Optical spring and optical resonance in the 40m Detuned RSE interferometer

LIGO seminar

November 1, 2005

Osamu Miyakawa, Robert Ward, Rana Adhikari, Matthew Evans, Benjamin Abbott, Rolf Bork, Daniel Busby, Hartmut Grote, Jay Heefner, Alexander Ivanov, Seiji Kawamura, Michael Smith, Robert Taylor, Monica Varvella, Stephen Vass, and Alan Weinstein

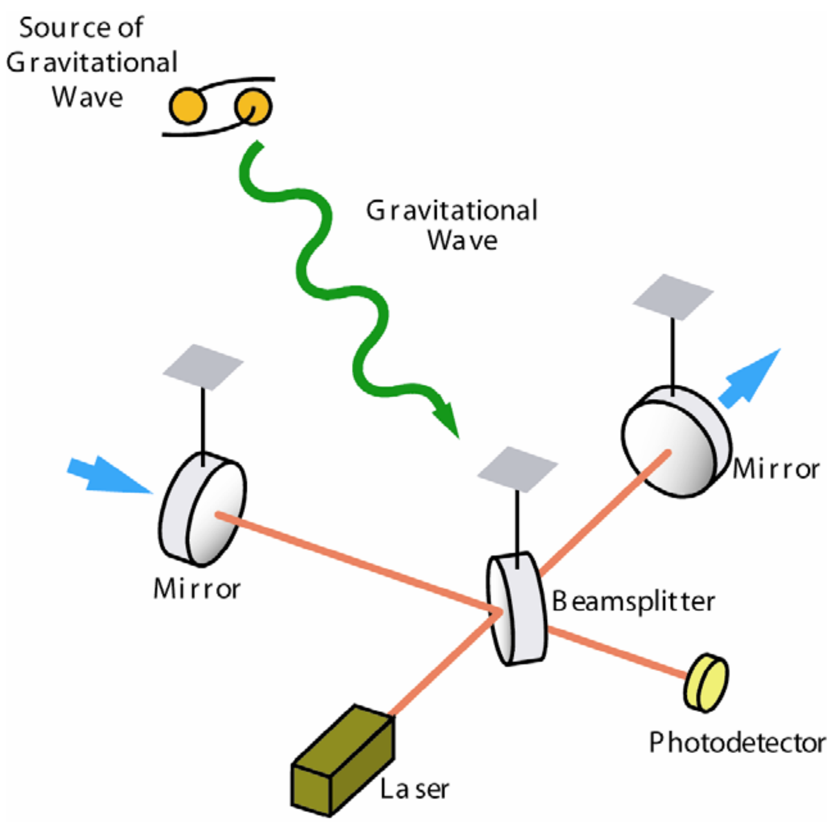
Today's talk

1. Advanced optical configuration
2. Caltech 40m prototype
3. Lock acquisition of detuned RSE
4. Optical spring and optical resonance

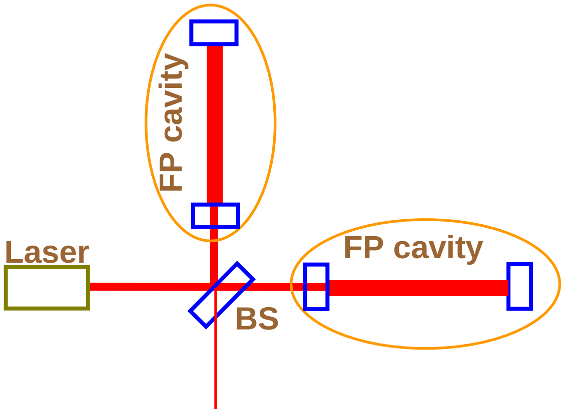
1. Advanced optical configuration

Development of Michelson type interferometer as a gravitational wave detector

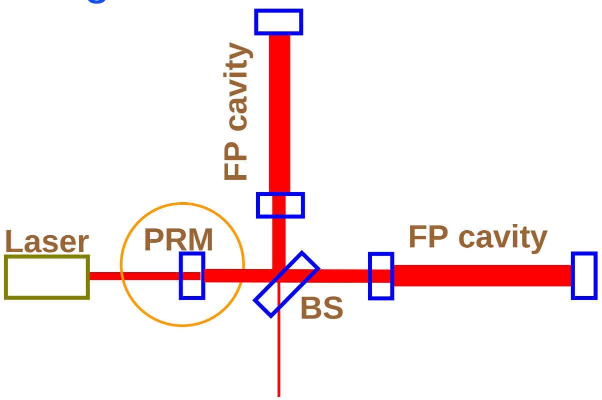
- Gravitational wave detection using Michelson interferometer



- Signal and power enhancement using Fabry-Perot cavity in each arm

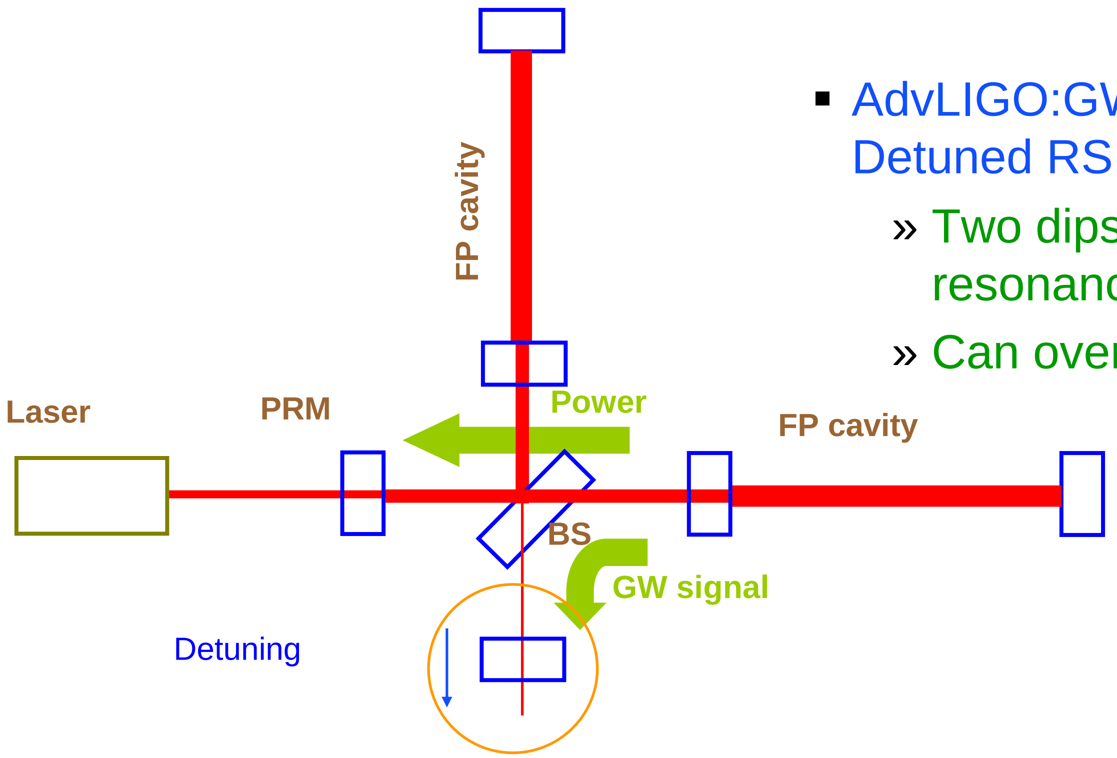


- Power enhancement using Power Recycling



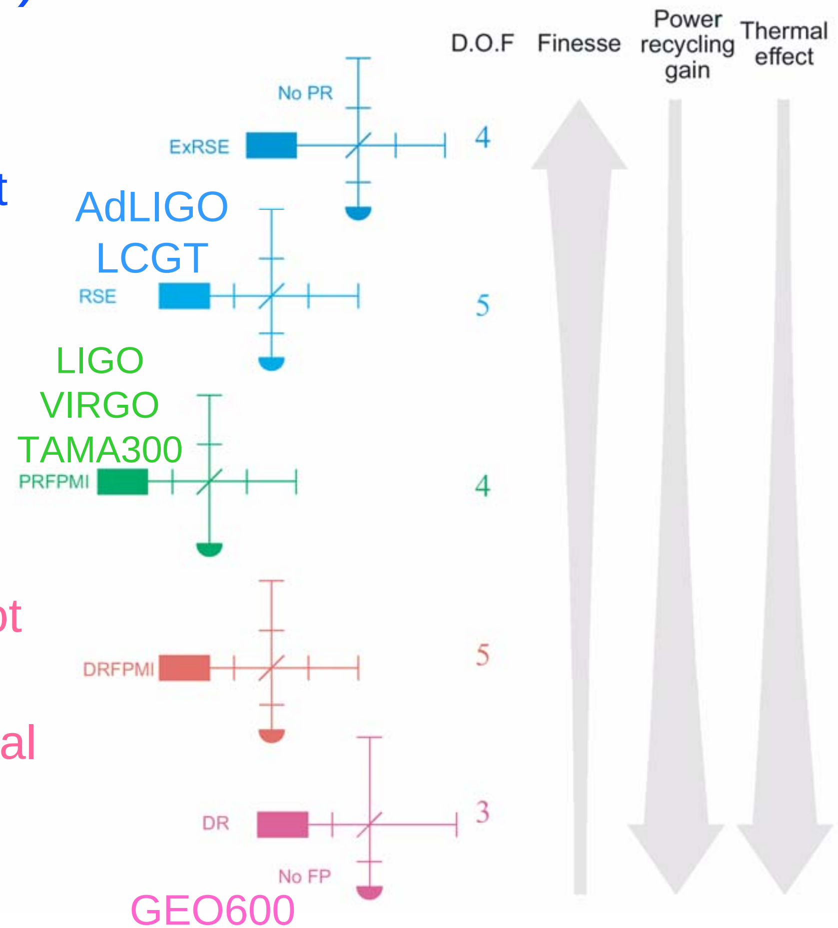
Advanced LIGO optical configuration

- 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

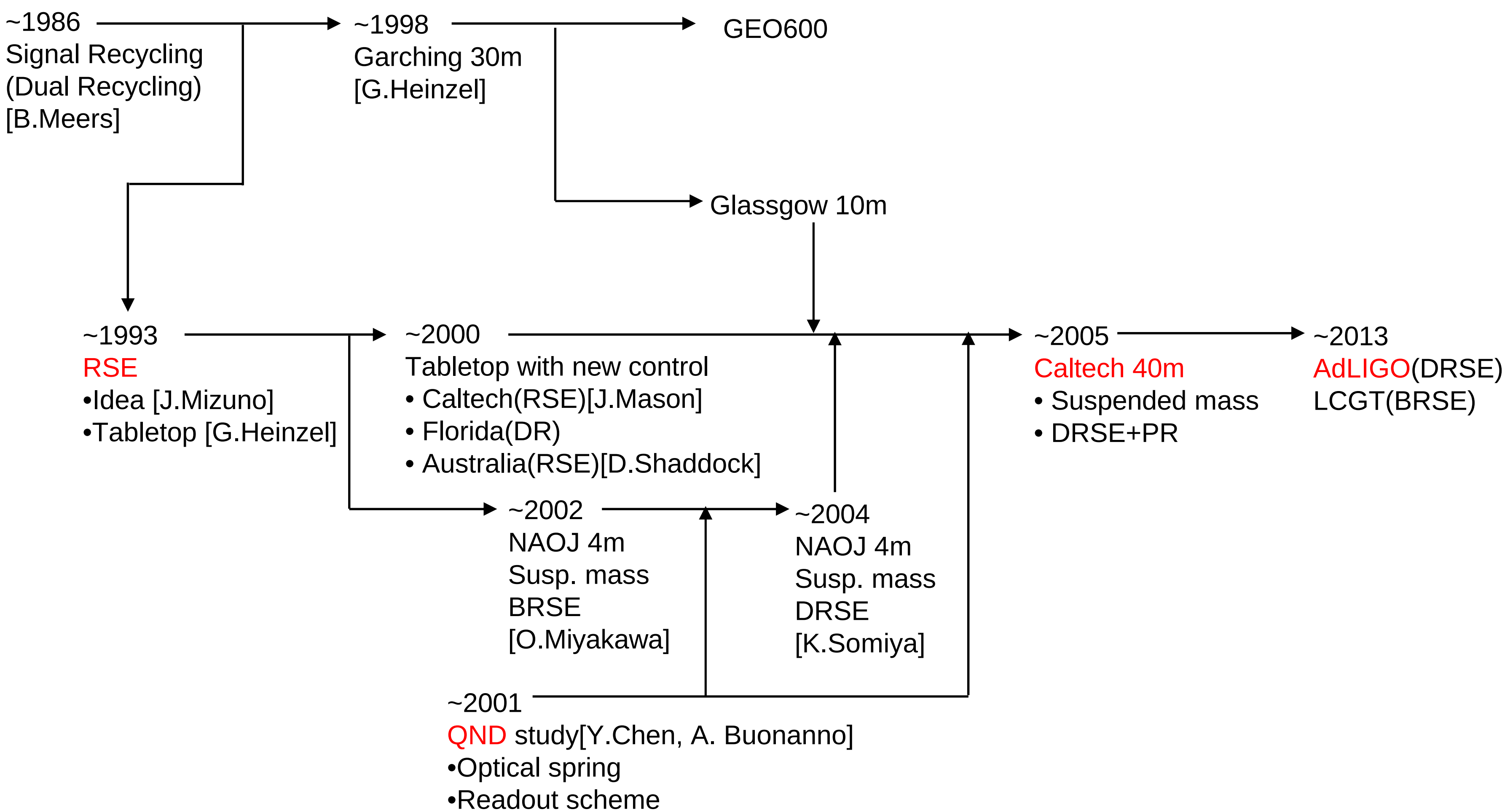


Resonant Sideband Extraction and Signal Recycling

- Resonant Sideband Extraction(RSE)
  - » Anti-resonant carrier on SRC
  - » High finesse arm cavities required
  - » Low power recycling, or power recycling not required
  - » Less thermal effect
  - » Better for long arm based interferometer
- Signal Recycling(SR)
  - » Resonant carrier on SRC
  - » Low finesse arm cavities, or arm cavities not required
  - » High power recycling required, so-called dual recycling(DR)
  - » Higher thermal effect
  - » Better for short arm based interferometer



Historical review of Advanced interferometer configuration



2. Caltech 40m prototype

Caltech 40 meter prototype interferometer

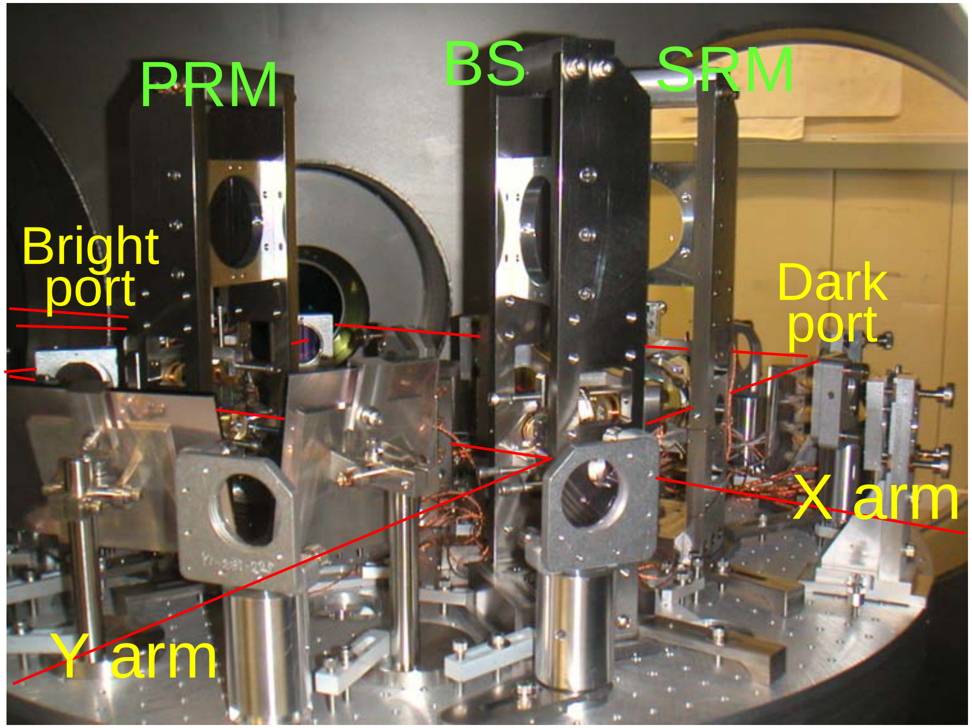
An interferometer as close as possible to
the Advanced LIGO optical configuration and control system

- Detuned Resonant Sideband Extraction(DRSE)
- Power Recycling
- Suspended mass
- Digital controls system

Caltech 40 meter prototype interferometer

Objectives

- Develop a **lock acquisition procedure** for suspended-mass detuned RSE interferometer with power recycling
- Verify **optical spring** and **optical resonance**
- Characterize noise mechanisms
- Develop **DC readout** scheme
- Extrapolate to AdLIGO via simulation



Optical spring

Optical spring in detuned RSE was predicted using two-photon mode.

