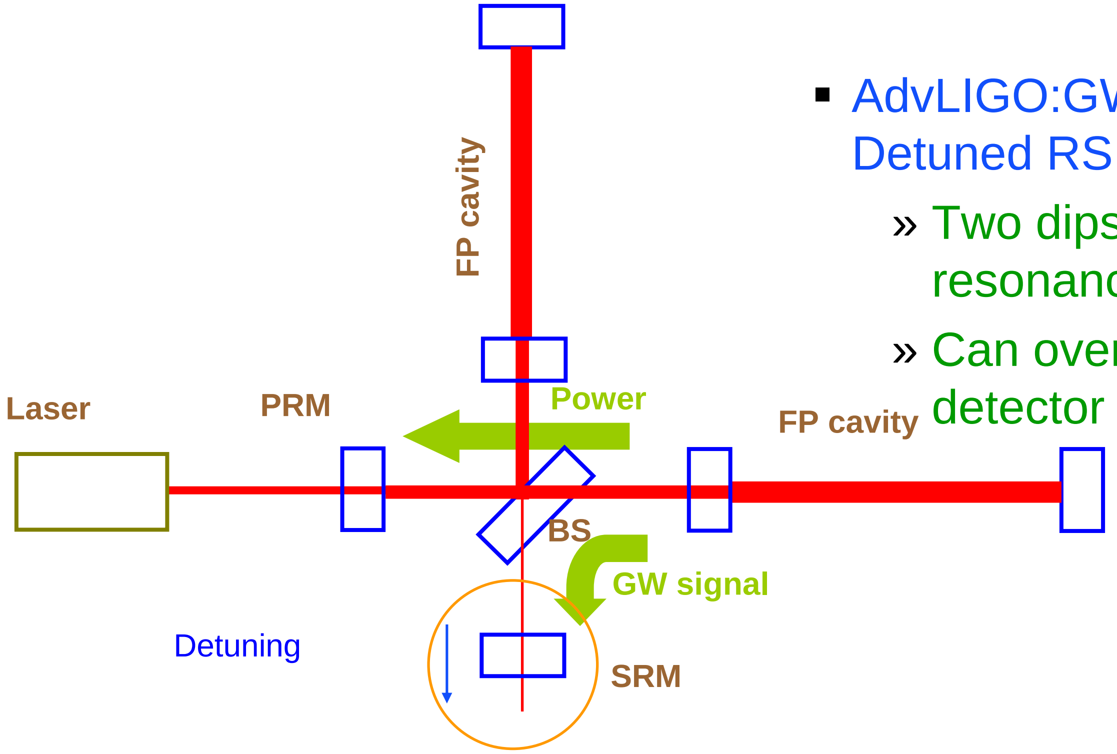
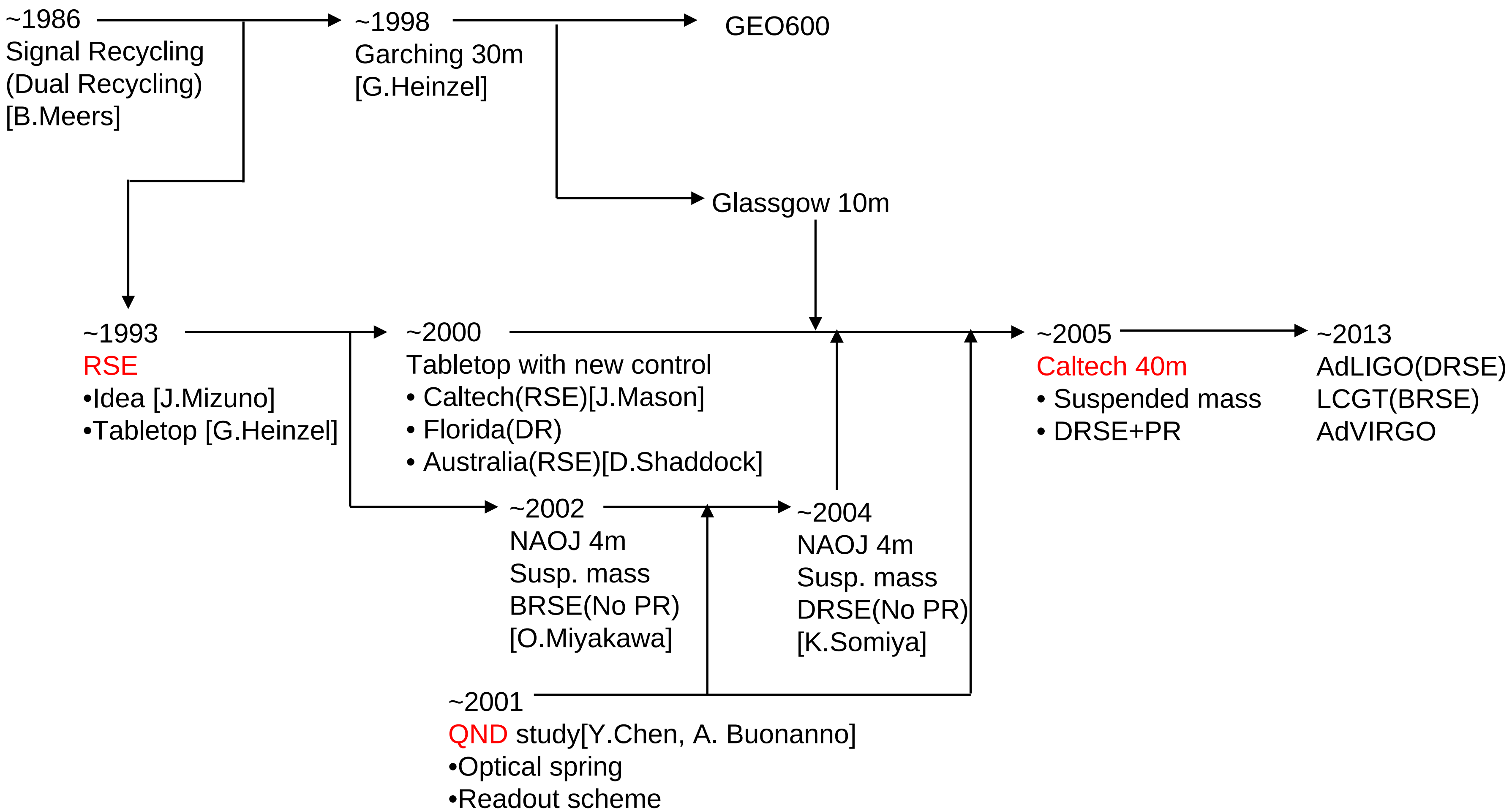
40m team

Advanced LIGO optical configuration

- LIGO:Power recycled FPMI
  - » Optical noise is limited by Standard Quantum Limit (SQL)
- AdvLIGO:GW signal enhancement using Detuned RSE
  - » Two dips by optical spring, optical resonance
  - » Can overcome the SQL ➡ QND detector



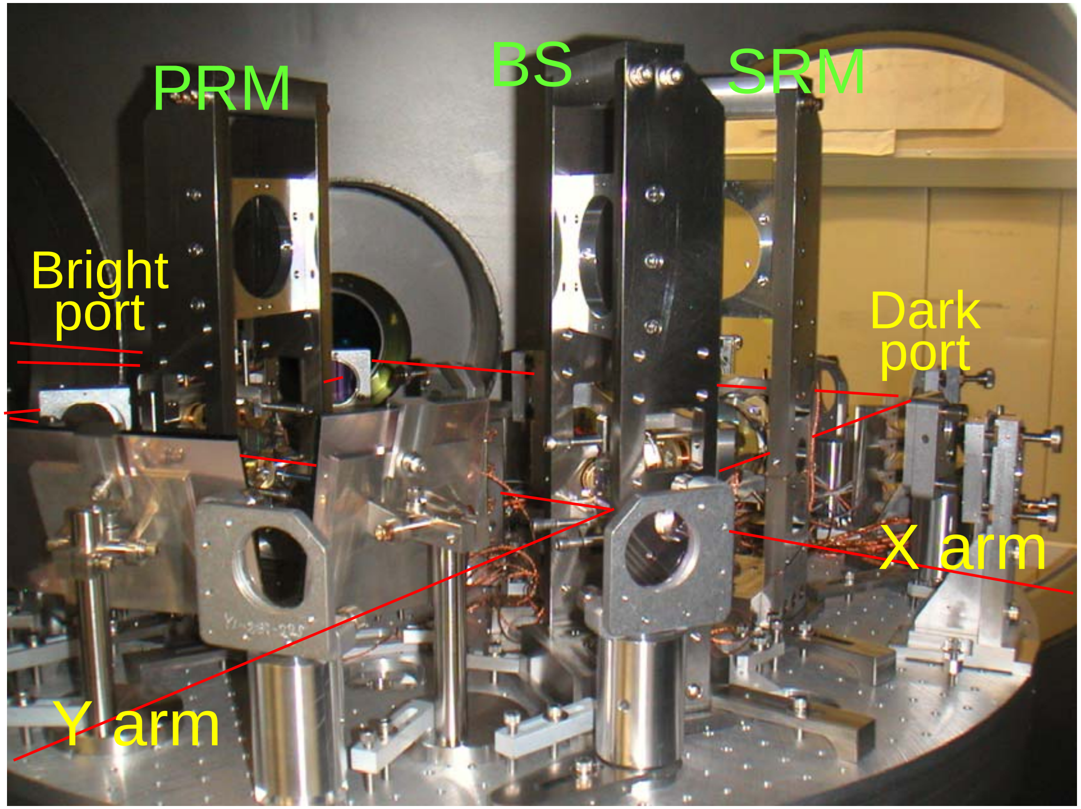
Historical review of Advanced interferometer configuration



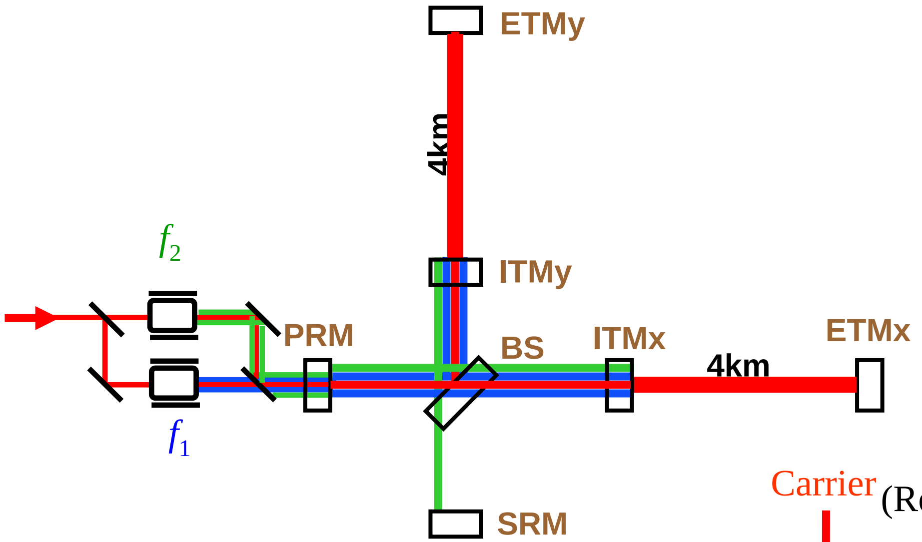
Caltech 40 meter prototype interferometer

An interferometer as close as possible to
the Advanced LIGO optical configuration and control system

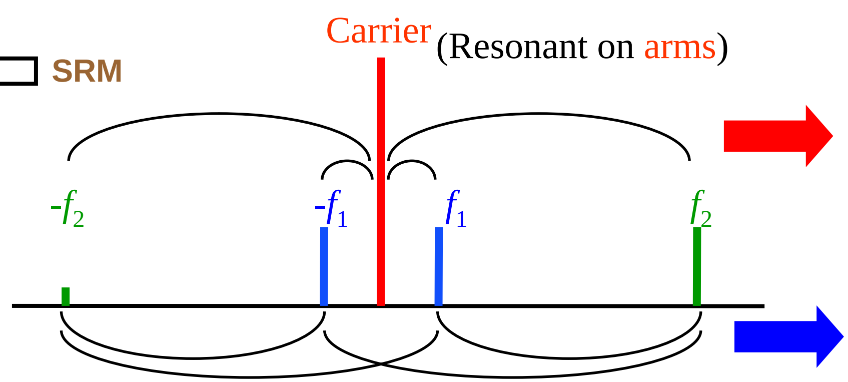
- Detuned Resonant Sideband Extraction(DRSE)
- Power Recycling
- Suspended mass
- Digital controls system
- To verify **optical spring** and **optical resonance**
- To develop **DC readout** scheme
- To extrapolate to AdLIGO via simulation



Signal extraction scheme



- Mach-Zehnder is installed to eliminate sidebands of sidebands.
- Only $+ f_2$ is resonant on SRC.
- Unbalanced sidebands of $+/-f_2$ due to detuned SRC produce good error signal for Central part.



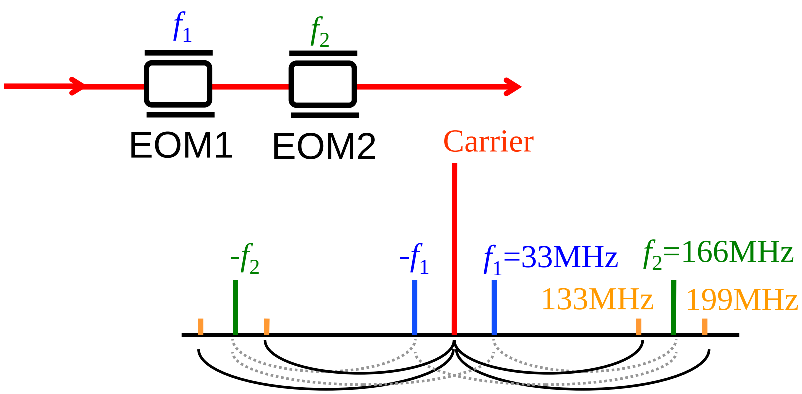
- Single demodulation
- Arm information

- Double demodulation
- Central part information

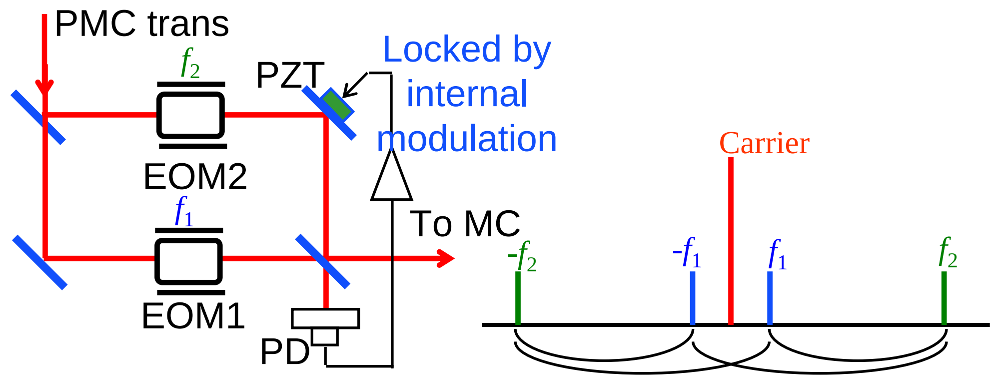
- Arm cavity signals are extracted from beat between carrier and f_1 or f_2.
- Central part (Michelson, PRC, SRC) signals are extracted from beat between f_1 and f_2, not including arm cavity information.

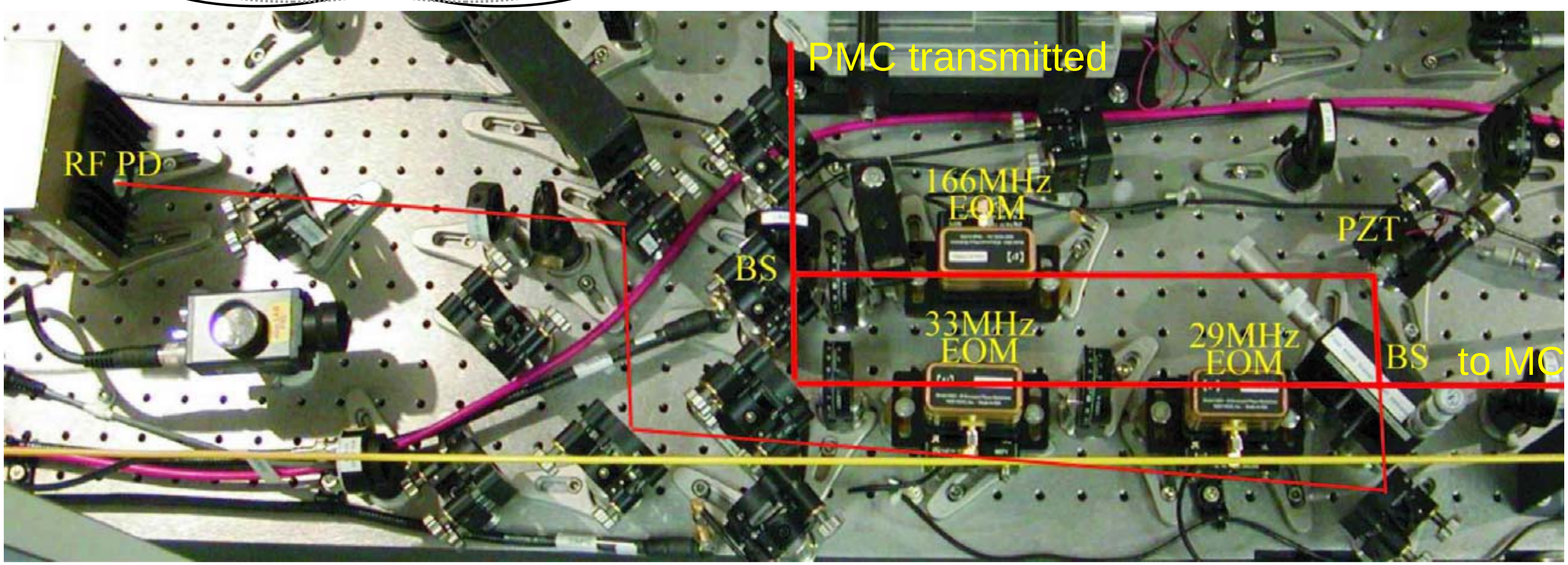
Mach-Zehnder interferometer to eliminate sidebands of sidebands