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

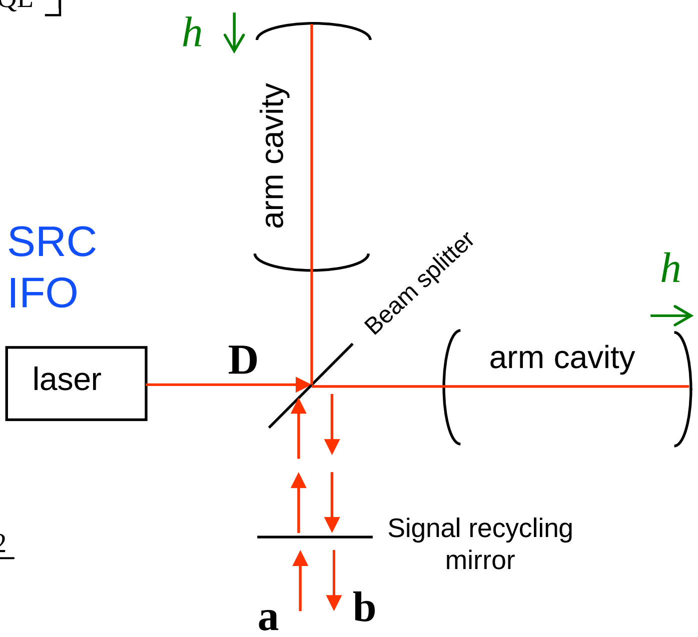
a :input vacuum
b :output
D :input carrier
M :constant
h :gravitational wave

h_{SQL}:standard quantum limit
♦: transmissivity of SRM
&: coupling constant
☞: GW sideband phase shift in SRC
ℓ: GW sideband phase shift in IFO

$$h_n = \frac{h_{\mathrm{SQL}}}{\sqrt{2\kappa}} \Delta b_\zeta$$

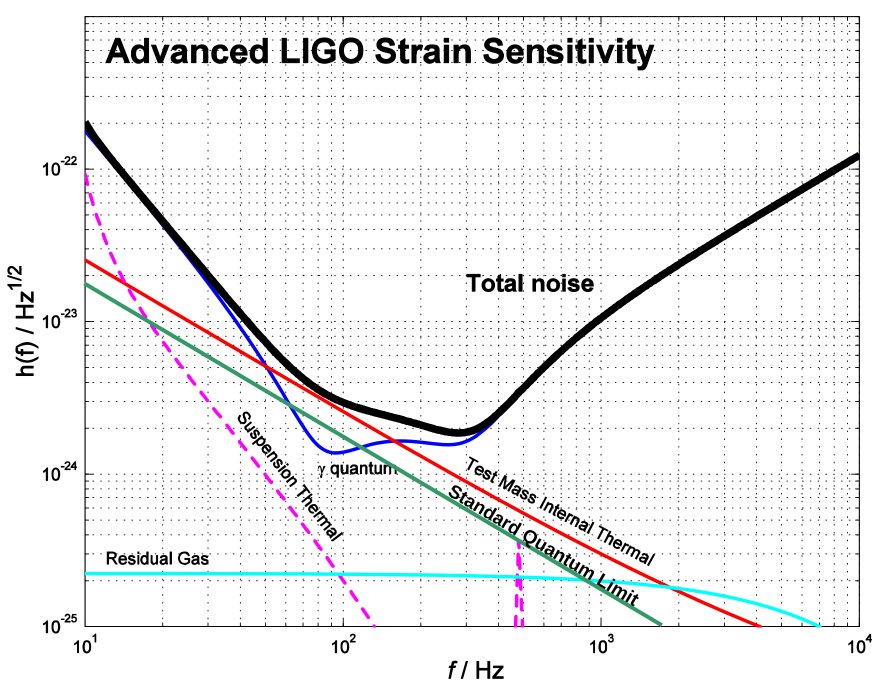
$$\Delta b_\zeta = \frac{(C_{11}\sin\zeta + C_{21}\cos\zeta)a_1 + (C_{12}\sin\zeta + C_{22}\cos\zeta)a_2}{\tau\,(D_1\sin\zeta + D_2\cos\zeta)}$$

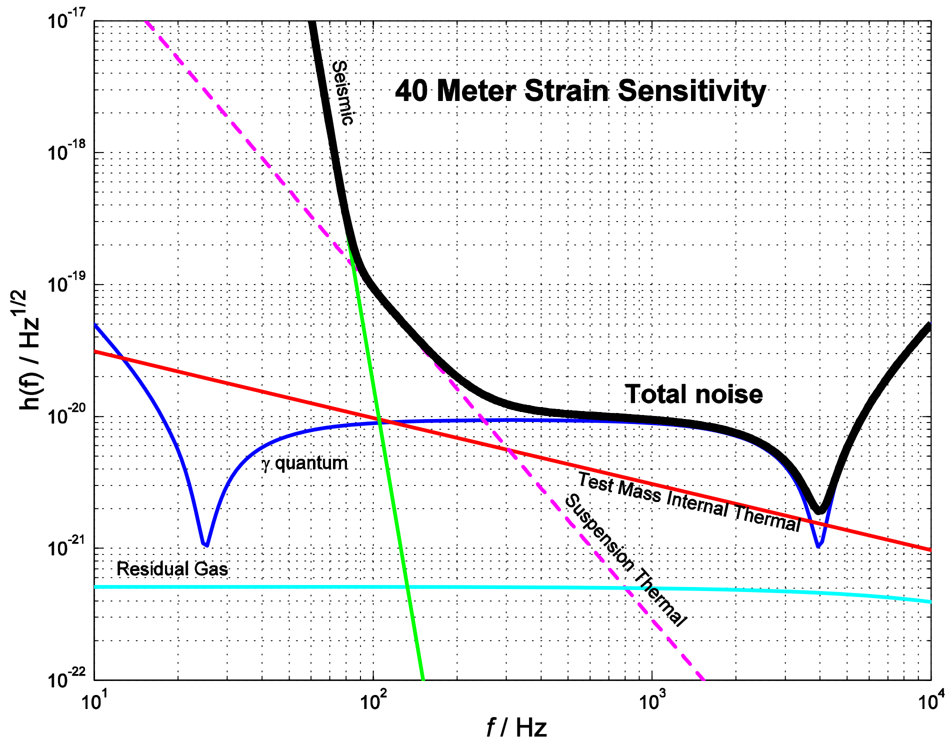
⌘: homodyne phase



A. Buonanno, Y.Chen, Phys. Rev. D 64, 042006 (2001)

Target sensitivity of AdvLIGO and 40m prototype



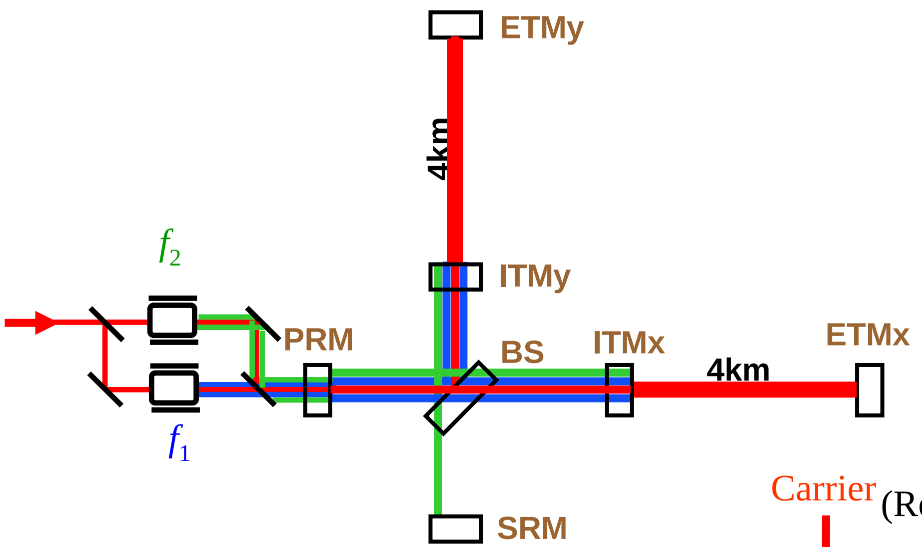


- 2 dips, optical spring and optical resonance in detuned RSE

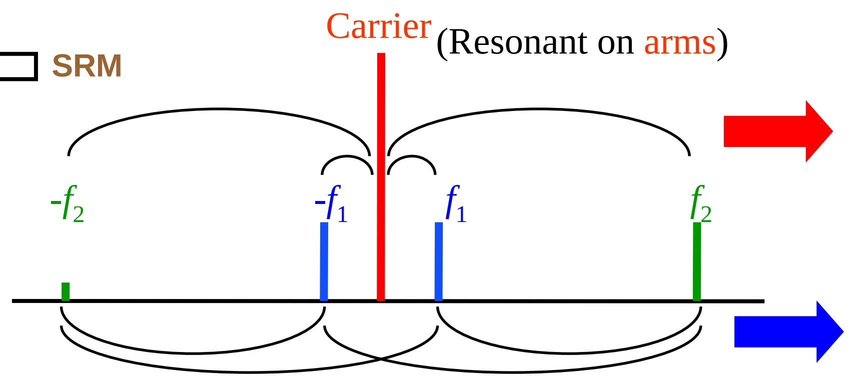
Differences between AdvLIGO and 40m prototype

- 100 times shorter cavity length
- Arm cavity finesse at 40m chosen to be = to AdvLIGO (= 1235)
  - » Storage time is x100 shorter
- Control RF sidebands are 33/166 MHz instead of 9/180 MHz
  - » Due to shorter PRC length, less signal separation
- LIGO-I 10-watt laser, negligible thermal effects
  - » 180W laser will be used in AdvLIGO.
- Noisier seismic environment in town, smaller isolation stacks
  - » ~1×10^{-6}m at 1Hz
- LIGO-I single pendulum suspensions
  - » AdvLIGO will use triple (MC, BS, PRM, SRM) and quad (ITMs, ETMs) suspensions.

AdLIGO signal extraction scheme



- Mach-Zehnder will be 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.



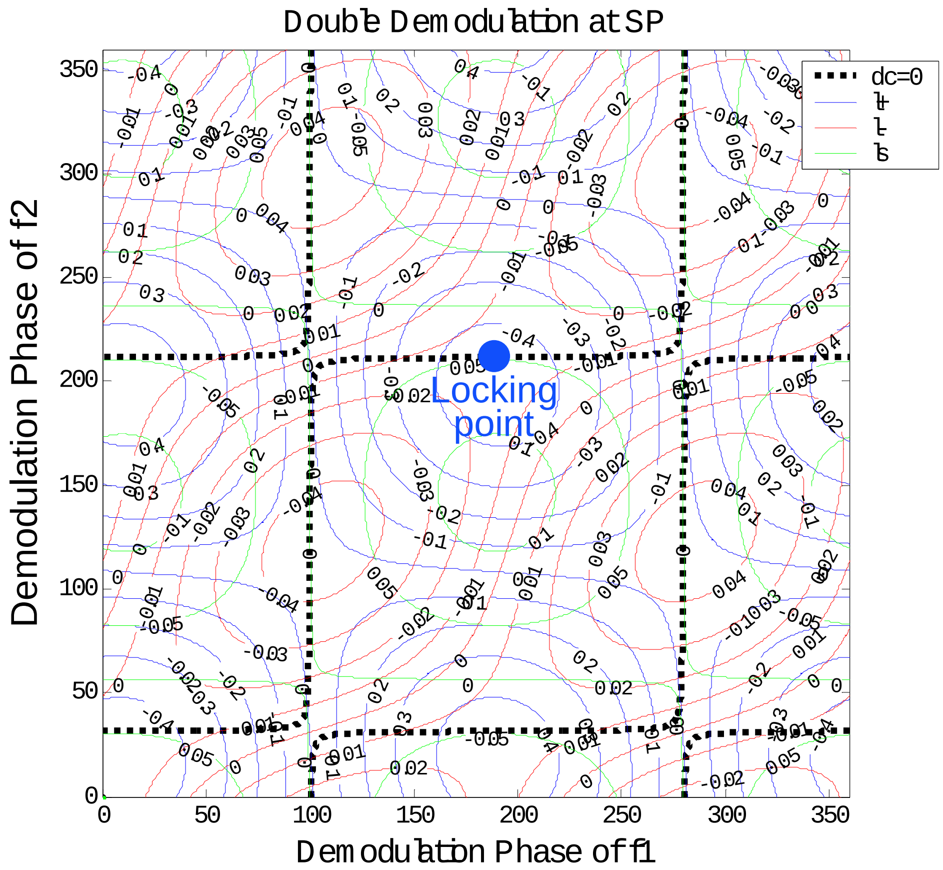
- Single demodulation
- Arm information

- 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.