Series EOMs
with sidebands of sidebands

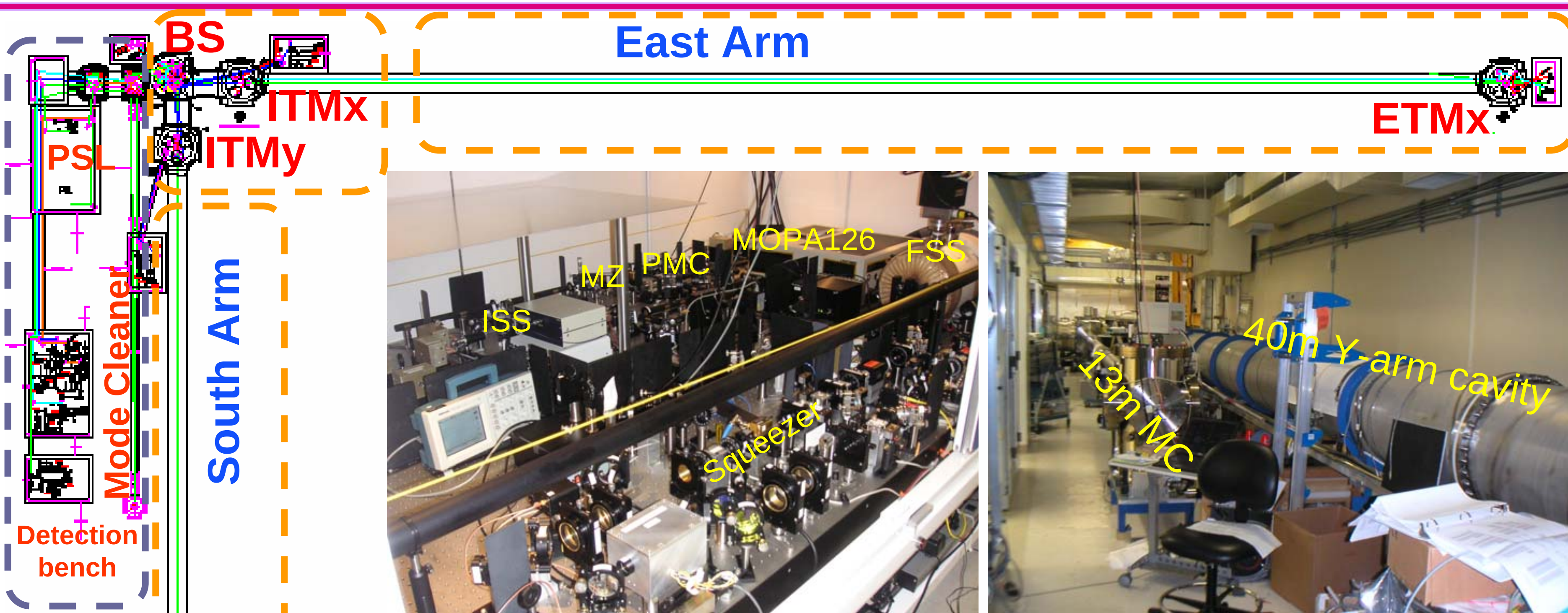


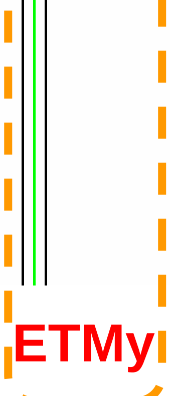
Mach-Zehnder interferometer
with no sidebands of sidebands





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

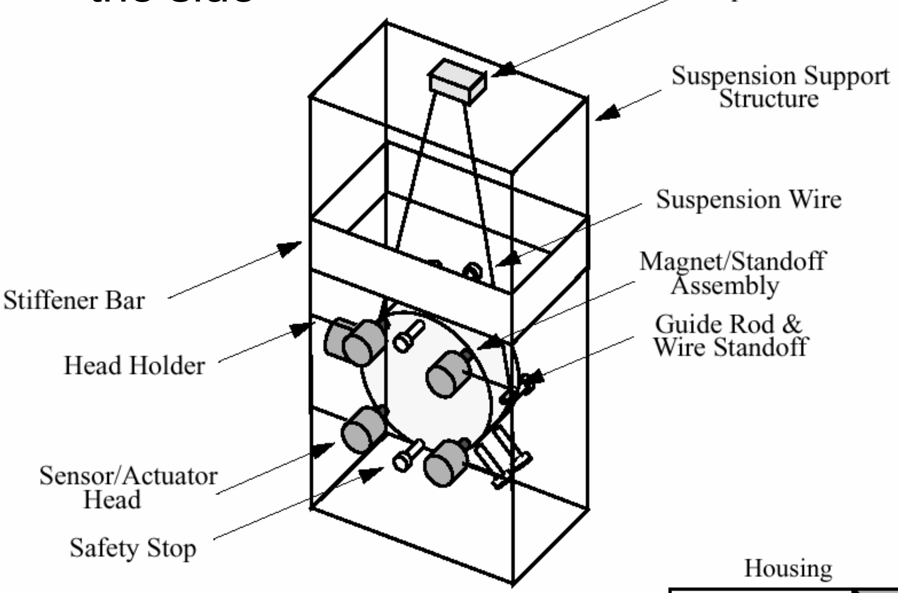




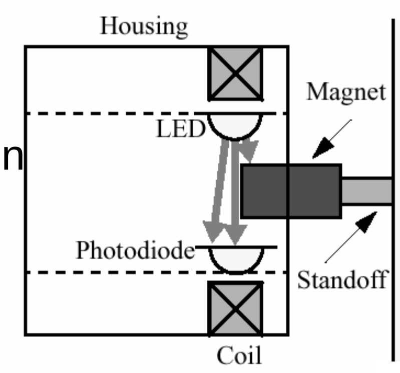
- 10W MOPA126
- Frequency Stabilization Servo (FSS)
- Pre-Mode Cleaner (PMC)
- Intensity Stabilization Servo(ISS)
- 13m suspended-mass Mode Cleaner

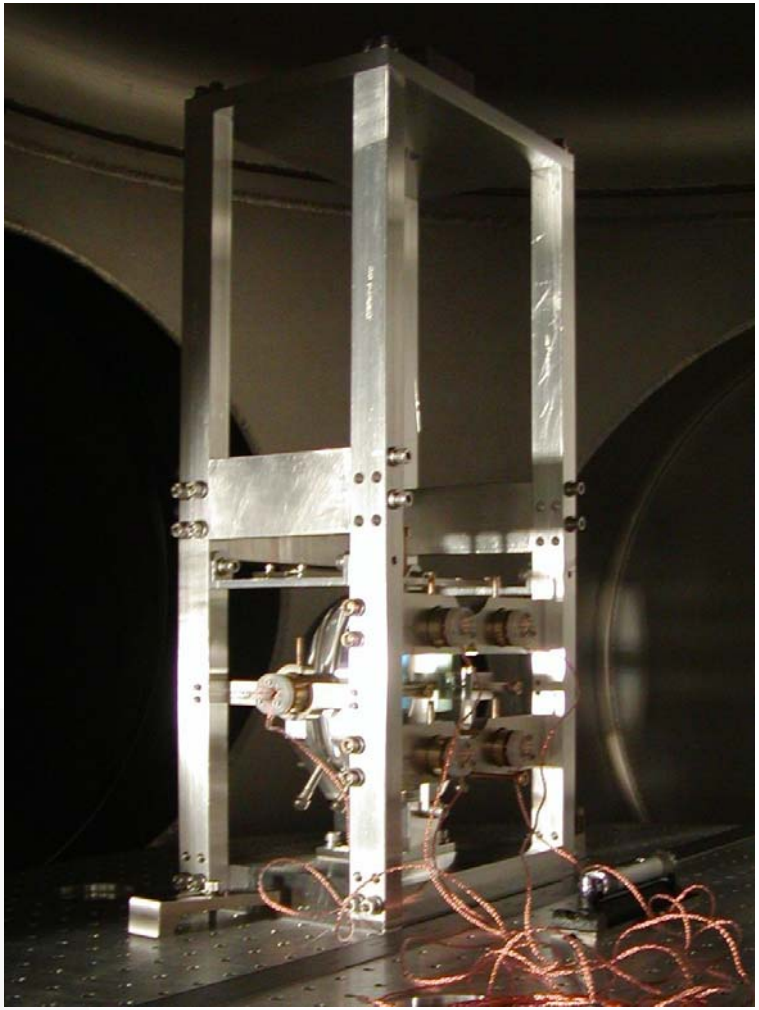
LIGO-I type single suspension

- Each optic has five OSEMs (magnet and coil assemblies), four on the back, one on the side



- The magnet occludes light from the LED, giving position
- Current through the coil creates a magnetic field, allowing mirror control



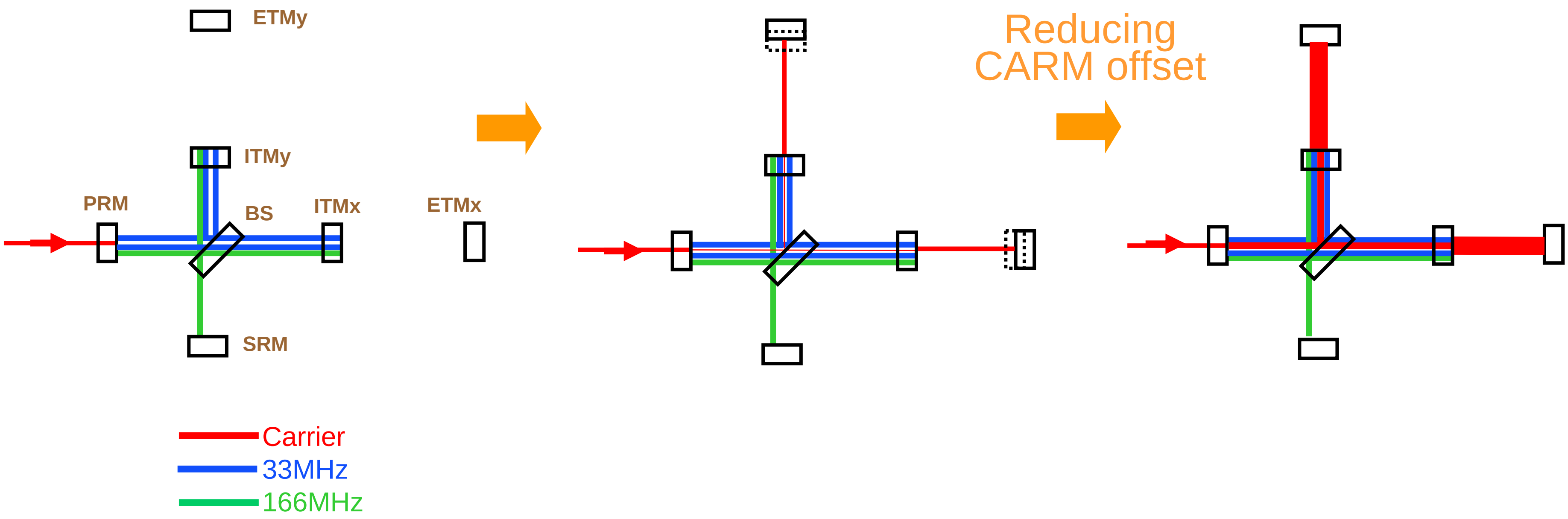


The way to full RSE

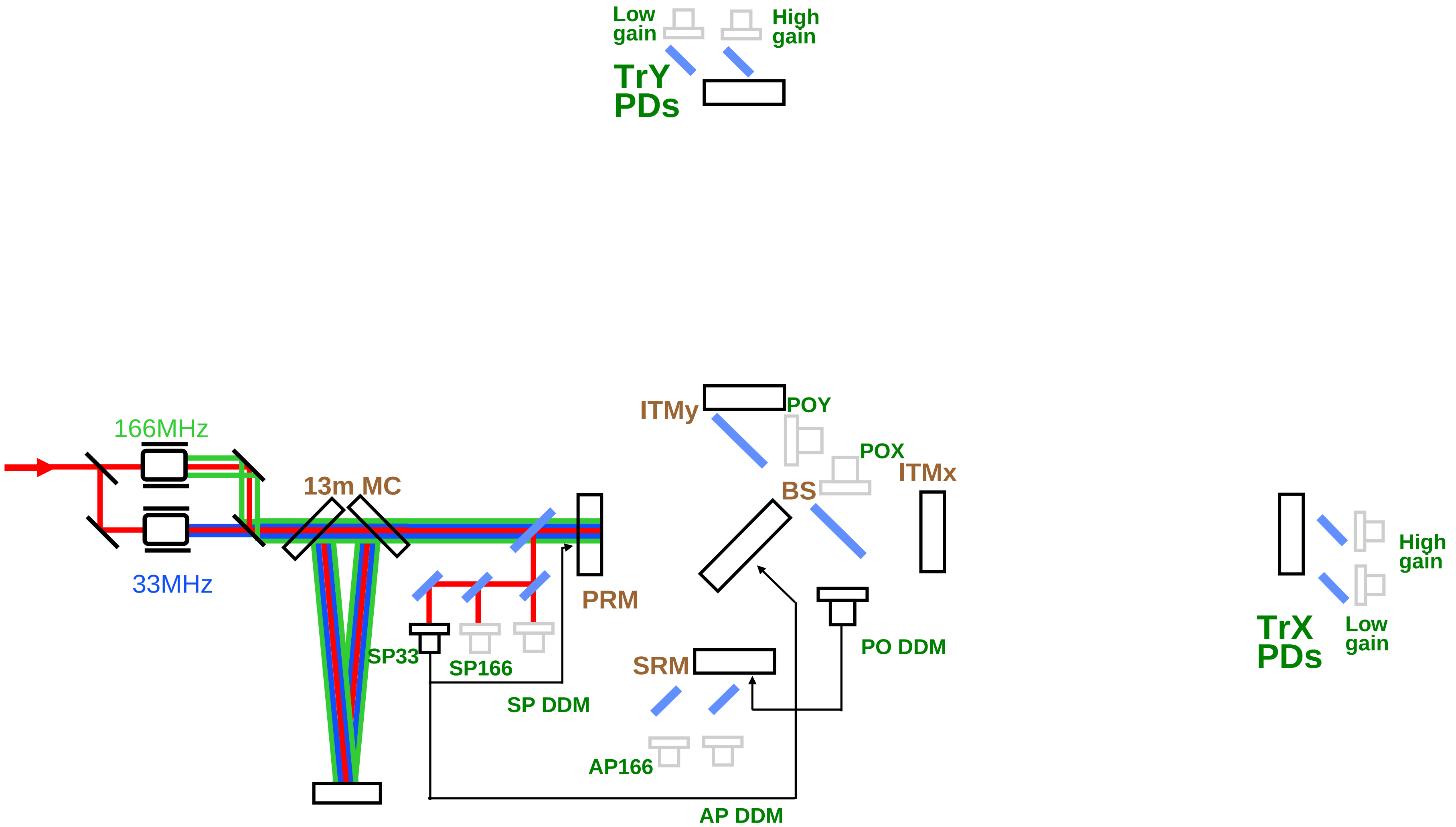
Detuned dual recycled Michelson

5 DOF lock with offset in CARM

RSE



Lock acquisition procedure towards detuned RSE

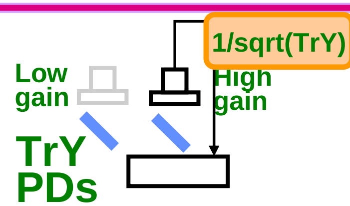


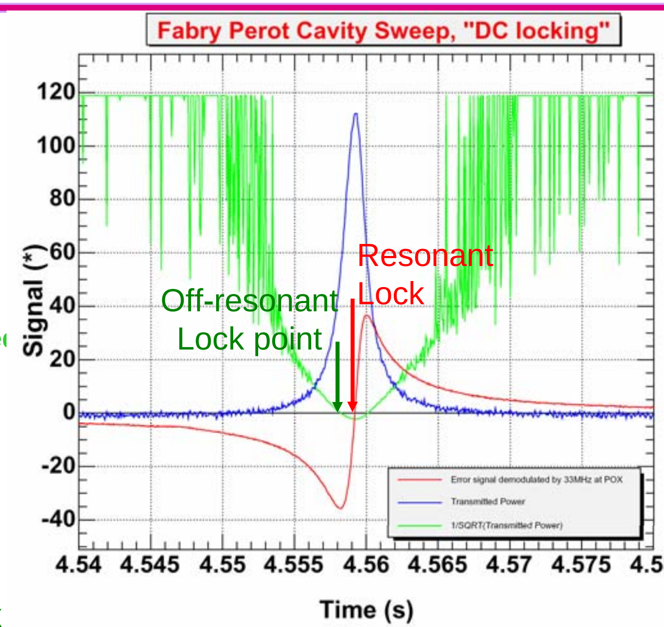
Lock acquisition procedure towards detuned RSE

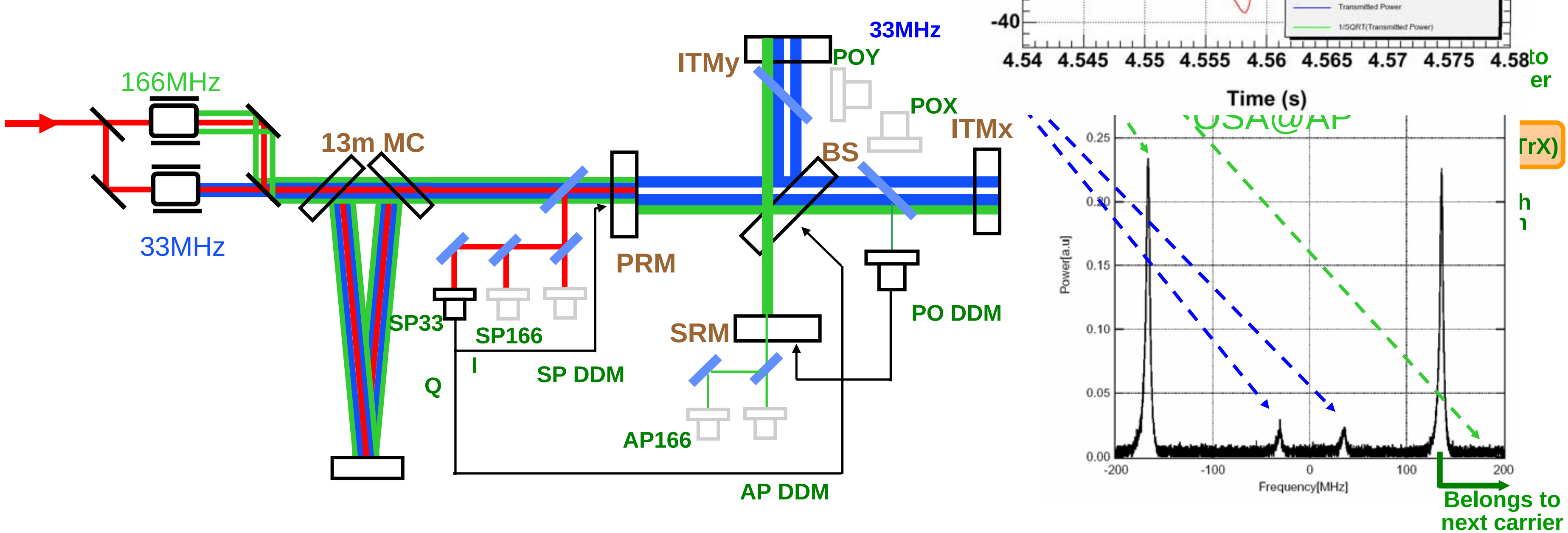
DRMI + 2arms with offset using digitally normalized