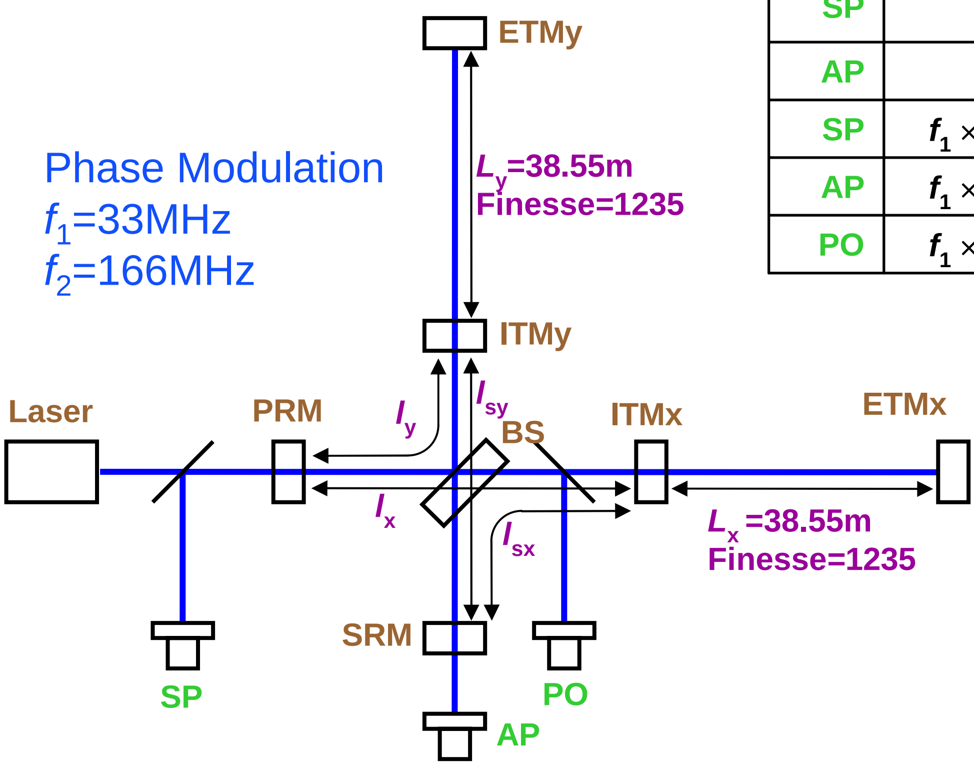
Double Demodulation

- Double Demodulation used for I_+, I_-, and I_s
- Demodulation phases optimized to suppress DC and to maximize desired signal



5 DOF for length control

Phase Modulation
f_1=33MHz
f_2=166MHz



Signal Extraction Matrix (in-lock)

Port	Dem. Freq.	L_+	L_-	l_+	l_-	l_s
SP	f_1	1	-3.8E-9	-1.2E-3	-1.3E-6	-2.3E-6
AP	f_2	-4.8E-9	1	1.2E-8	1.3E-3	-1.7E-8
SP	$f_1 \times f_2$	-1.7E-3	-3.0E-4	1	-3.2E-2	-1.0E-1
AP	$f_1 \times f_2$	-6.2E-4	1.5E-3	7.5E-1	1	7.1E-2
PO	$f_1 \times f_2$	3.6E-3	2.7E-3	4.6E-1	-2.3E-2	1

Common of arms : $L_+ = (L_x + L_y) / 2$

Differential of arms : $L_- = L_x - L_y$

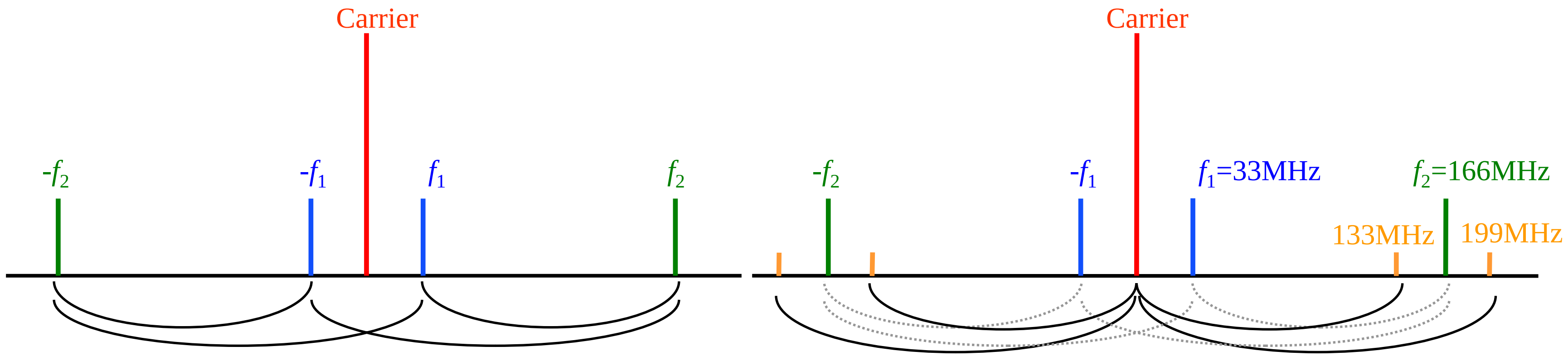
Power recycling cavity: $l_+ = (l_x + l_y) / 2$ =2.257m

Michelson : $l_- = l_x - l_y$ = 0.451m

Signal recycling cavity: $l_s = (l_{sx} + l_{sy}) / 2$ =2.15m

Disturbance by sidebands of sidebands

Original concept　　　　　　　　Real world

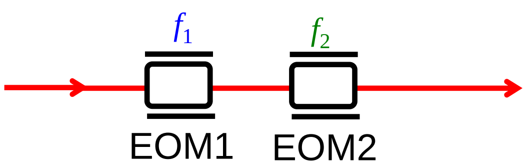


- Sidebands of sidebands are produced by two series EOMs.
- Beats between carrier and f_2 +/- f_1 disturb central part.

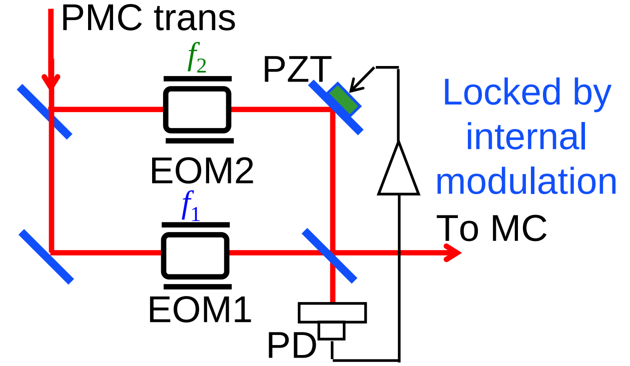
Port	Dem. Freq.	L_+	L_-	l_+	l_-	l_s
SP	f_1	1	-1.4E-8	-1.2E-3	-1.3E-6	-6.2E-6
AP	f_2	1.2E-7	1	1.4E-5	1.3E-3	6.5E-6
SP	$f_1 \times f_2$	7.4	-3.4E-4	1	-3.3E-2	-1.1E-1
AP	$f_1 \times f_2$	-5.7E-4	32	7.1E-1	1	7.1E-2
PO	$f_1 \times f_2$	3.3	1.7	1.9E-1	-3.5E-2	1

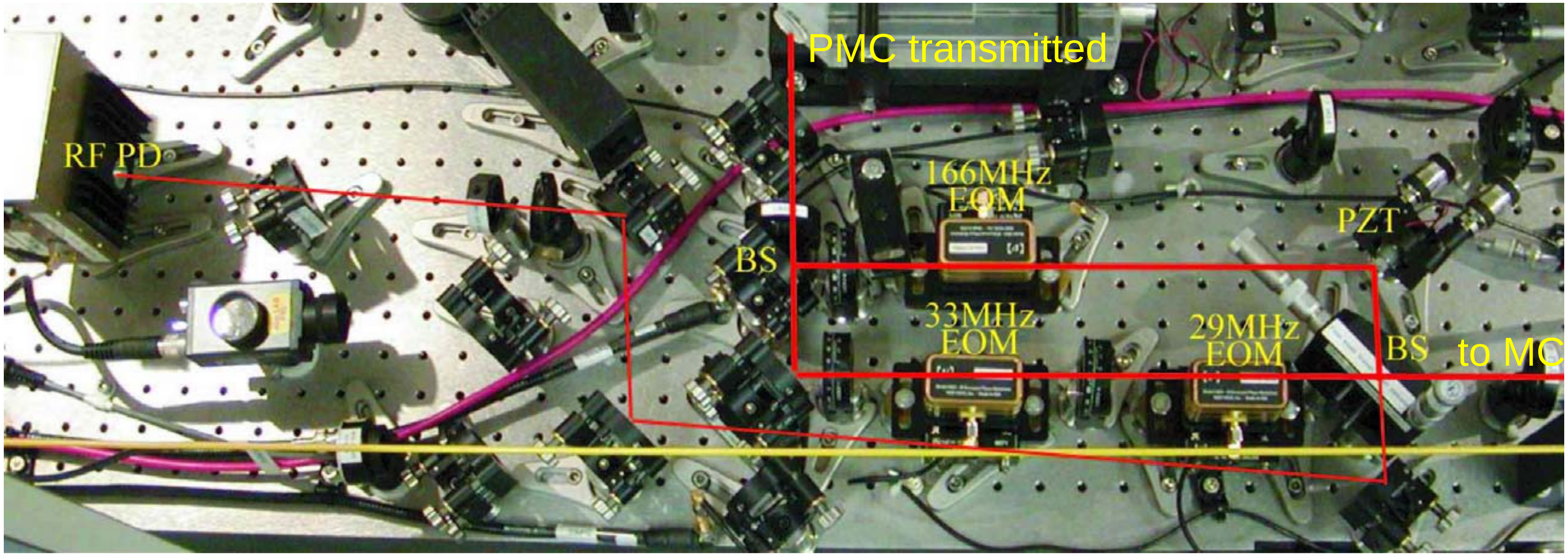
Mach-Zehnder interferometer on 40m PSL to eliminate sidebands of sidebands

Series EOMs
with sidebands of sidebands

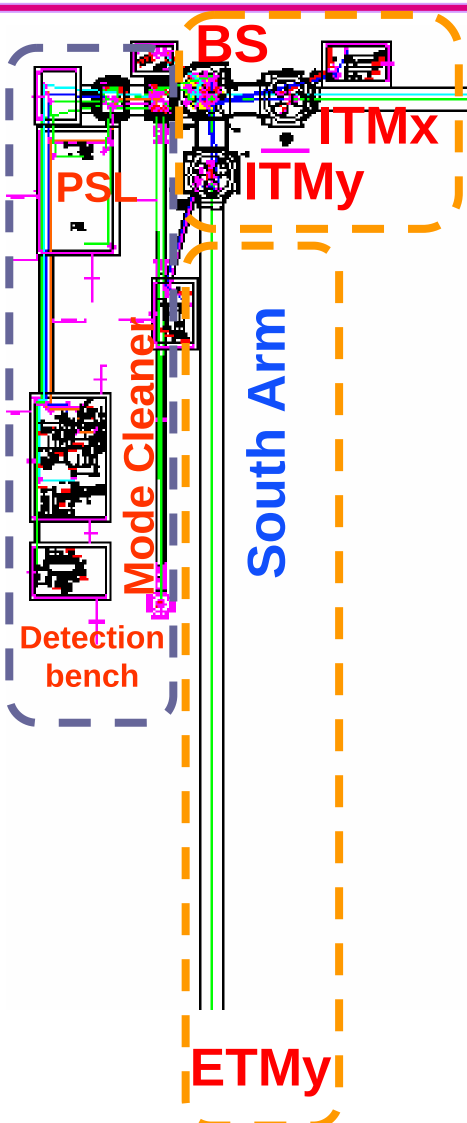


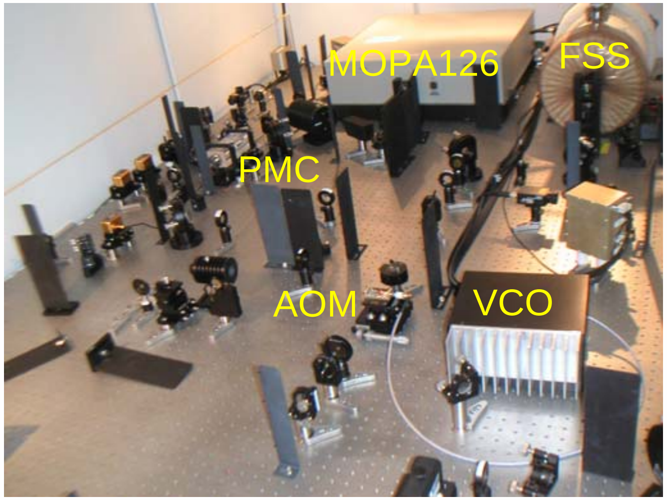
Mach-Zehnder interferometer
with no sidebands of sidebands





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

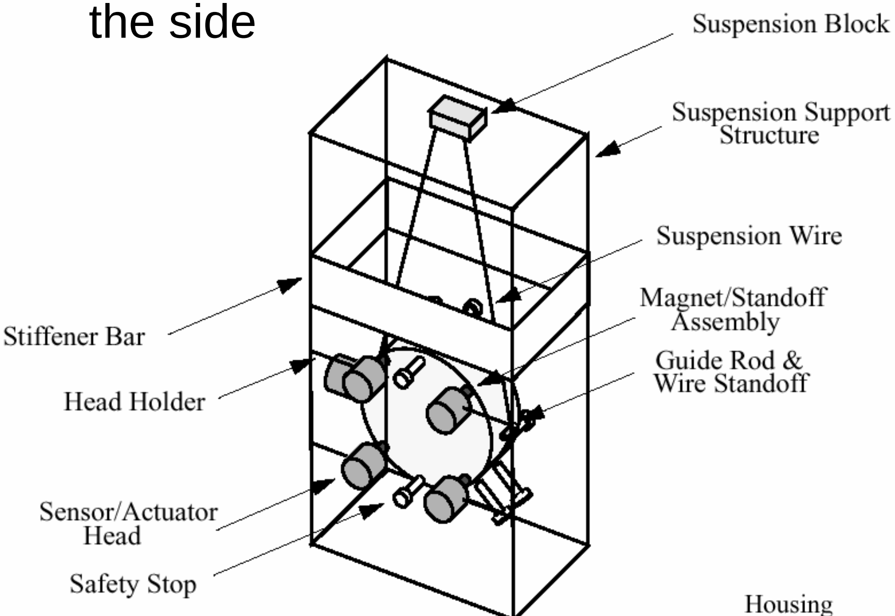


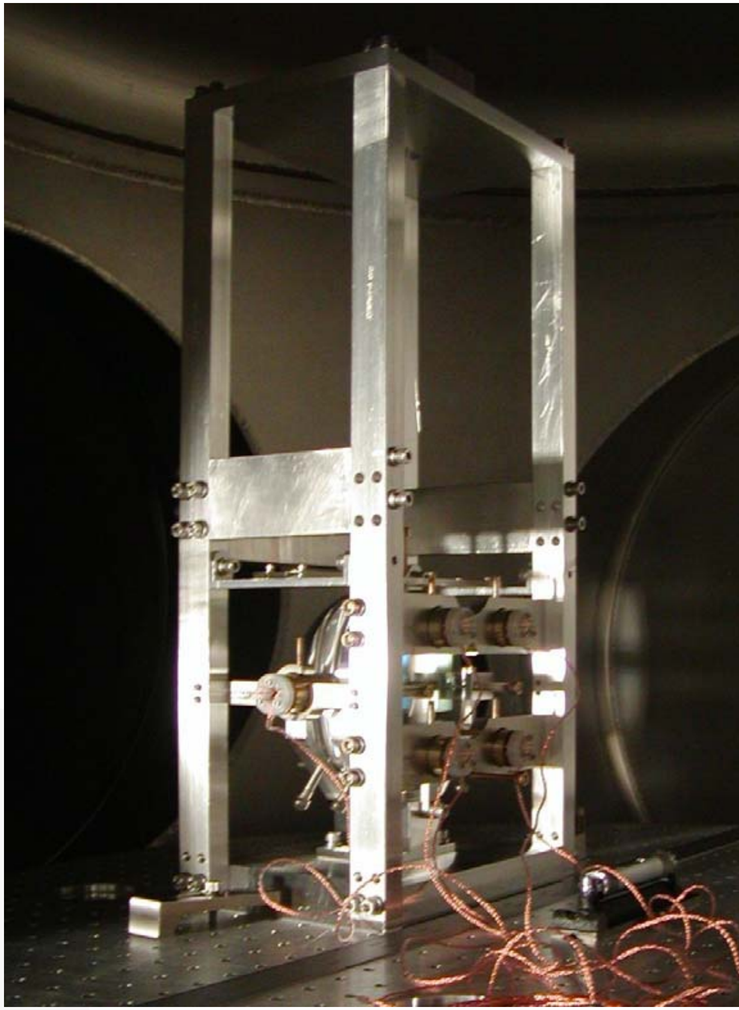


- 10W MOPA126
- Frequency Stabilization Servo (FSS)
- Pre-Mode Cleaner (PMC)
- 13m Mode Cleaner