$$\frac{1}{\sqrt{\text{Transmitted power}}} + \text{offset}$$

1. Avoids coupling of carrier in PRC
2. Lock with low bandwidth control
3. High cavity pole







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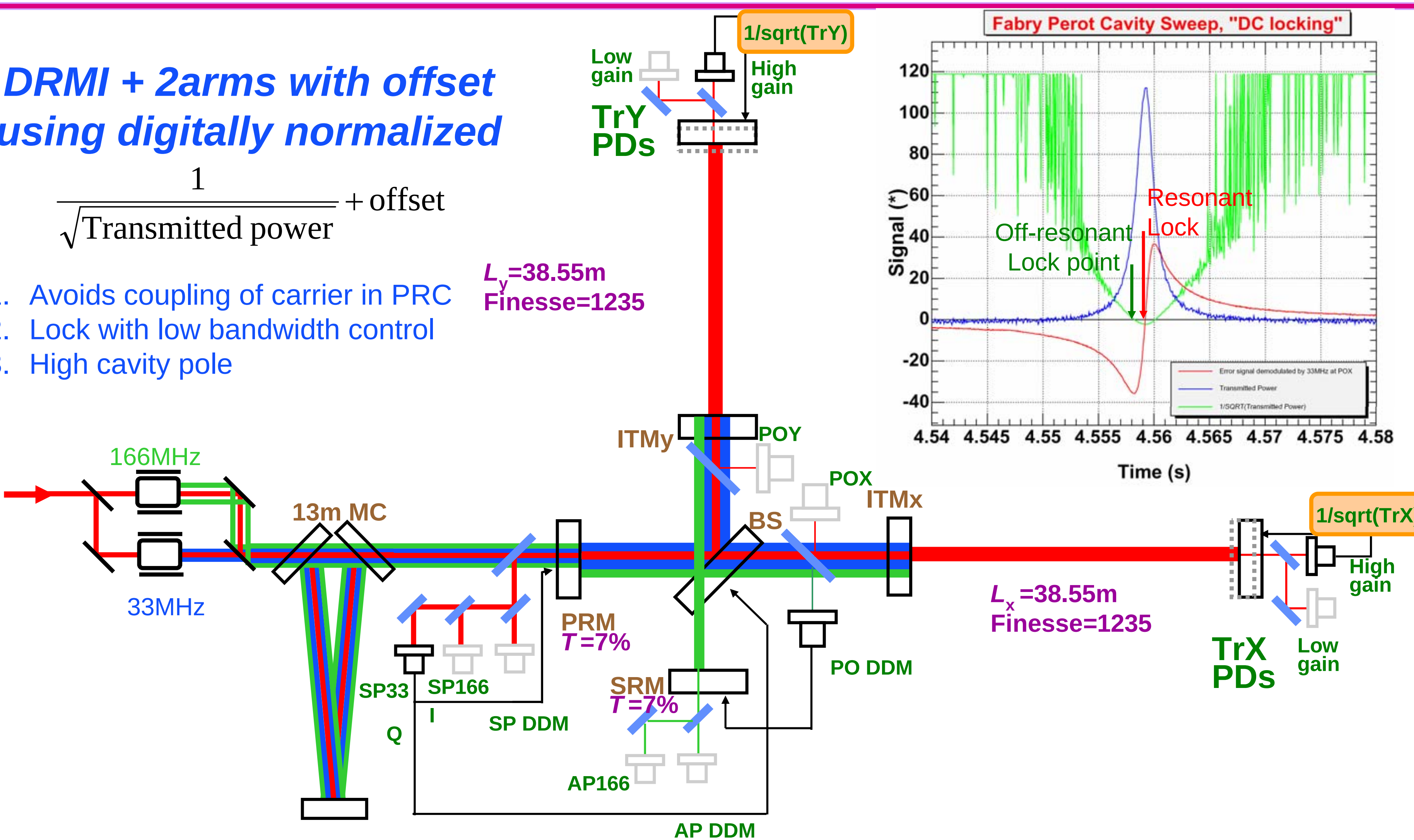
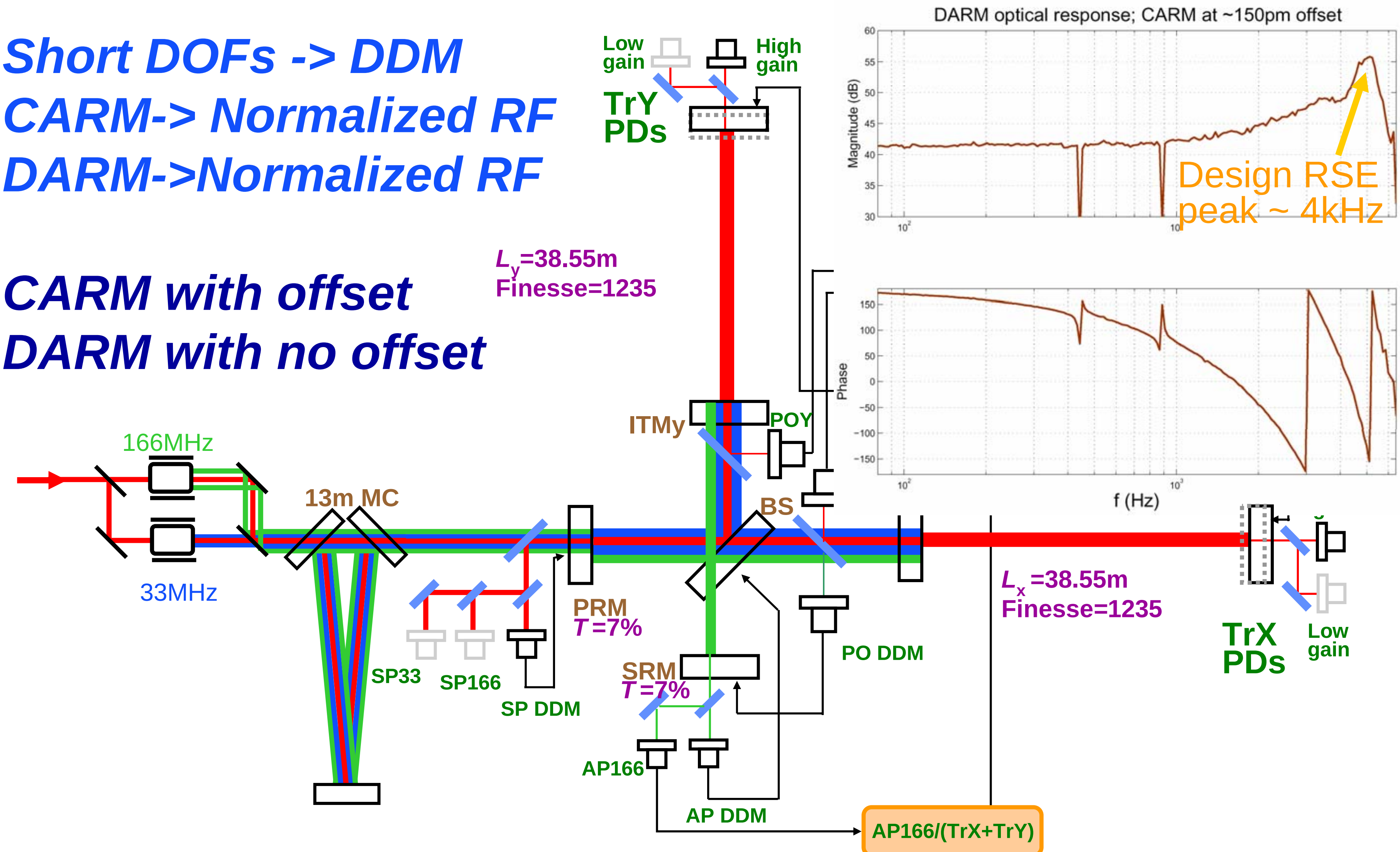


Lock acquisition procedure towards detuned RSE

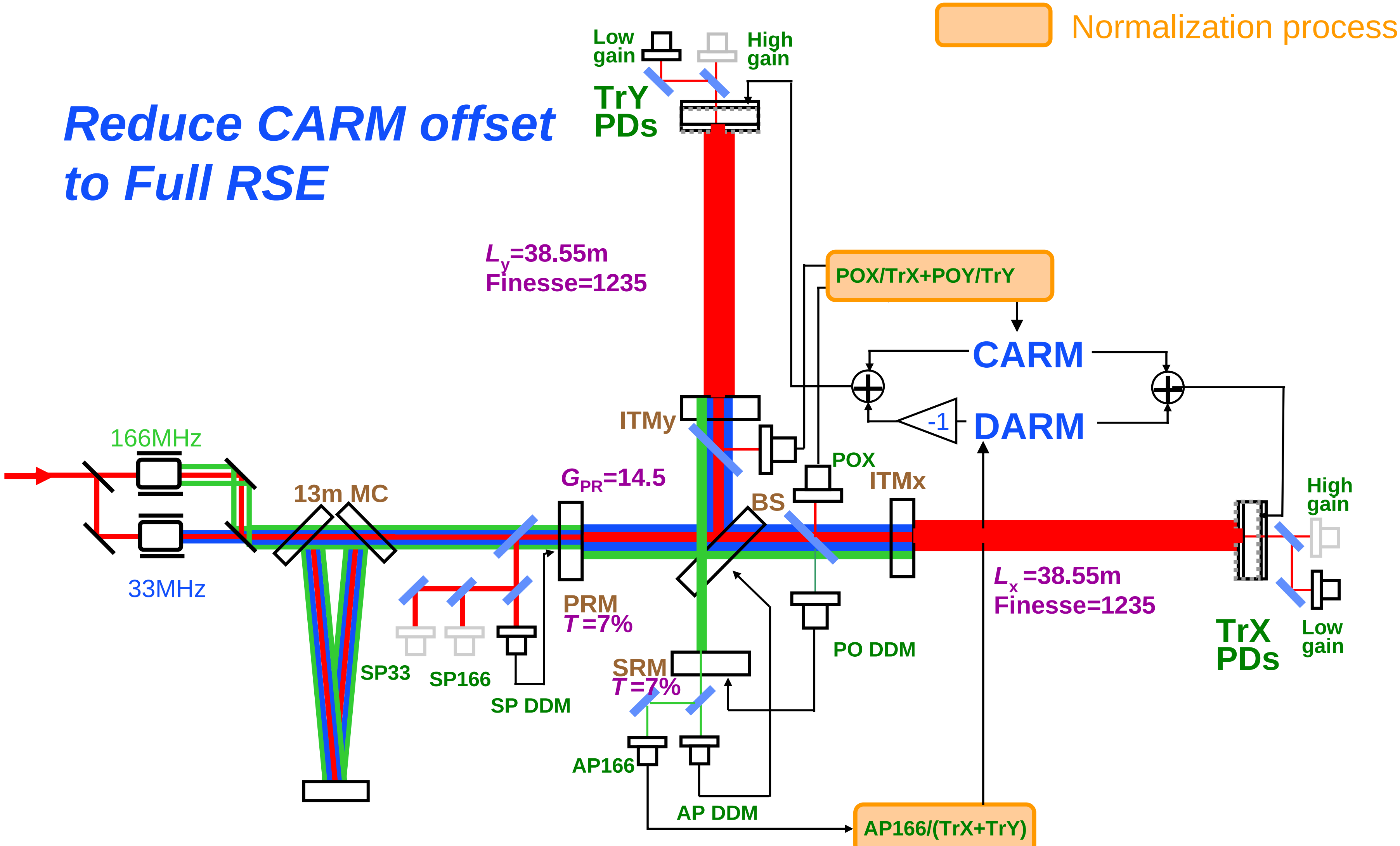
Short DOFs -> DDM
CARM-> Normalized RF
DARM->Normalized RF