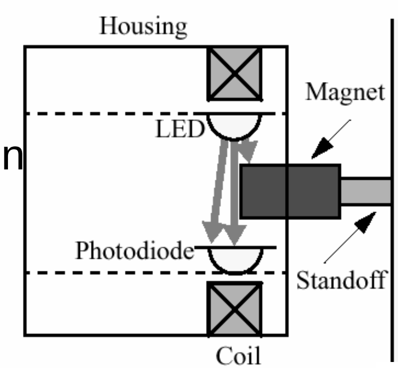
LIGO-I type single suspension

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

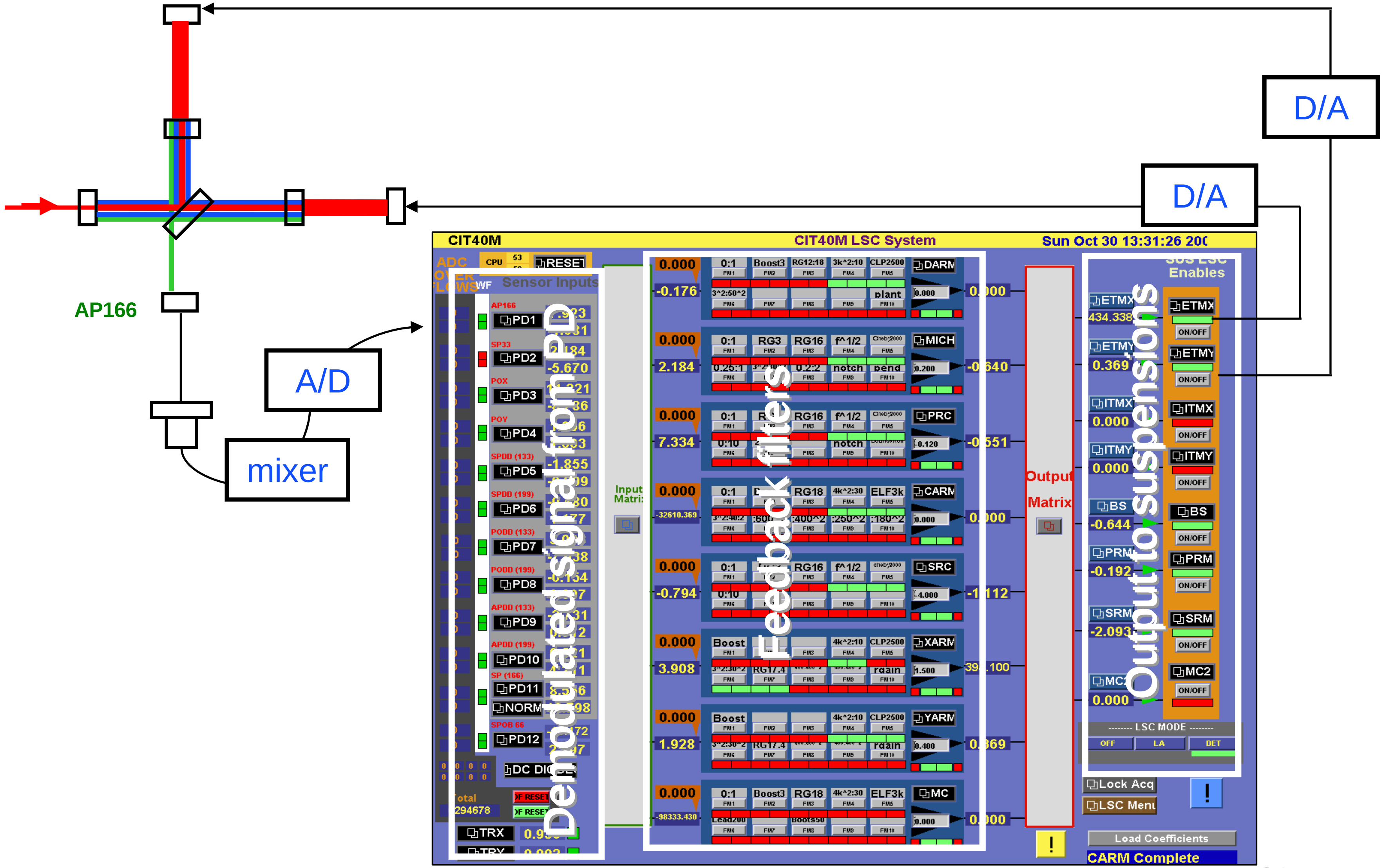




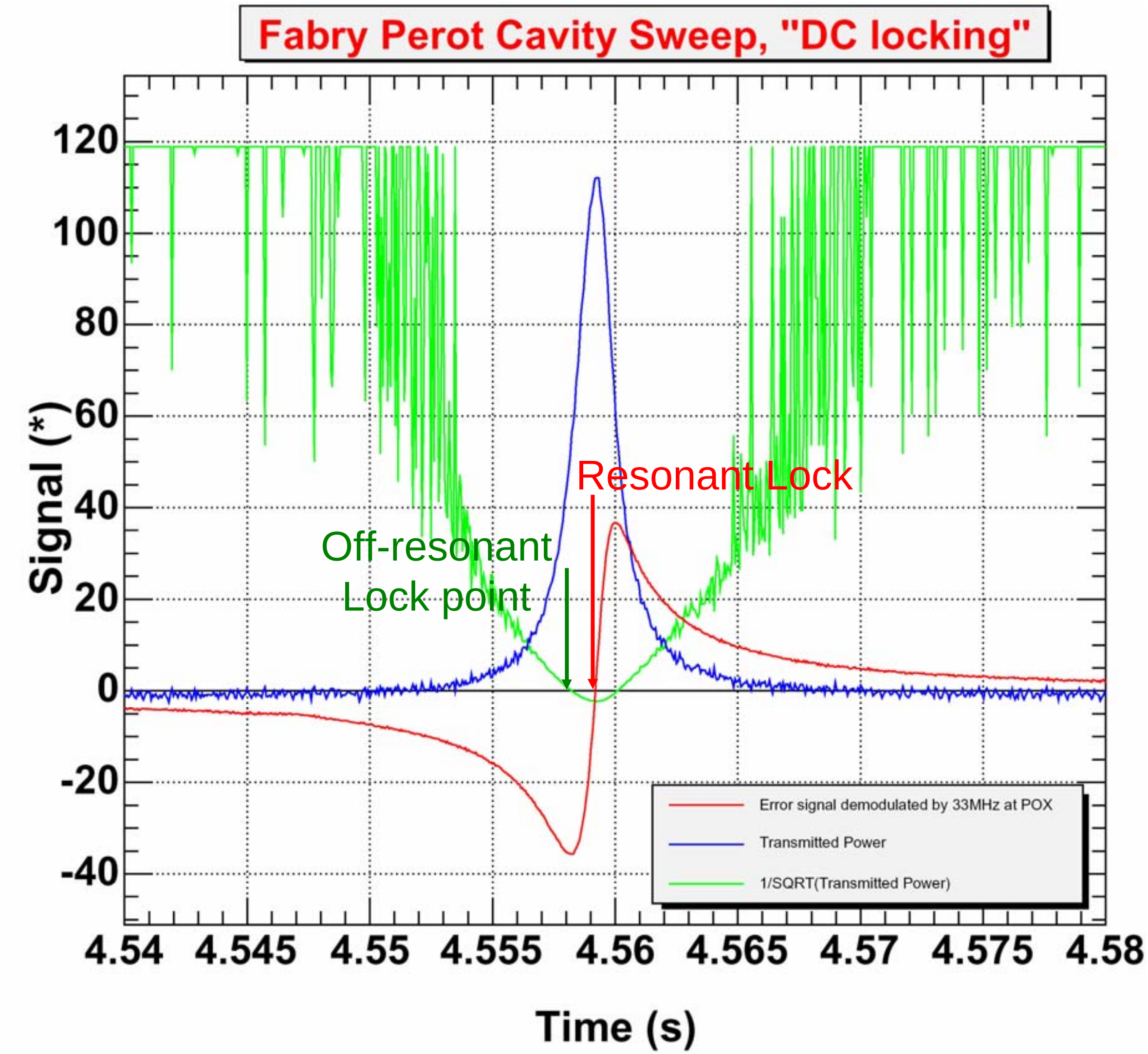
- The magnet occludes light from the LED, giving position
- Current through the coil creates a magnetic field, allowing mirror control



Digital length control system



Off-resonant lock scheme for arm cavity



Transmitted light is used as

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

to avoid coupling of carrier in PRC when arm cavity is locked.

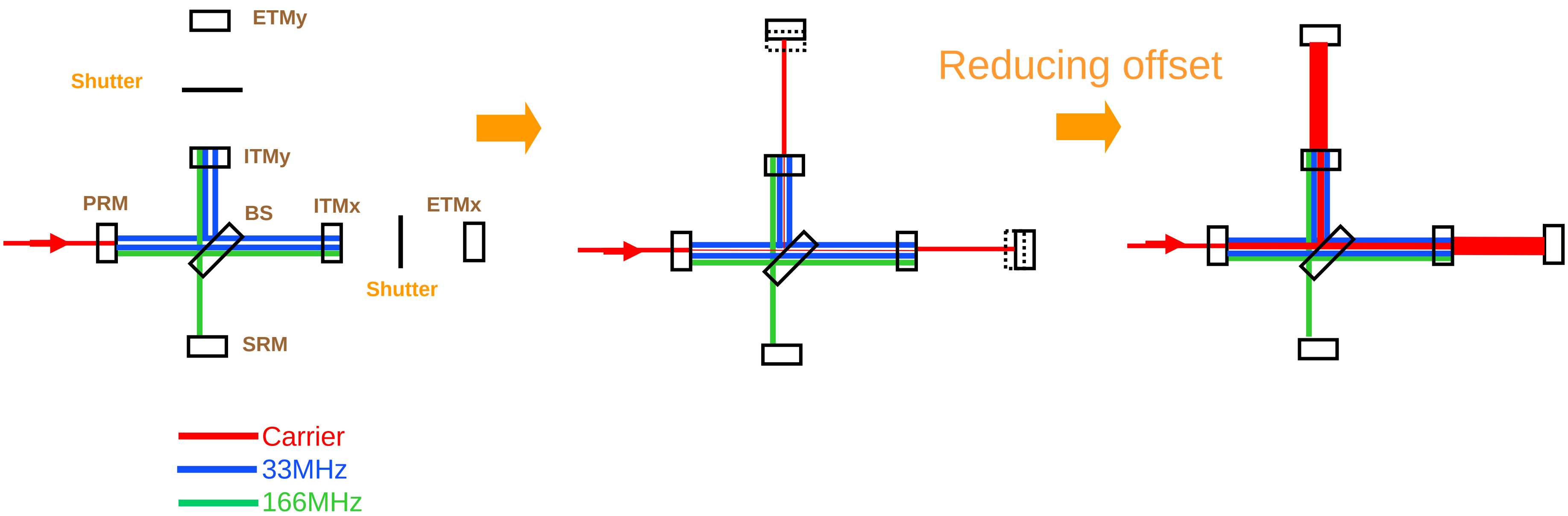
3. Lock acquisition of detuned RSE

The way to full RSE

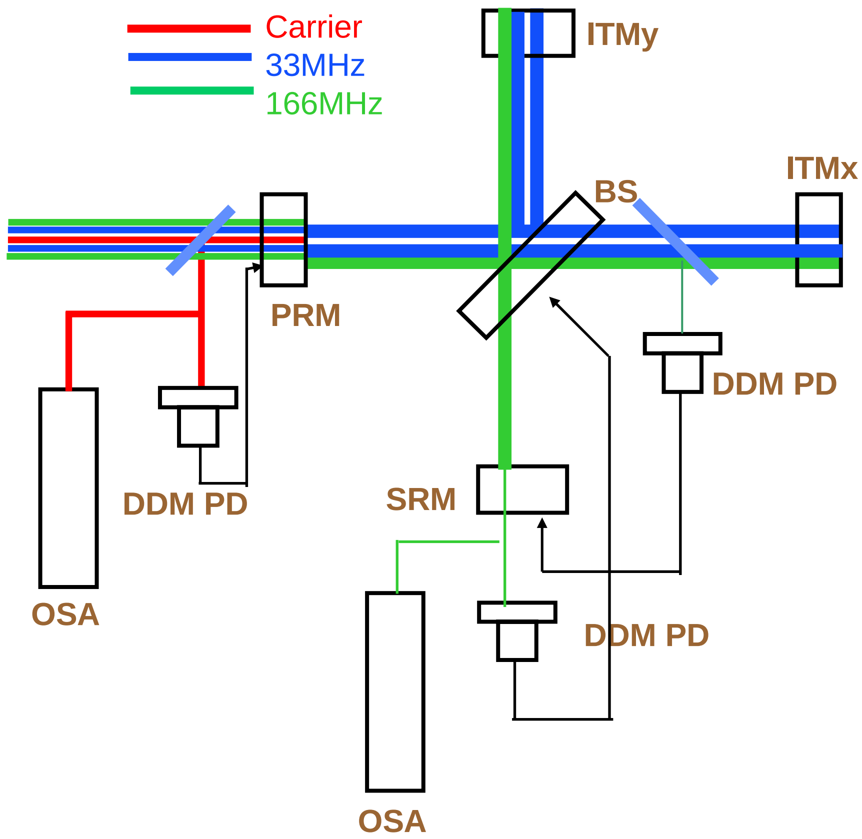
Oct. 2004
Detuned dual recycled Michelson

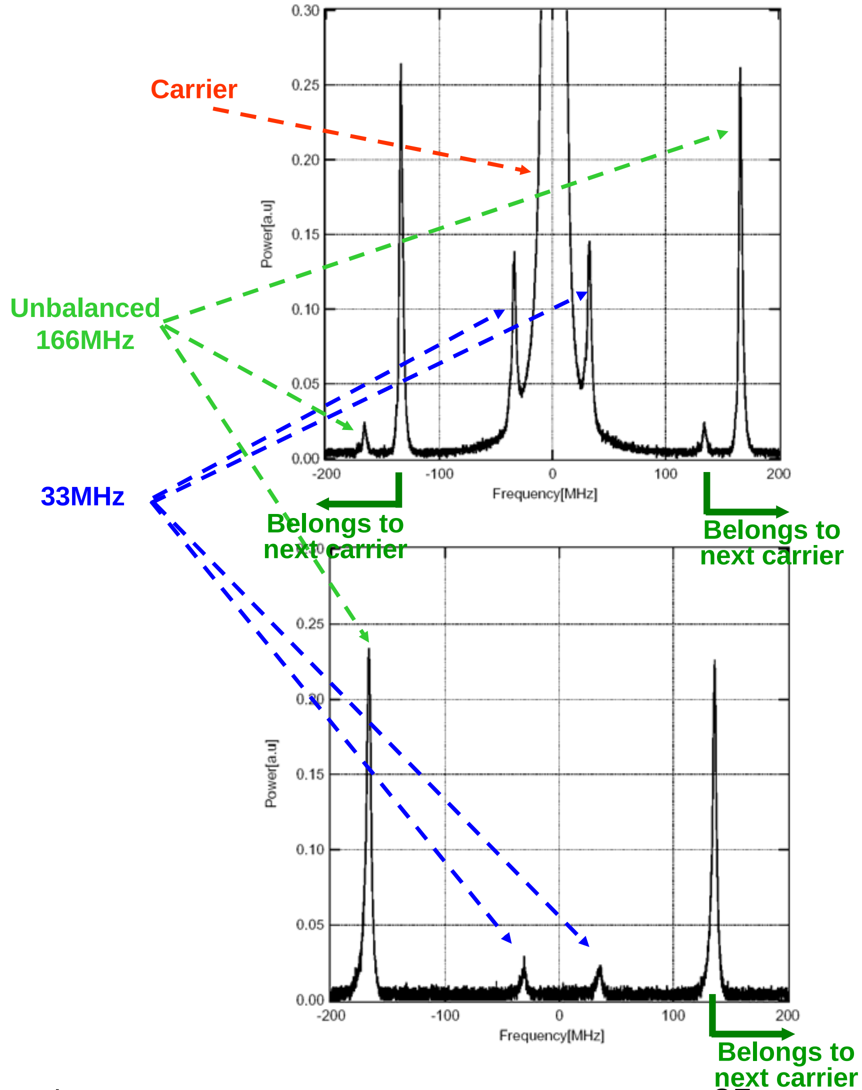
Nov. 2004
Arm lock with offset in common mode