CARM with offset
DARM with no offset



Lock acquisition procedure towards detuned RSE

Reduce CARM offset to Full RSE



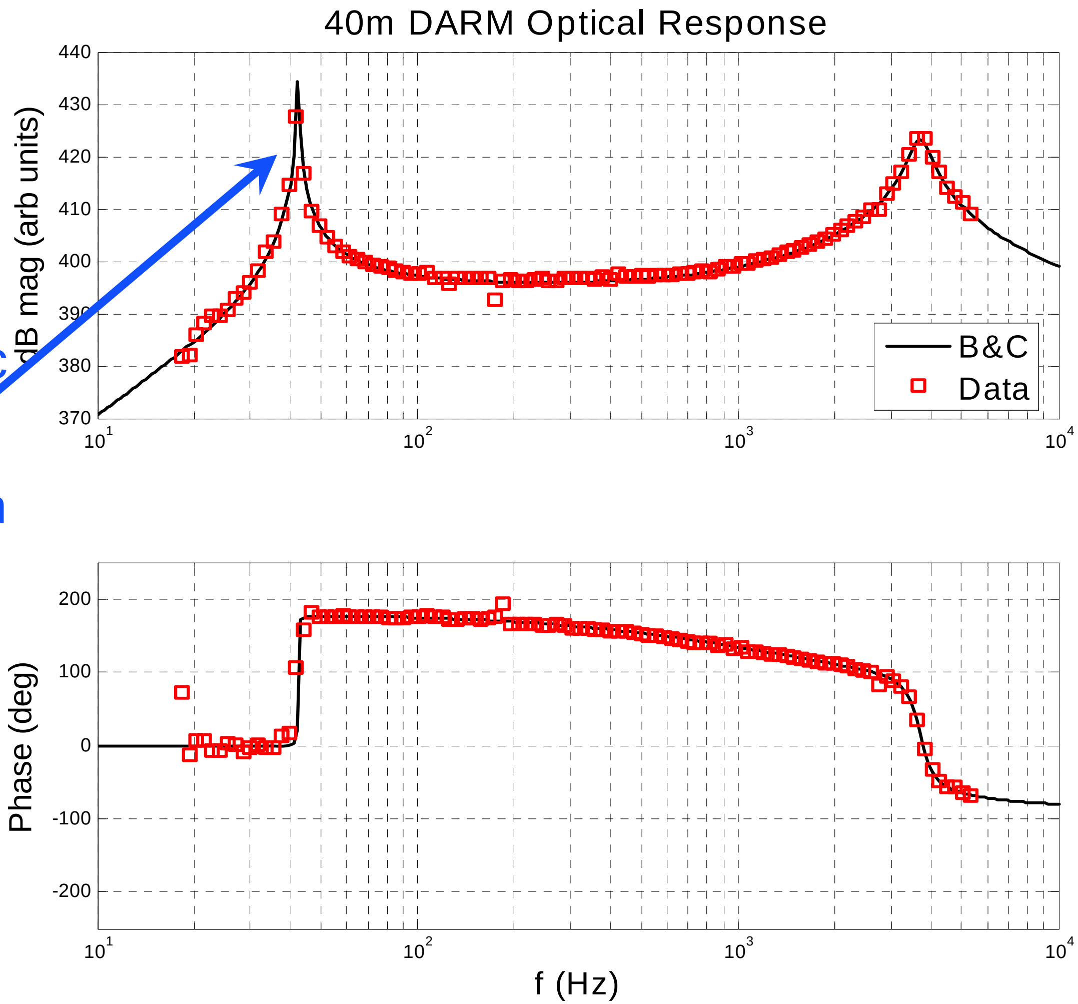
DARM Optical response with fit to A.Buonanno & Y.Chen formula

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

Radiation pressure:F = 2 P / c
Detuned Cavity -> dF/dx

Optical Spring stiffness ~10^7 N/m

BMW Z4 ~ 10^4 N/m



Description of data, fit: http://arxiv.org/abs/gr-qc/0604078

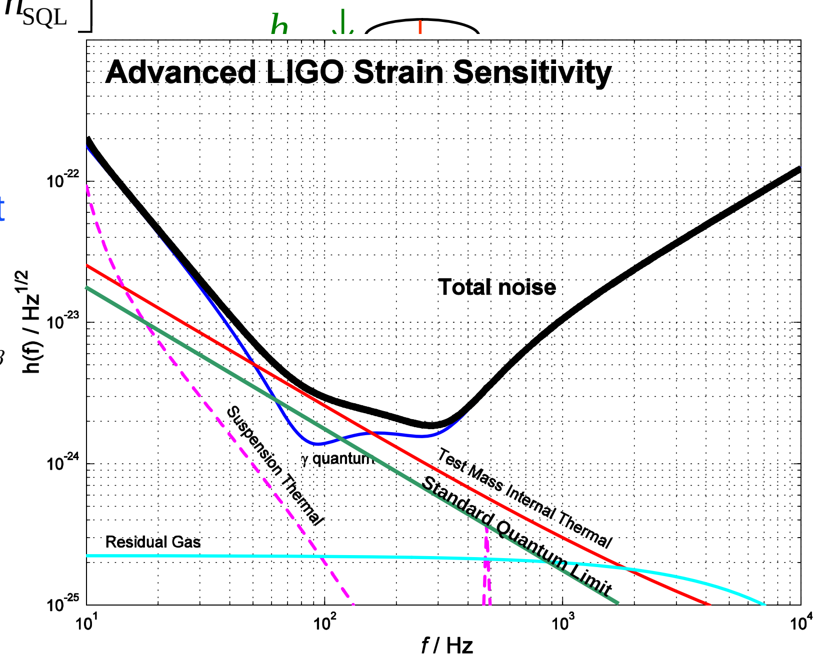
Mathematical description for optical spring in detuned RSE

ABYC equation: relation using two photon mode 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
&: input power coupling
ß: GW sideband phase shift



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**

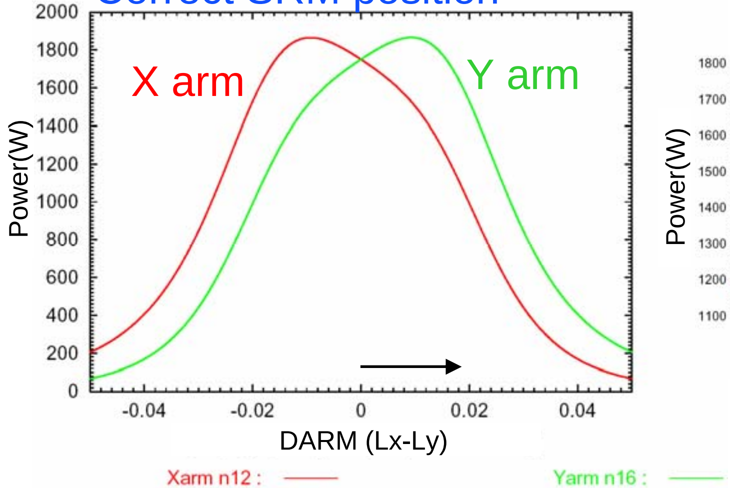
$$\frac{b_\varsigma}{h} = \frac{\sqrt{2\kappa}\,\tau}{h_{\mathrm{SQL}}}\left[\frac{D_1 \sin\varsigma + D_2 \cos\varsigma}{M} \right] e^{i\beta}$$

a <<*h*; non-quantum measurement

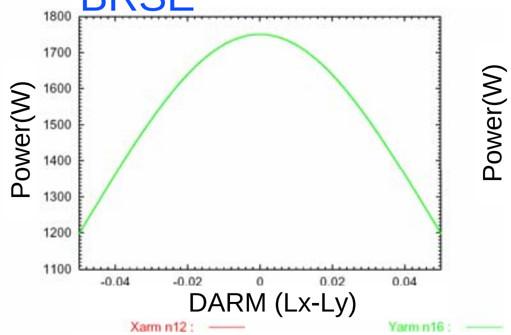
Simple picture of optical spring in detuned RSE