Oct. 2005
RSE



DRMI lock using double demodulation with unbalanced sideband by detuned cavity

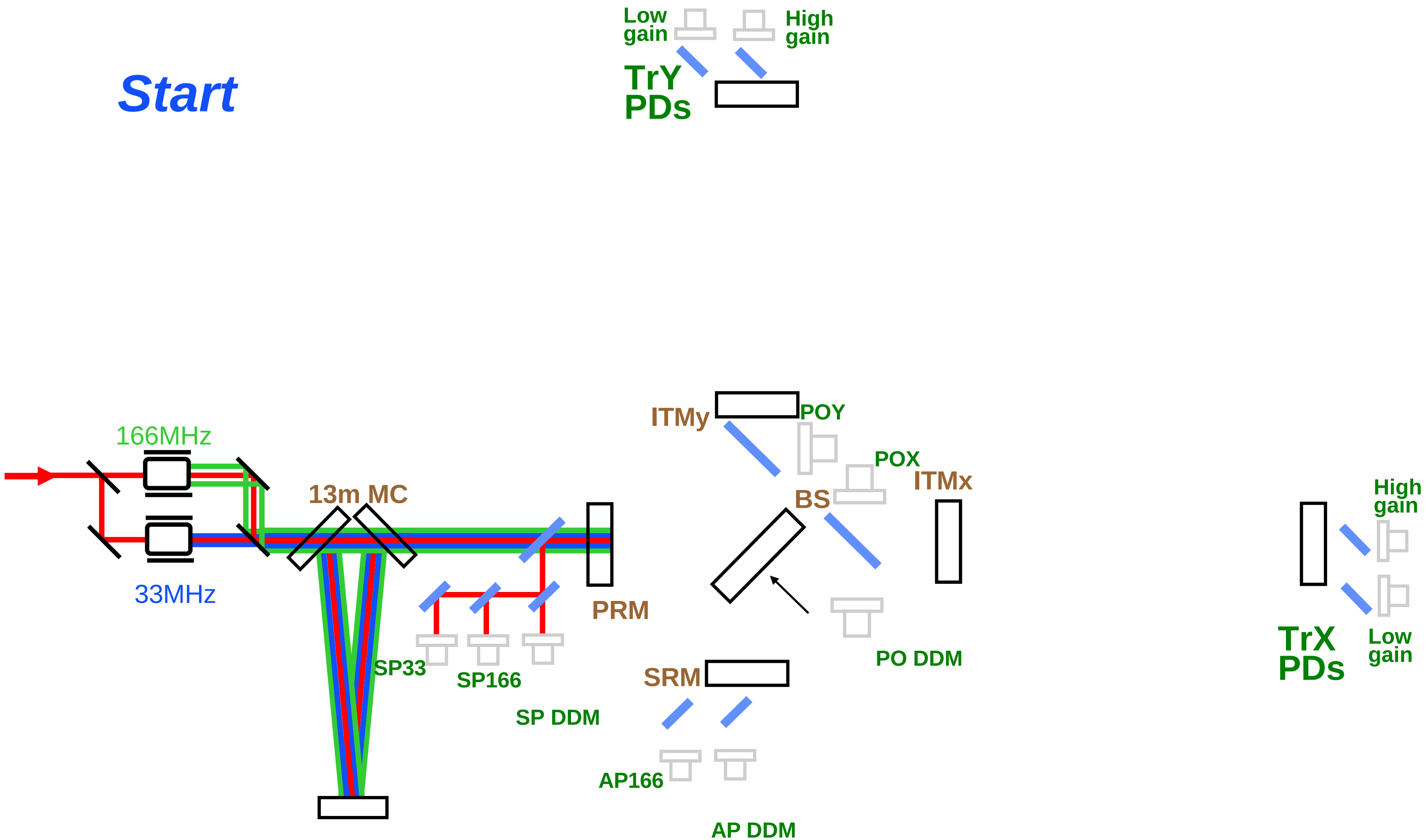




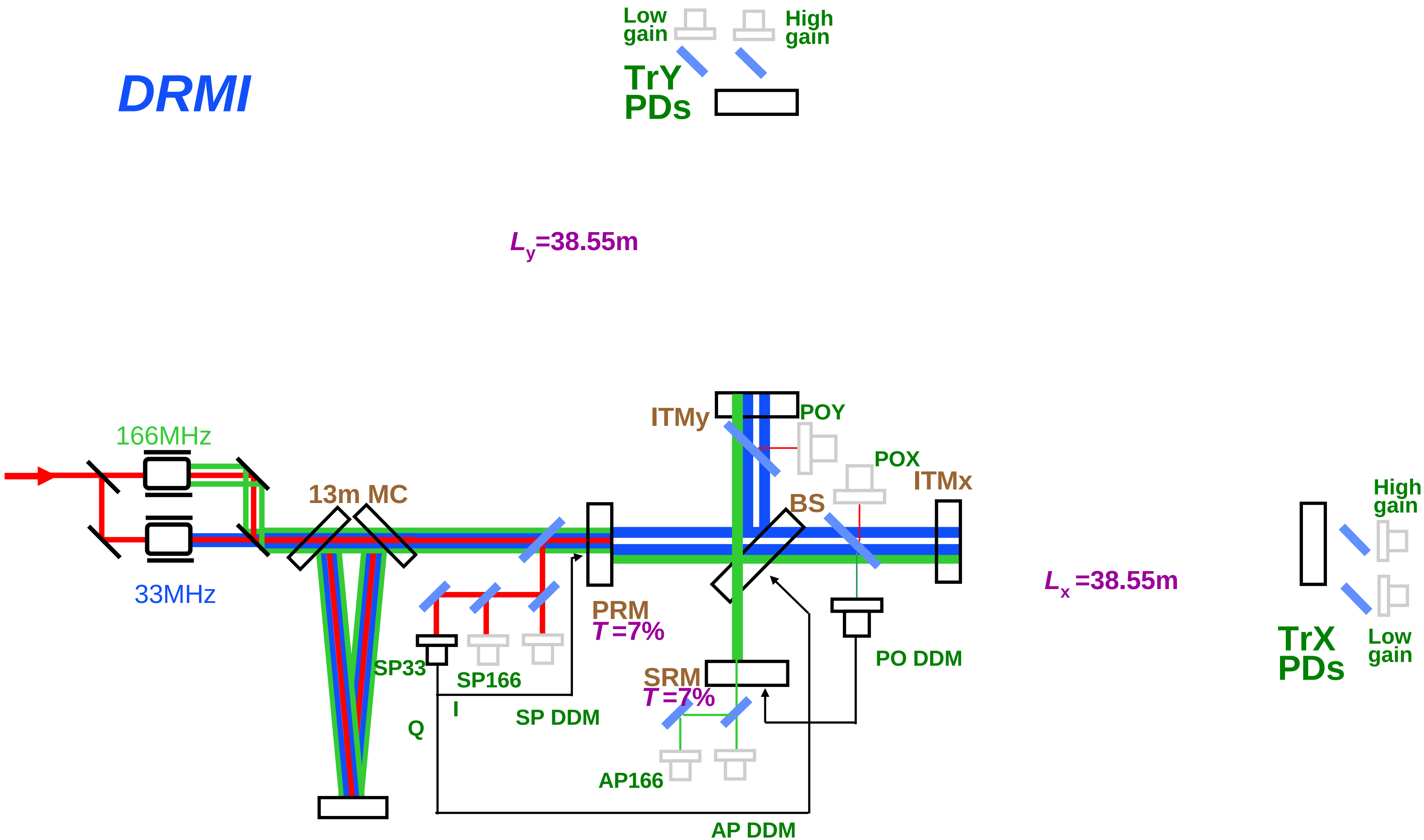
Typical lock acquisition time : ~1min

Lock acquisition procedure towards detuned RSE

Start



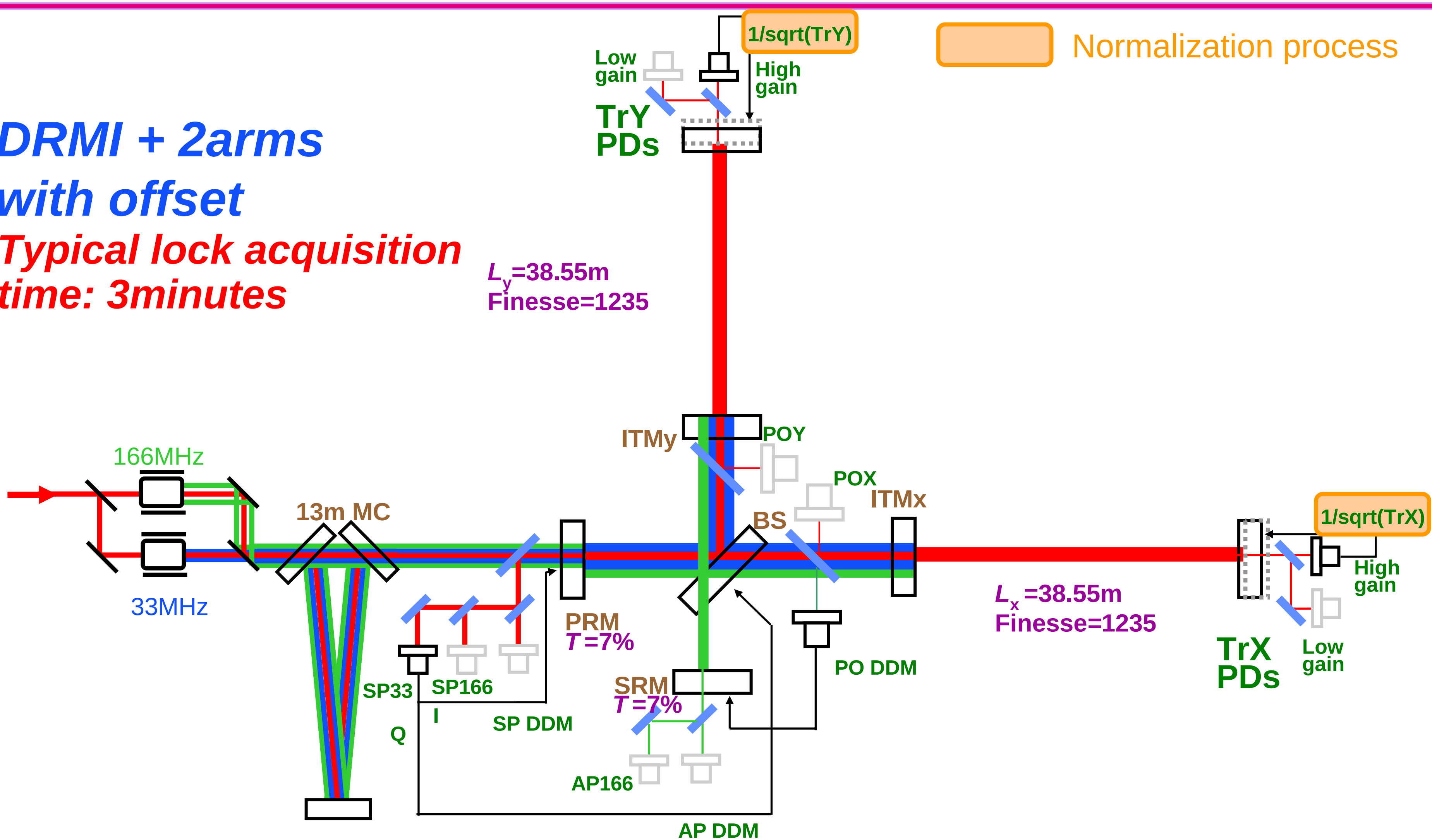
Lock acquisition procedure towards detuned RSE