Let's move arm differentially, X arm longer, Y arm shorter from full RSE

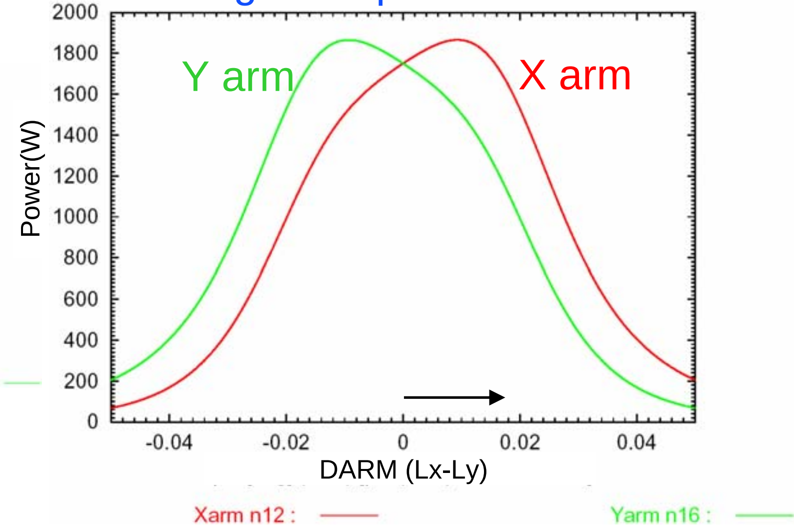
Correct SRM position



BRSE



Wrong SRM position



- Power

X arm down, Y arm up	X arm down, Y arm down	X arm up, Y arm down

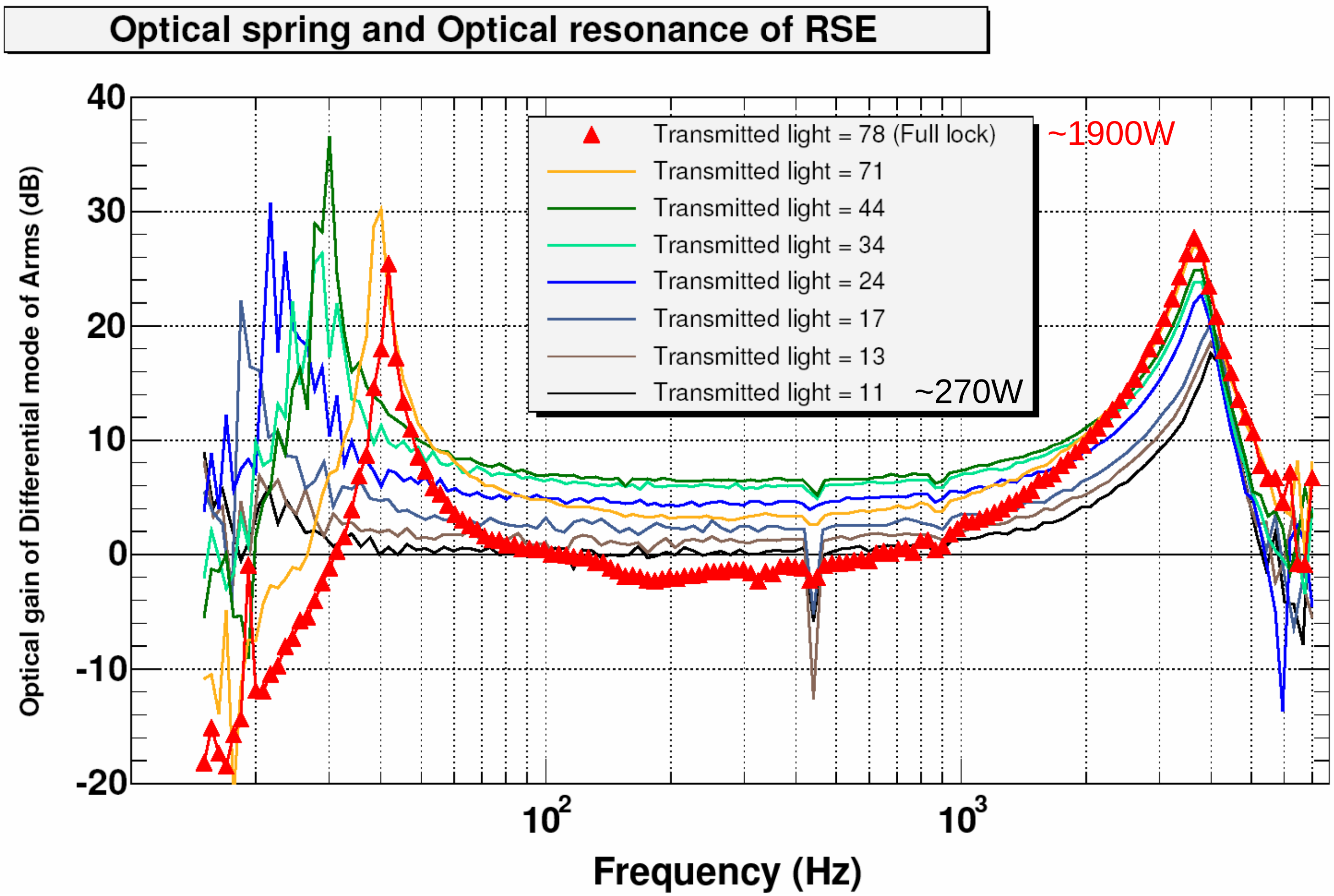
- Radiation pressure

X arm down, Y arm up	X arm down, Y arm down	X arm up, Y arm down

- Spring constant

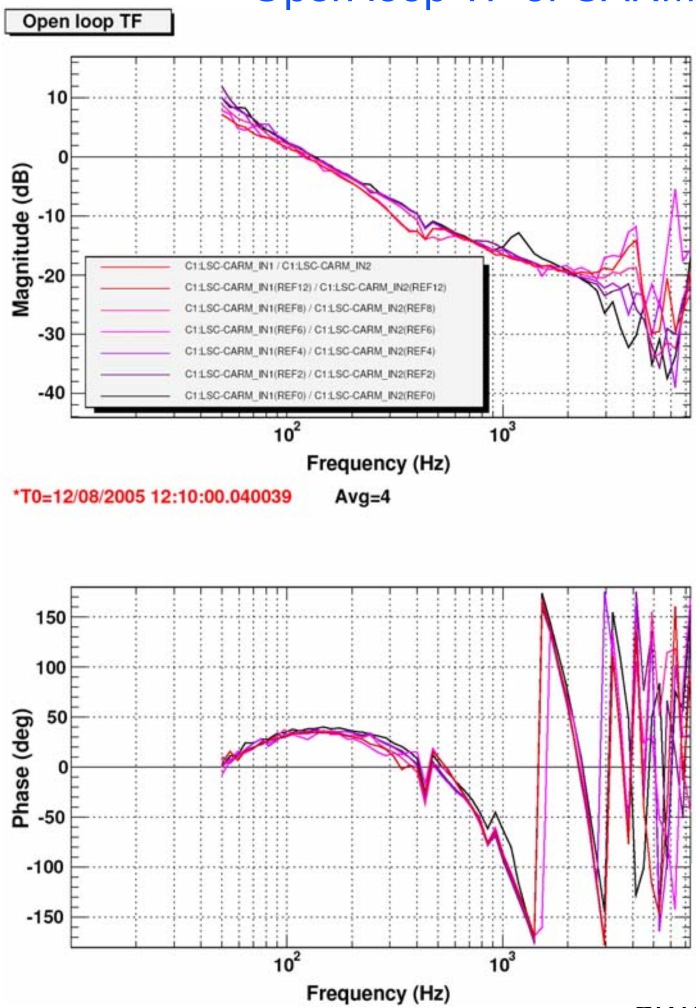
Positive (optical spring)	N/A	Negative (no optical spring)

Frequency sweep of optical spring

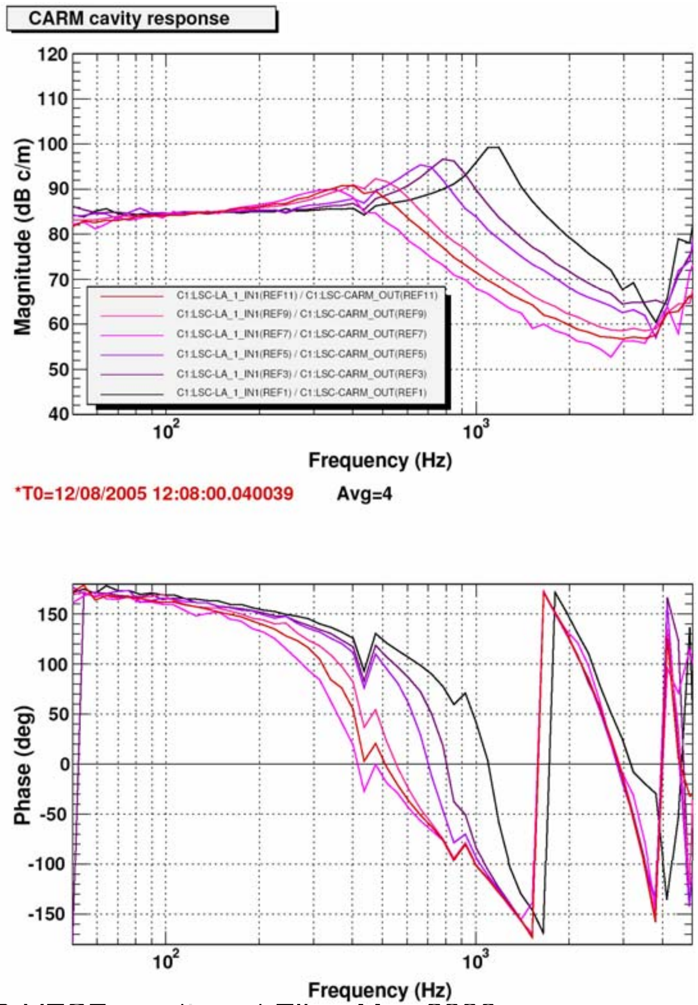


CARM optical resonance and Dynamic compensative filter

Open loop TF of CARM



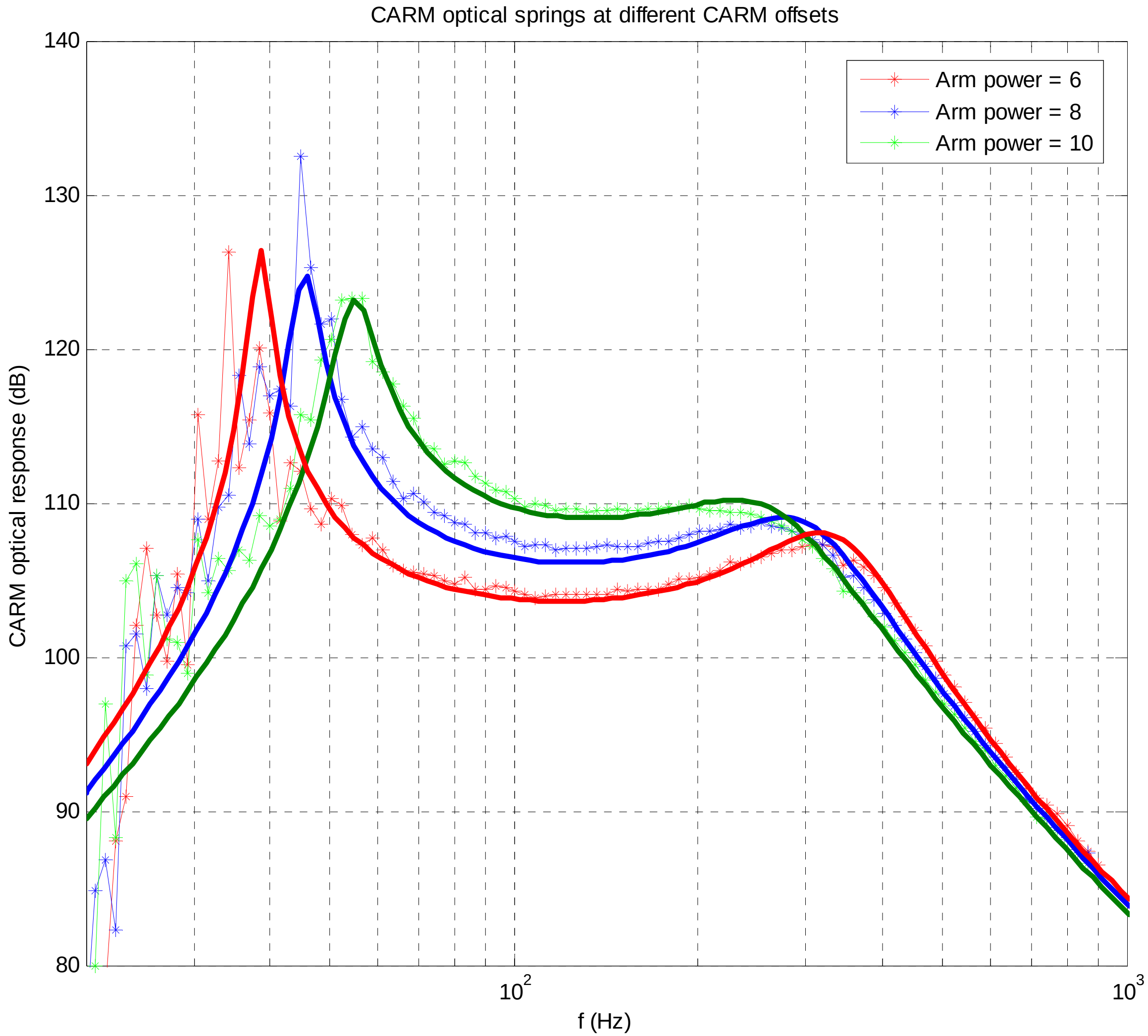
Optical gain of CARM



- 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.