Lock acquisition procedure towards detuned RSE

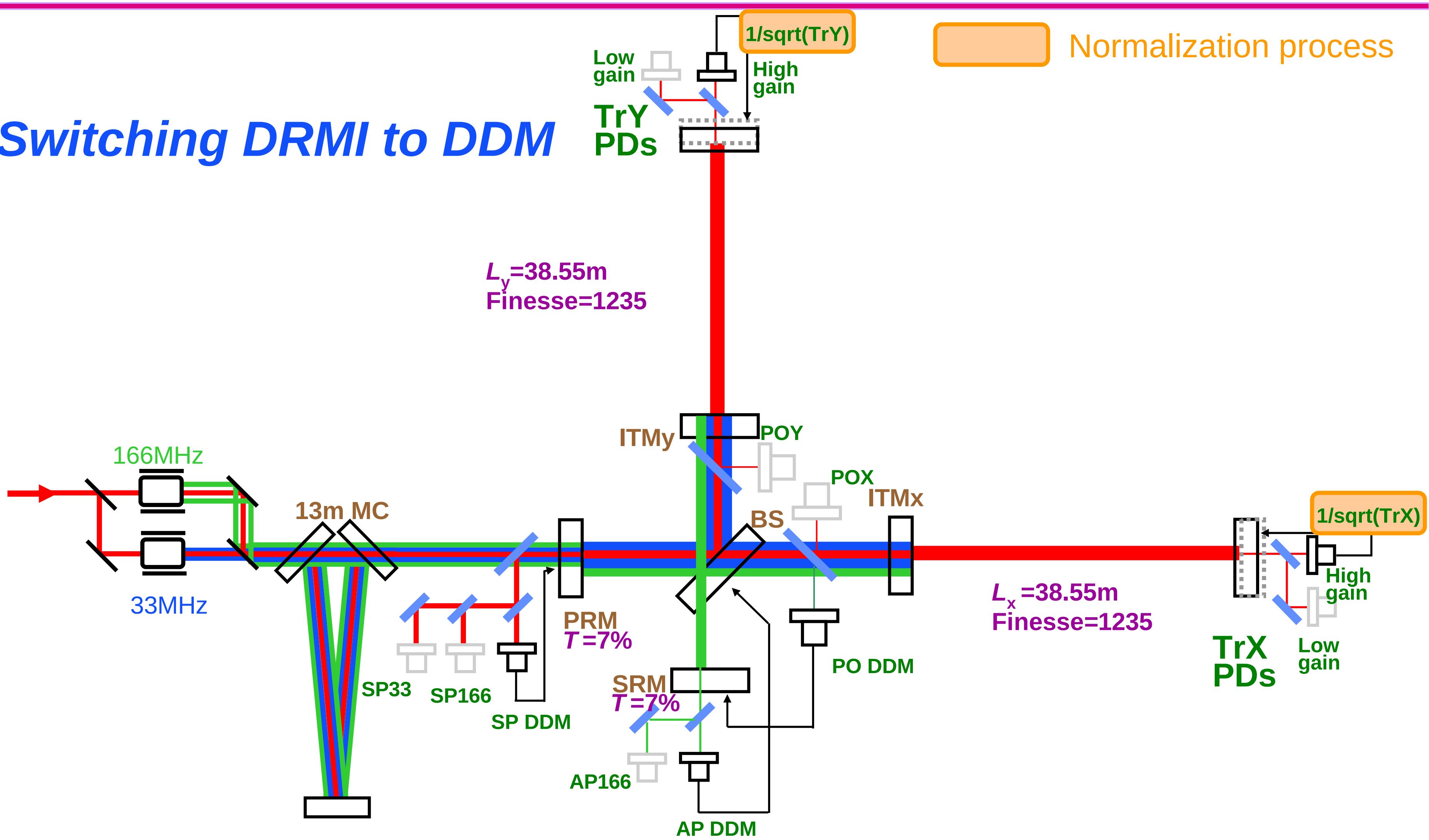
DRMI + 2arms with offset

Typical lock acquisition time: 3minutes



Lock acquisition procedure towards detuned RSE

Switching DRMI to DDM

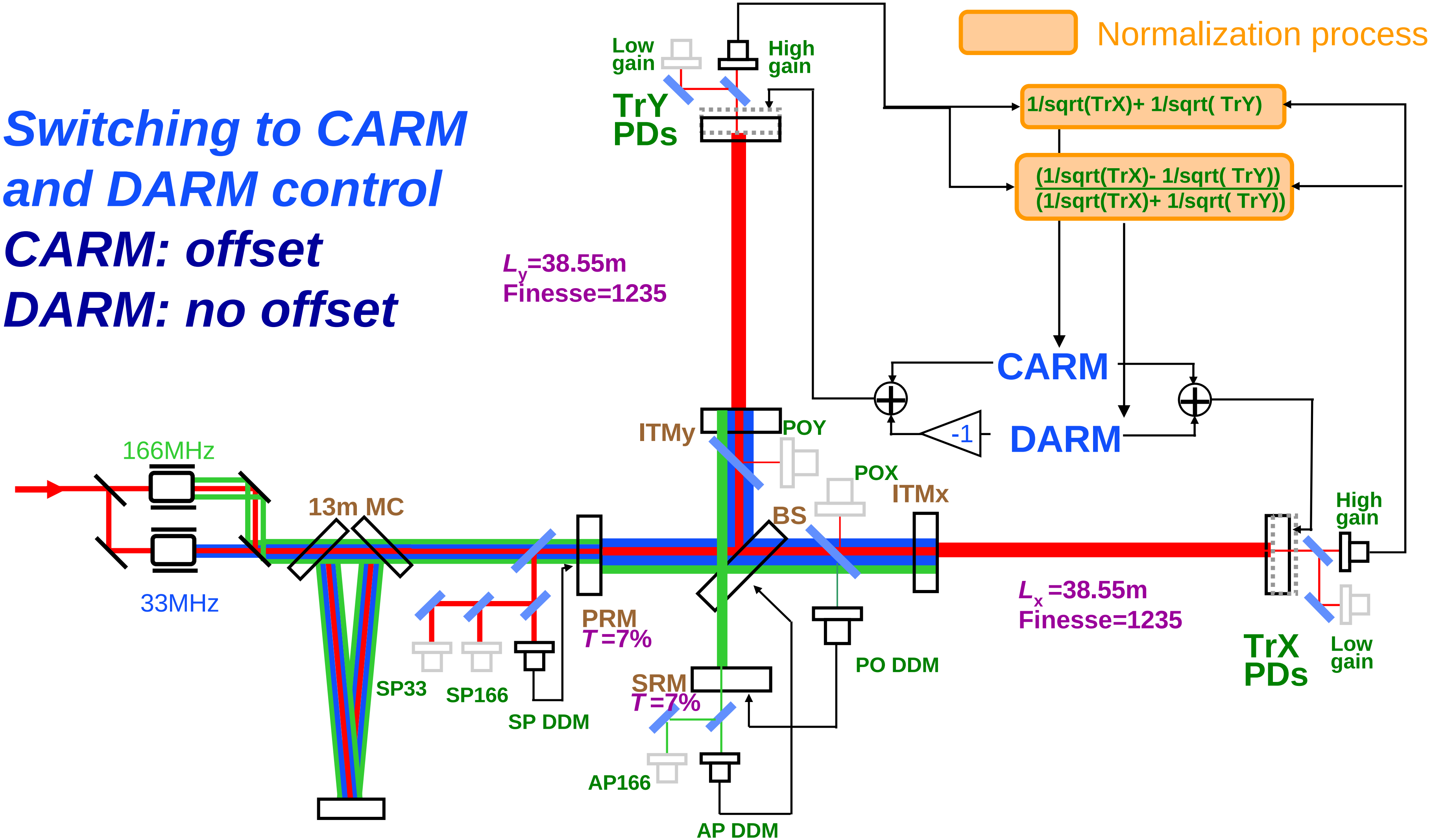


Lock acquisition procedure towards detuned RSE

Switching to CARM and DARM control

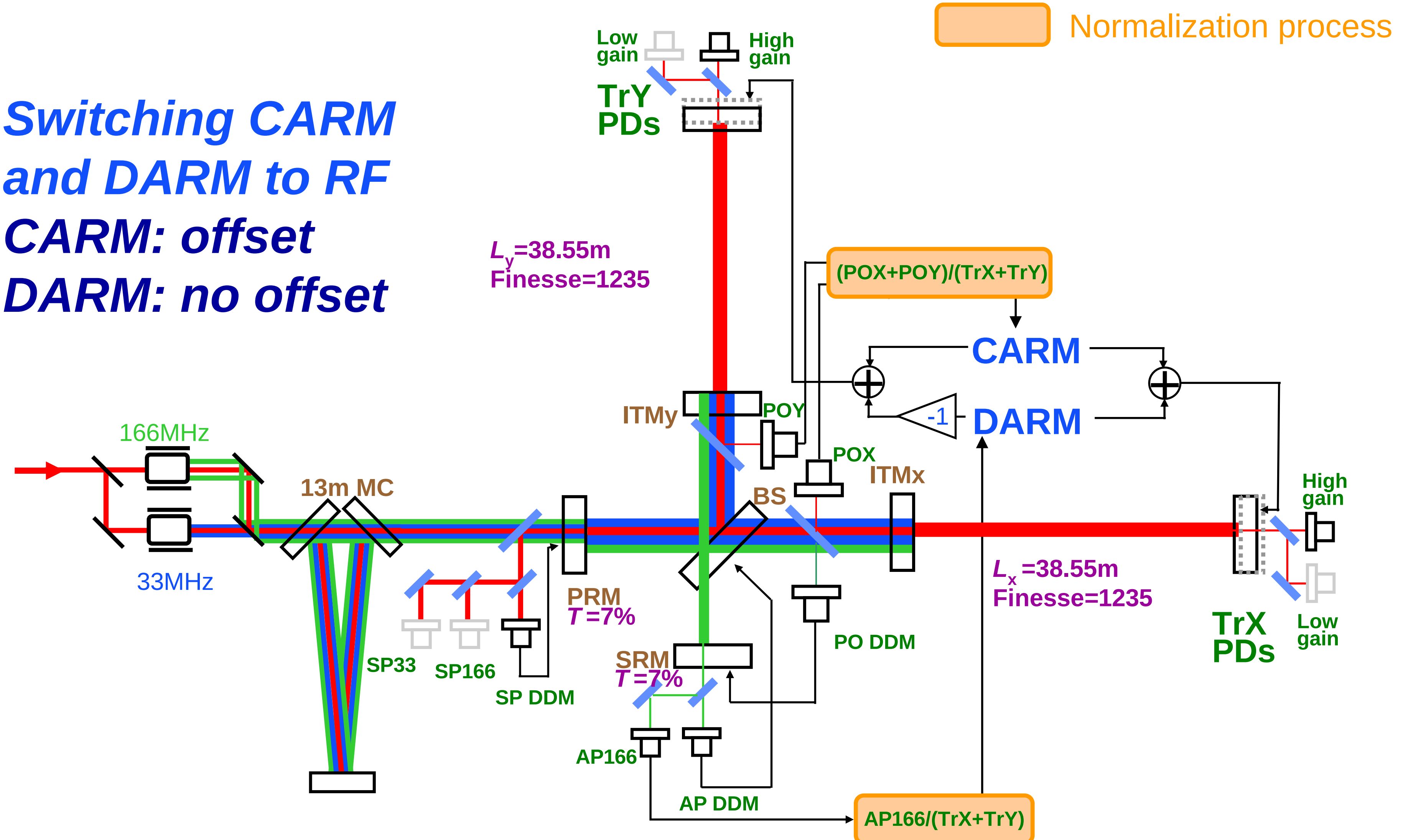
CARM: offset

DARM: no offset



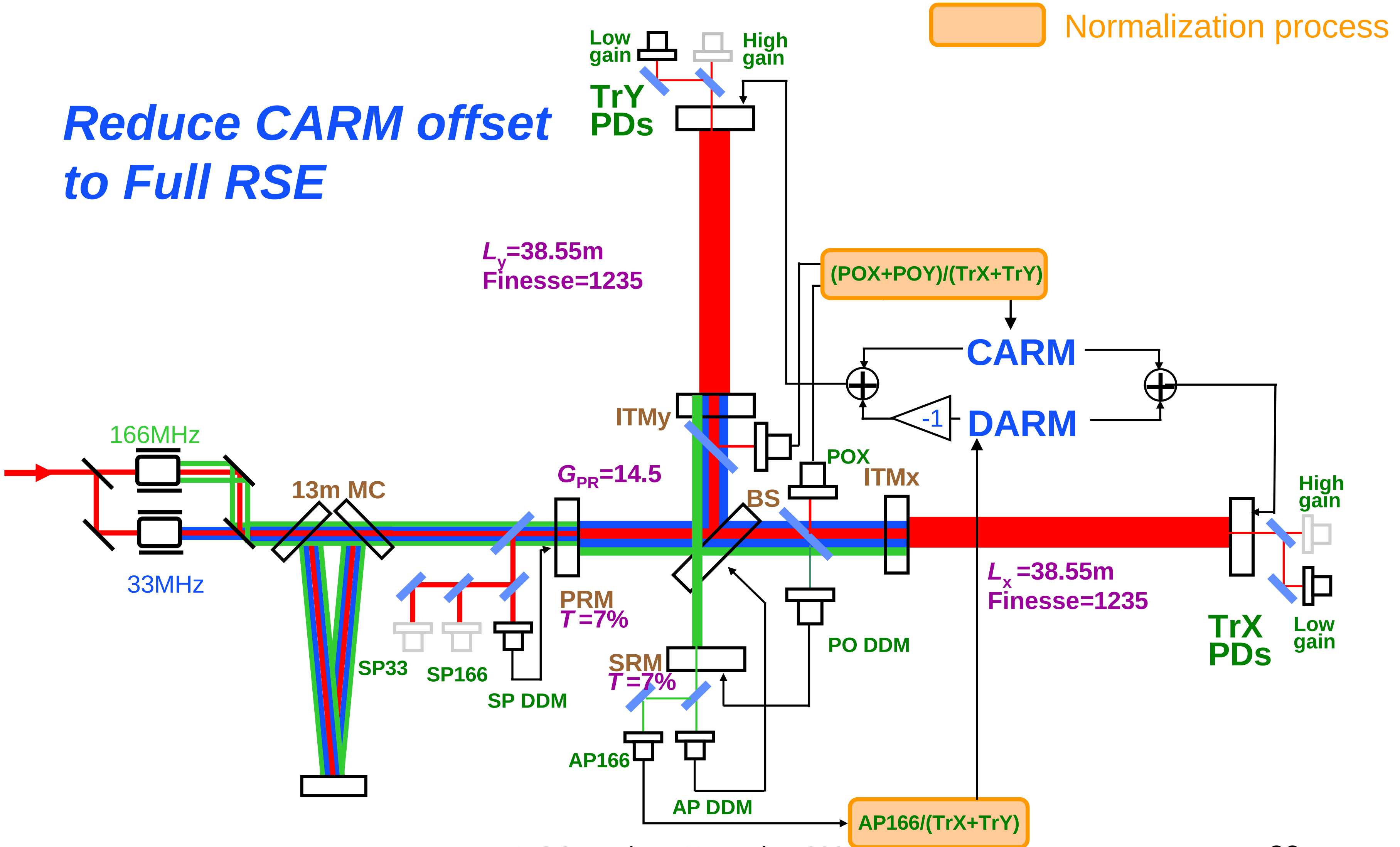
Lock acquisition procedure towards detuned RSE

Switching CARM and DARM to RF
CARM: offset
DARM: no offset



Lock acquisition procedure towards detuned RSE

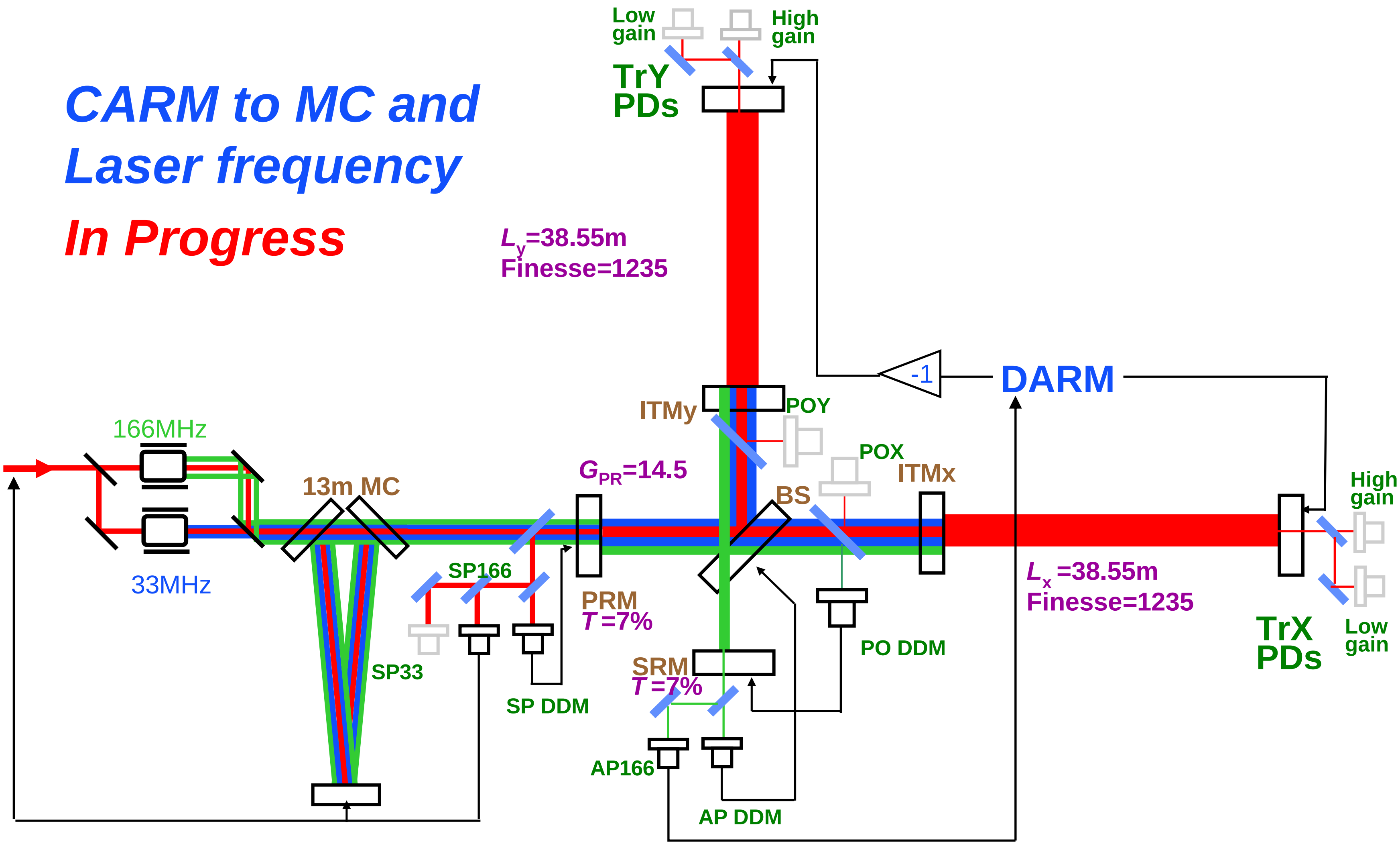
Reduce CARM offset to Full RSE



Lock acquisition procedure towards detuned RSE

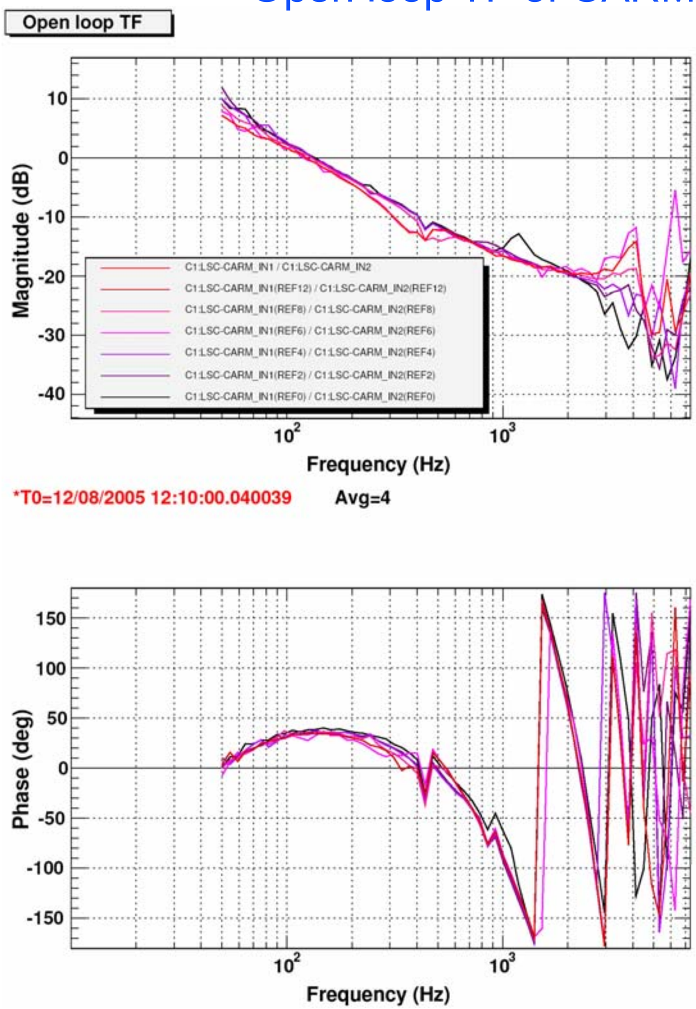
CARM to MC and Laser frequency

In Progress

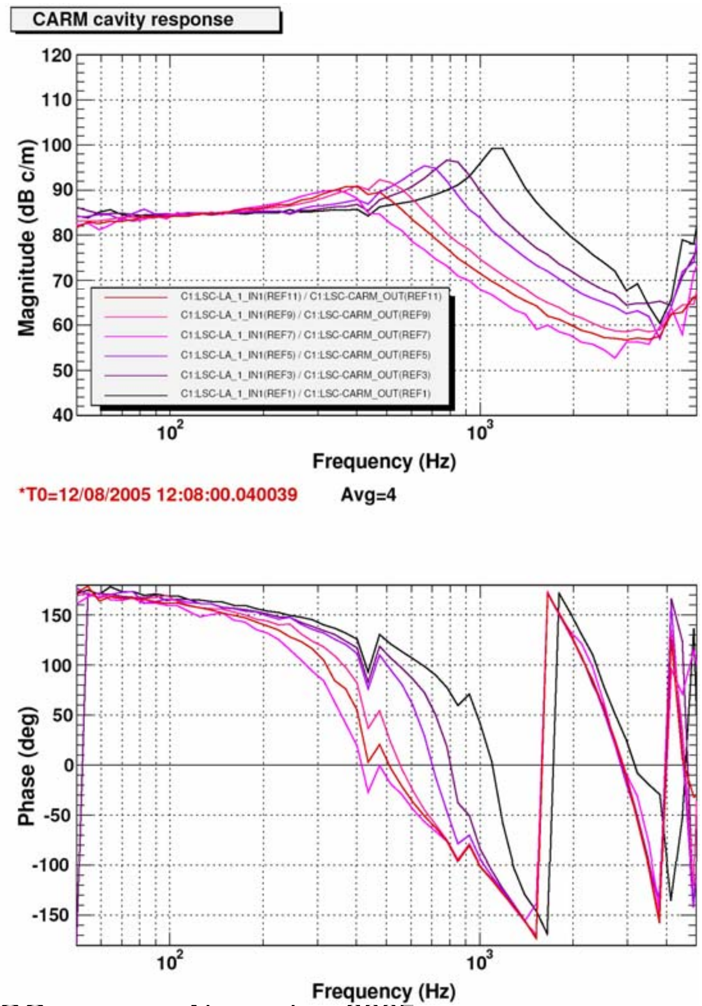


Dynamic compensative filter for CARM servo by Rob Ward

Open loop TF of CARM

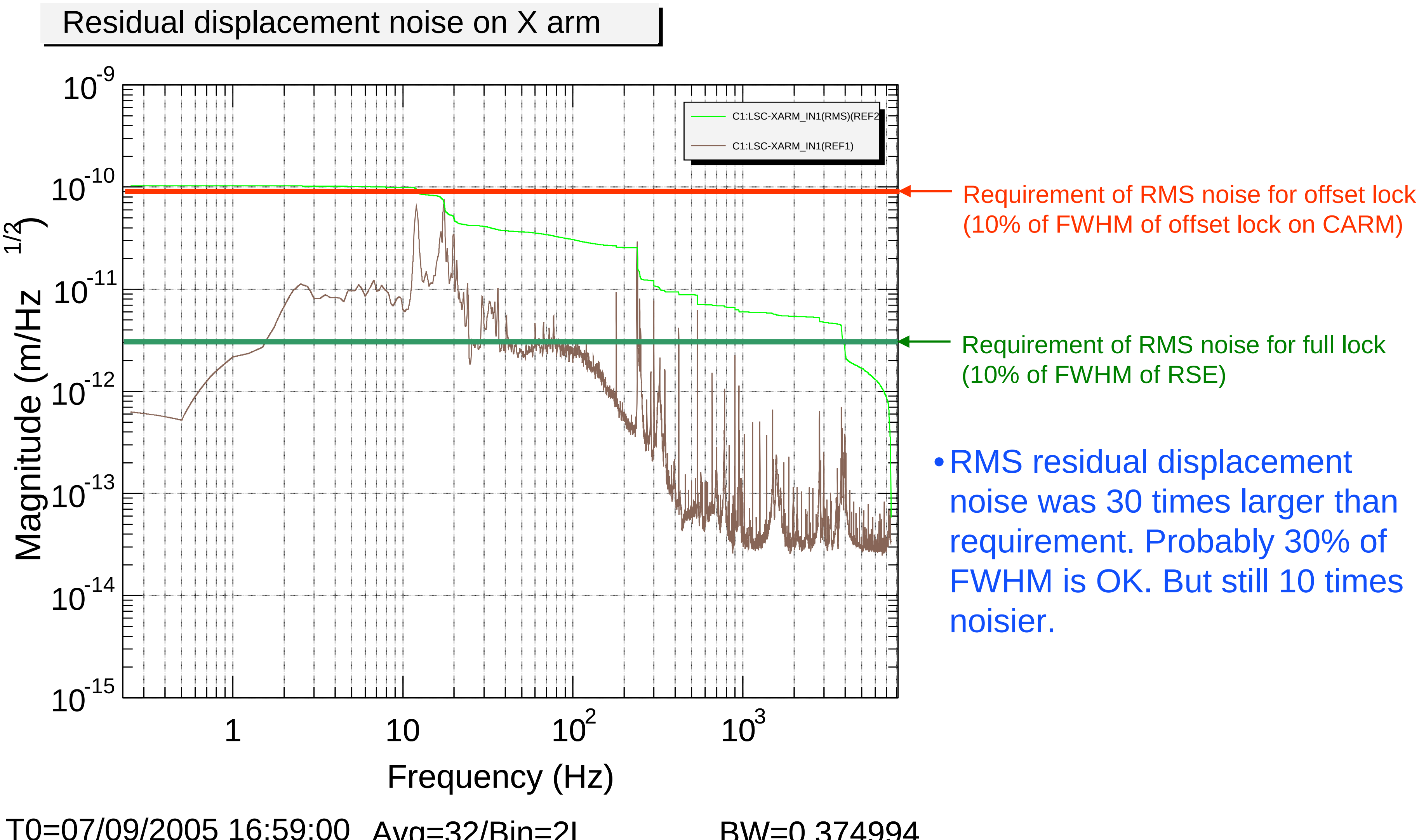


Optical gain of CARM



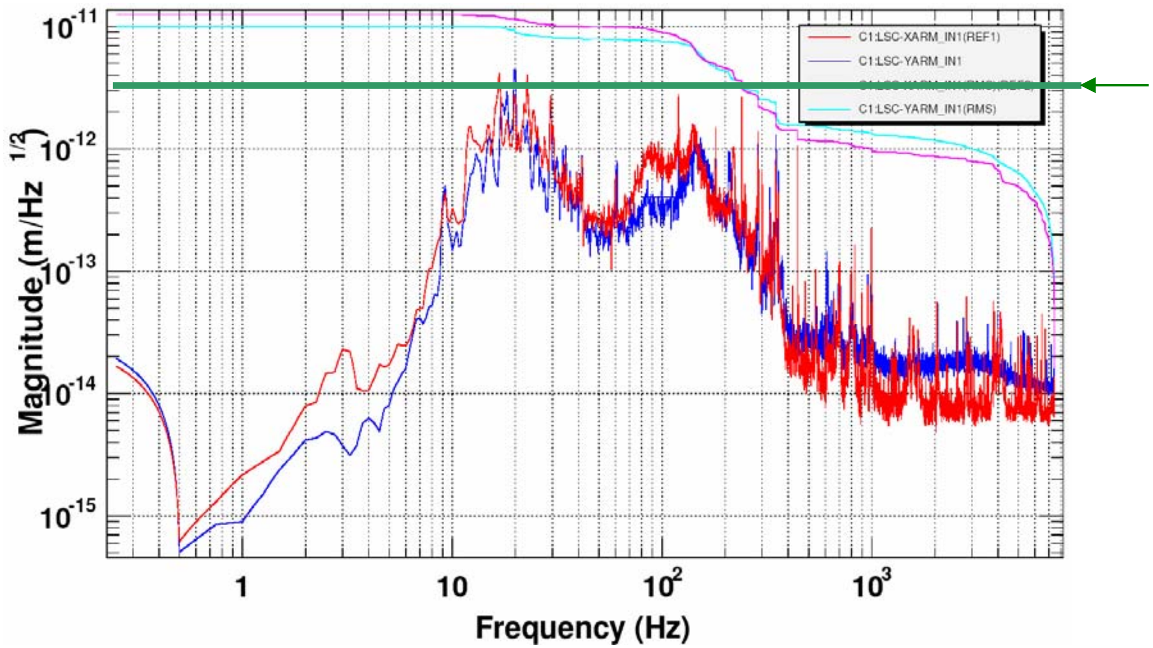
- Optical gain (normalized by transmitted power) shows moving peaks due to reducing CARM offset.
- We have a dynamic compensative filter having an exactly the same shape as optical gain except for upside down.
- Open loop transfer function has no phase delay in all CARM offset.

Residual displacement noise on arm

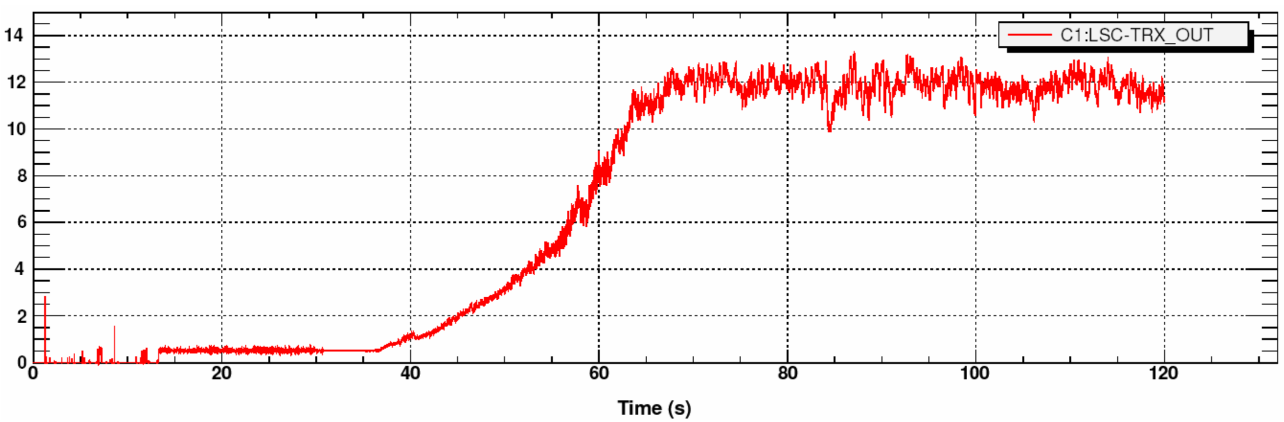


- RMS residual displacement noise was 30 times larger than requirement. Probably 30% of FWHM is OK. But still 10 times noisier.