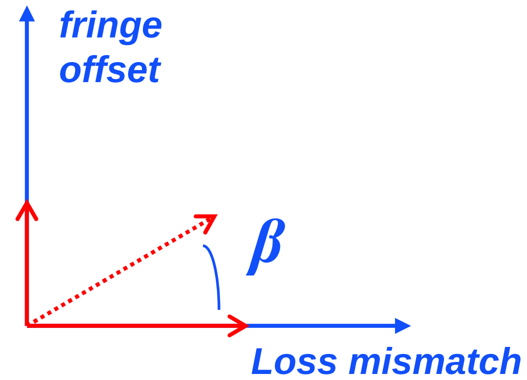
CARM optical springs

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

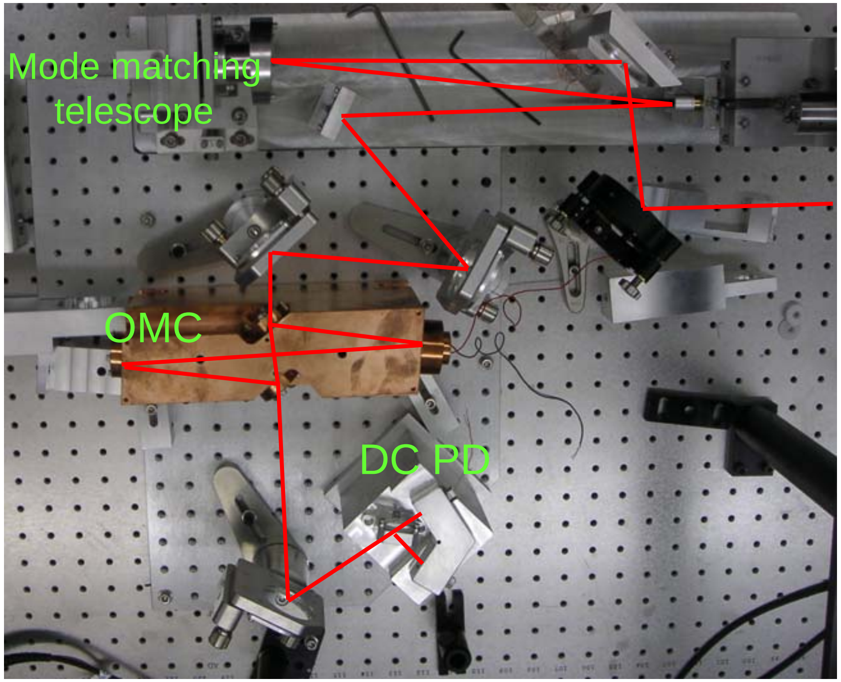


GW readout, Systems

- DC rather than RF for GW sensing
  - » Requires Output Mode-Cleaner to reject RF
  - » Offset ~ 1 picometer from dark fringe can tune from 0 to 80 deg with 0-100 mW of fringe offset power

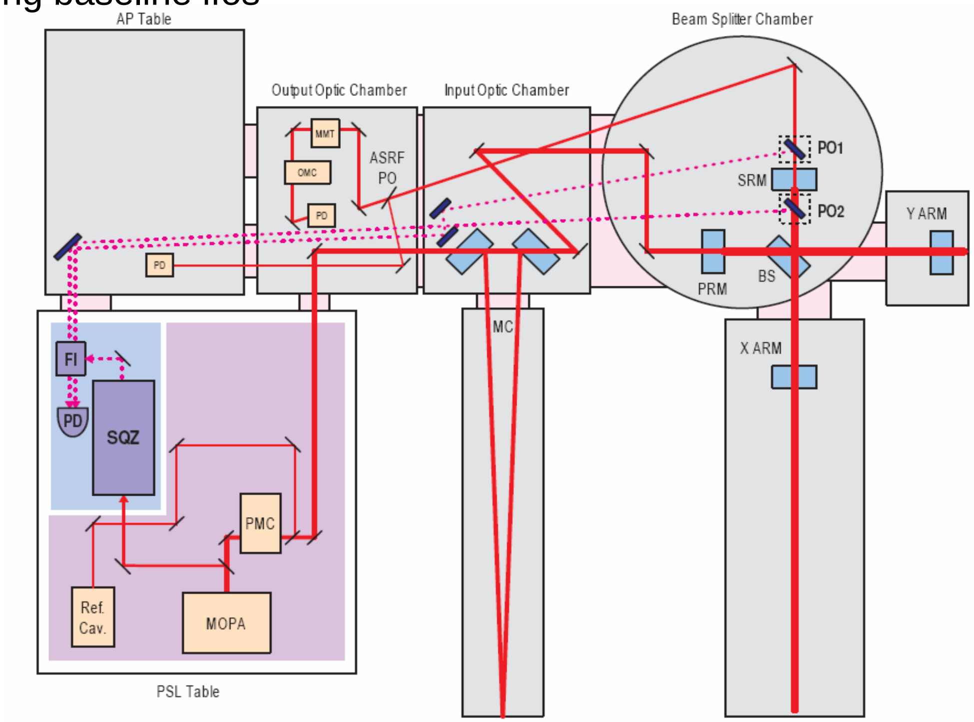


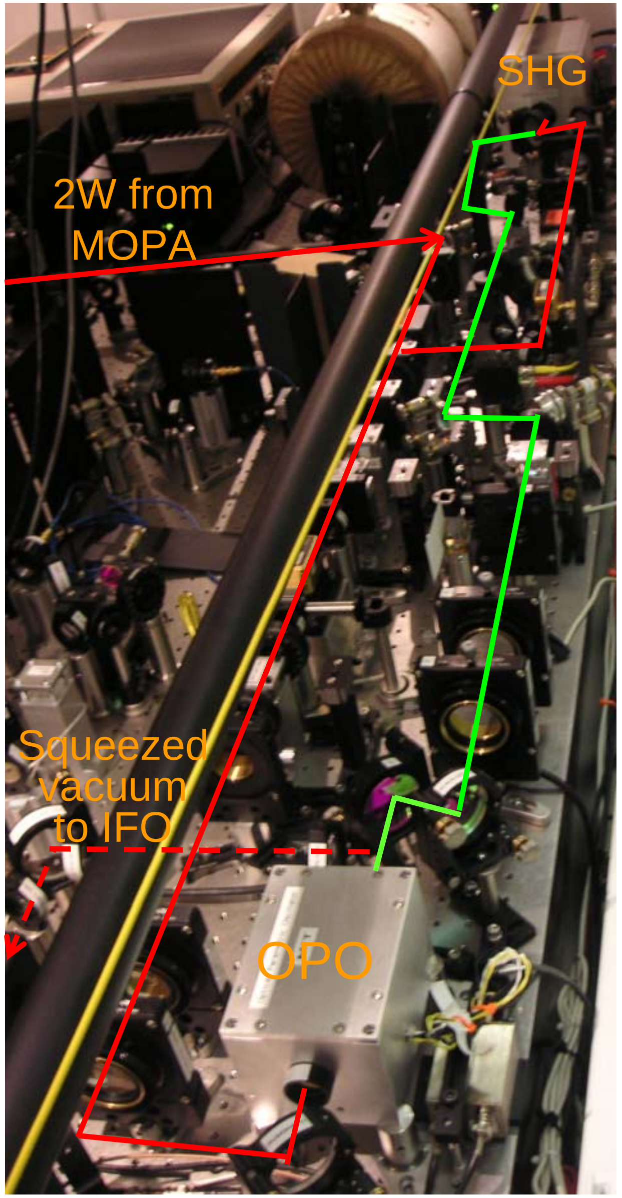
Noise Source	***RF readout***	***DC readout***
Laser frequency noise	~10x more sensitive	Less sensitive since carrier is filtered
Laser amplitude noise	Sensitivity identical for frequencies below ~100 Hz; both driven by technical radiation pressure	
	10-100x more sensitive above 100Hz	Carrier is filtered
Laser pointing noise	Sensitivity essentially the same	
Oscillator phase noise	-140 dBc/rtHz at 100 Hz	NA



Squeezing Tests at the 40m

- Go from MIT group brought an audio frequency squeezer to 40m, and injection of squeezed vacuum will be tested.
- SHG, OPO ready, homodyne detector being developed.
- Time to take steps toward injection to 40m interferometer
  - » DRSE configuration will be tested
  - » LIGO-like control systems for eventually porting squeezing technology to long baseline ifos





Other ideas

- Low frequency-low frequency RF modulation scheme (40m:33-55MHz, AdLIGO:27-45MHz) instead of LF-HF RF
- Alignment Sensing and Control (ASC) on detuned RSE with LF-LF RF modulation
- ASC with lighter mirrors in order to investigate pitch and yaw optical springs
- Variable band operation using SRC error signal normalized by LF f2 power