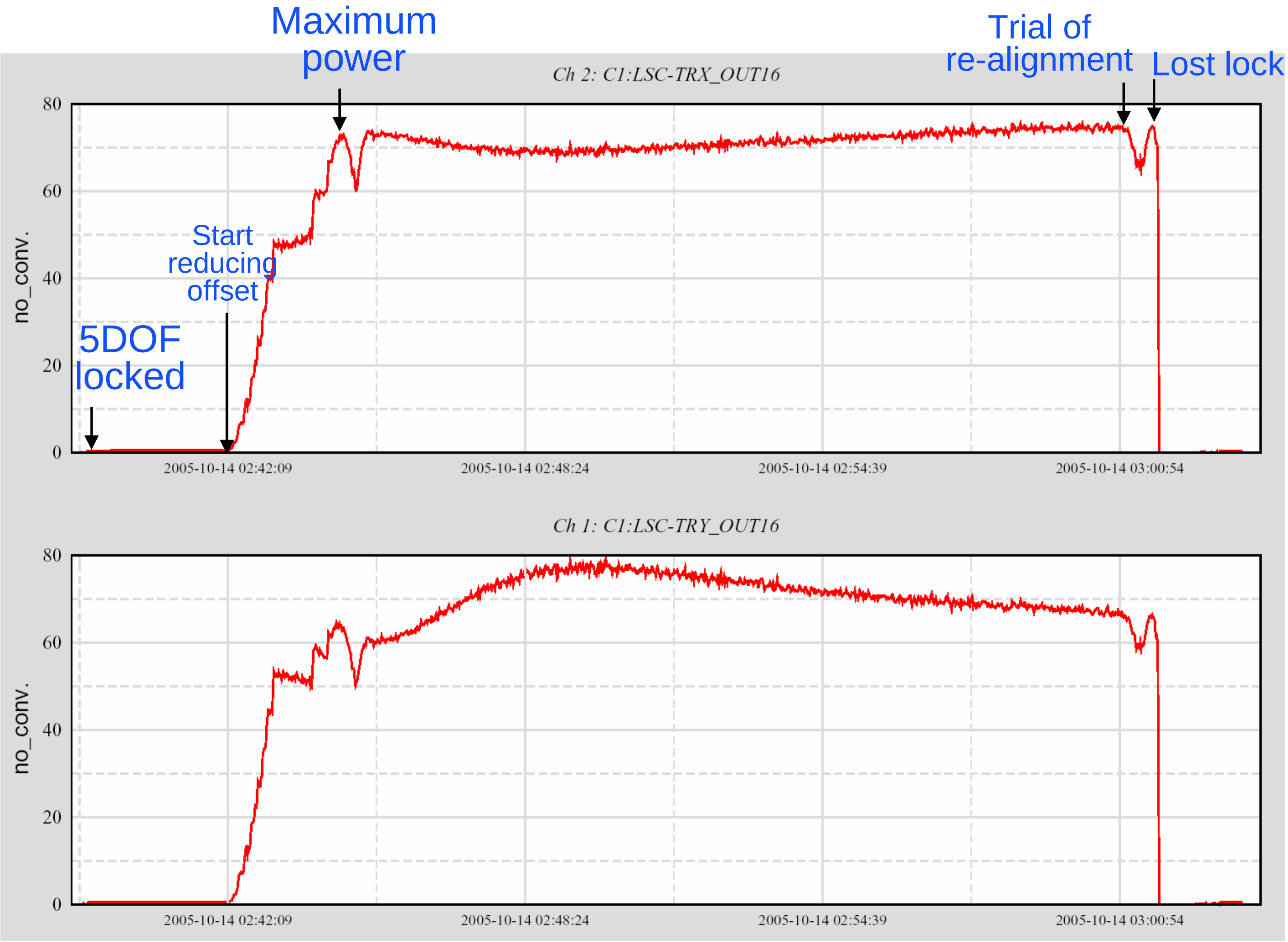
Noise investigation in DRMI+single arm



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



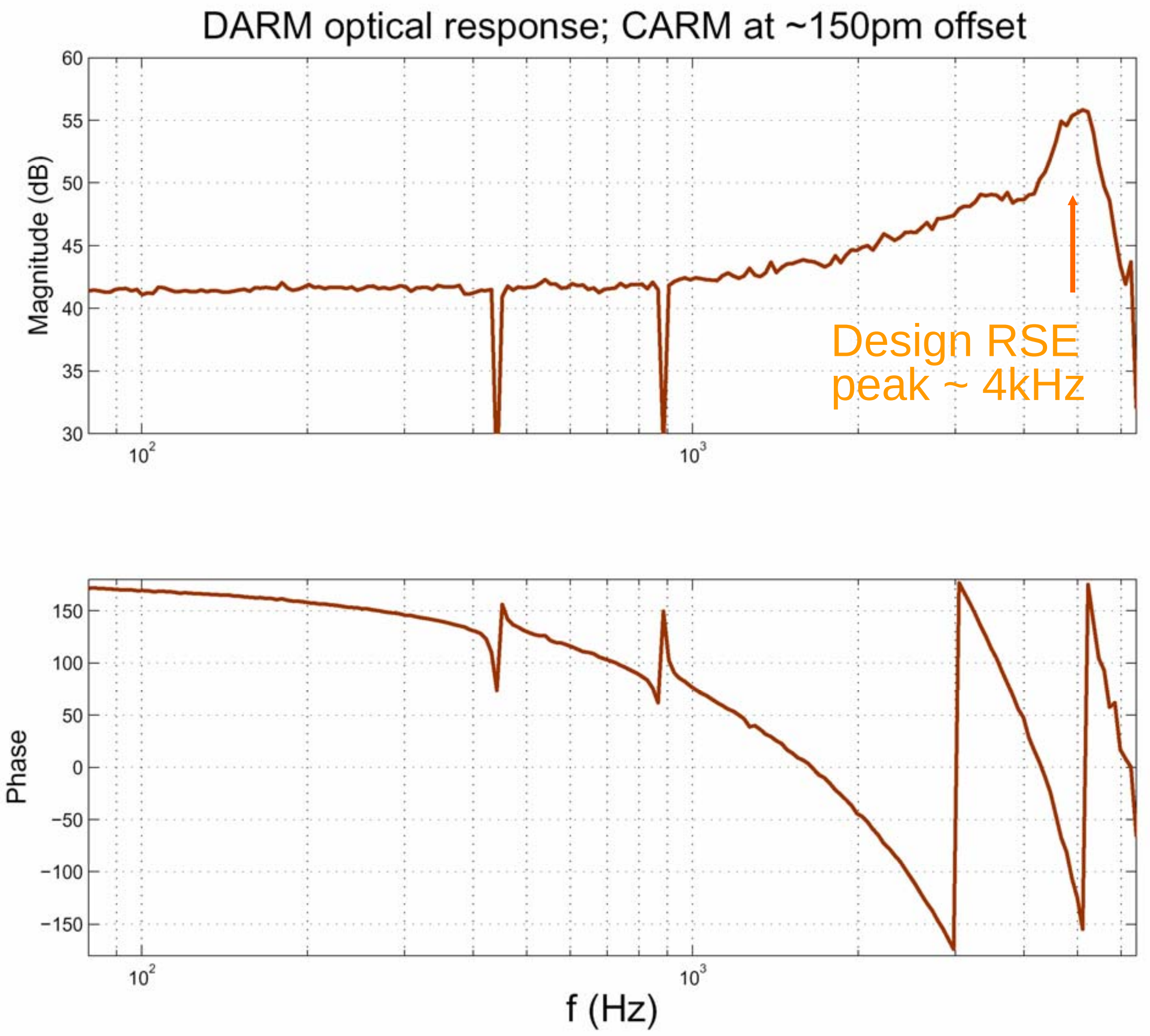
Lock acquisition for DRMI+2arms



- Lock lasts 1-2hours
- Lock acquisition time 5-10minutes
- Drift exists by alignment, offset, or thermal effect.

4. Optical spring and optical resonance

L- optical gain with RSE peak



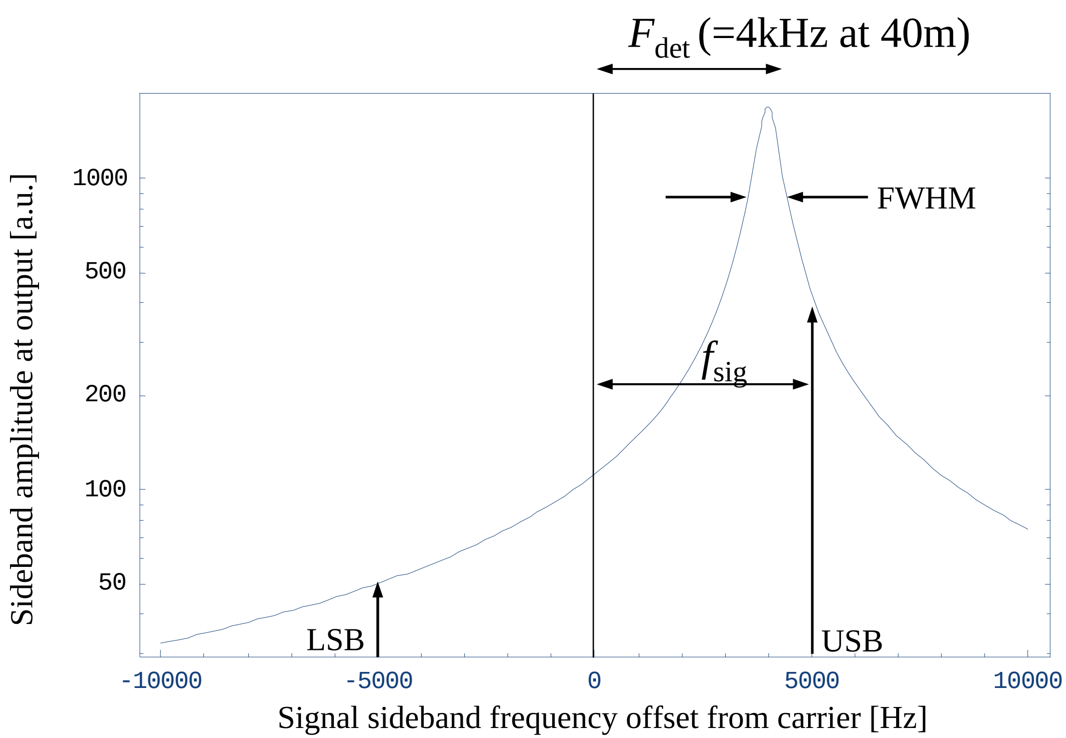
Measured in June 2005

- Optical gain of L- loop
  DARM_IN1/DARM_OUT,divided by pendulum transfer function

- No offset on *L*- loop
- 150pm offset on *L*+ loop

- Optical resonance of detuned RSE can be seen around the design RSE peak of 4kHz.
- Q of this peak is about 6.

Simple picture of optical resonance

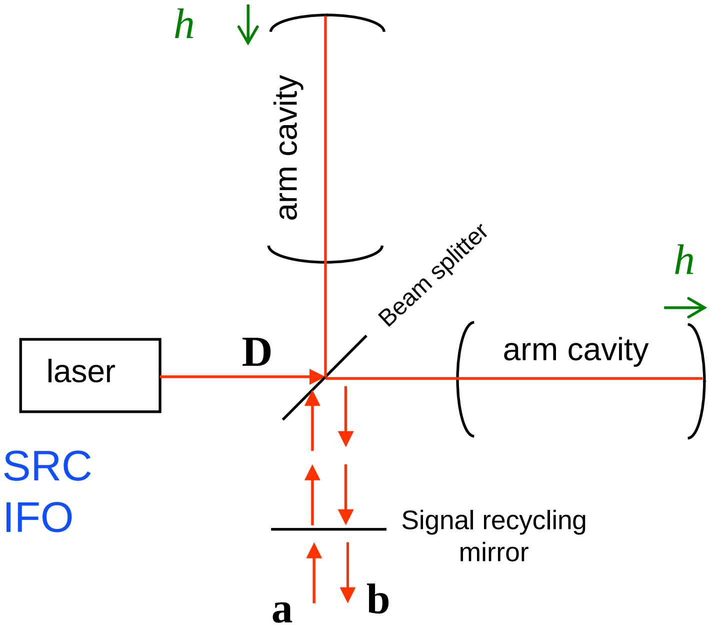


- Response between GW USB and GW LSB is different due to the detuned signal recycling cavity.
- the resonance of the SR cavity and is maximally enhanced for

$$f_{sig} = f_{det}$$

Mathematical description for optical spring in detuned RSE

$$\mathbf{b} = \frac{1}{M}\left[e^{2i(\beta+\Phi)}\mathbf{C}\,\mathbf{a} + \sqrt{2\kappa}\;\tau\; e^{i(\beta+\Phi)}\mathbf{D}\,\frac{h}{h_{\rm SQL}} \right]$$



a :input vacuum
b :output
D :input carrier
M :constant
h :gravitational wave

$h_{\rm SQL}$:standard quantum limit
♦: transmissivity of SRM
&: coupling constant
☞: GW sideband phase shift in SRC
♌: GW sideband phase shift in IFO

Measurement of optical transfer function

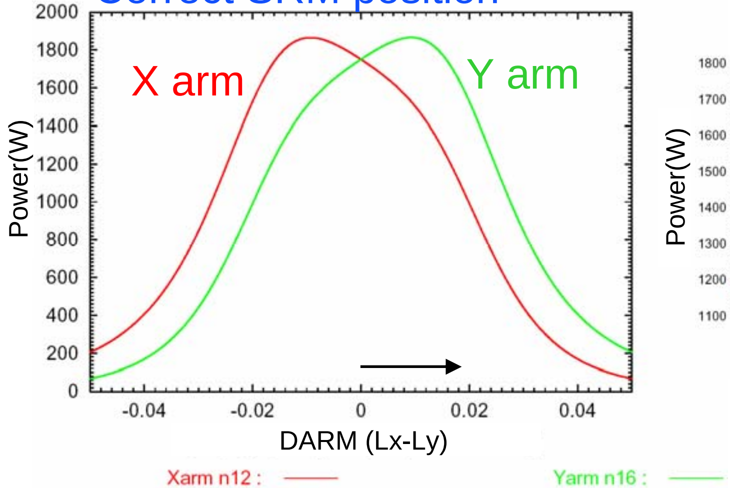
$$\frac{\mathbf{b}}{h} = \frac{1}{M}\left[\sqrt{2\kappa}\;\tau\; e^{i(\beta+\Phi)}\mathbf{D}\,\frac{1}{h_{\rm SQL}} \right]$$

a <<h; non-quantum measurement

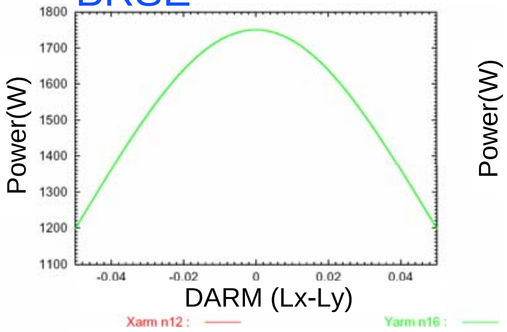
Simple picture of optical spring in detuned RSE

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

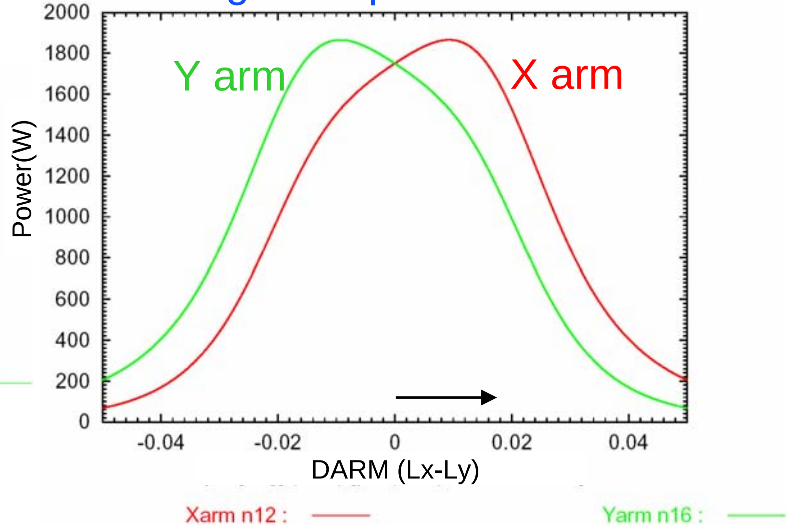
Correct SRM position



BRSE



Wrong SRM position



- Power

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

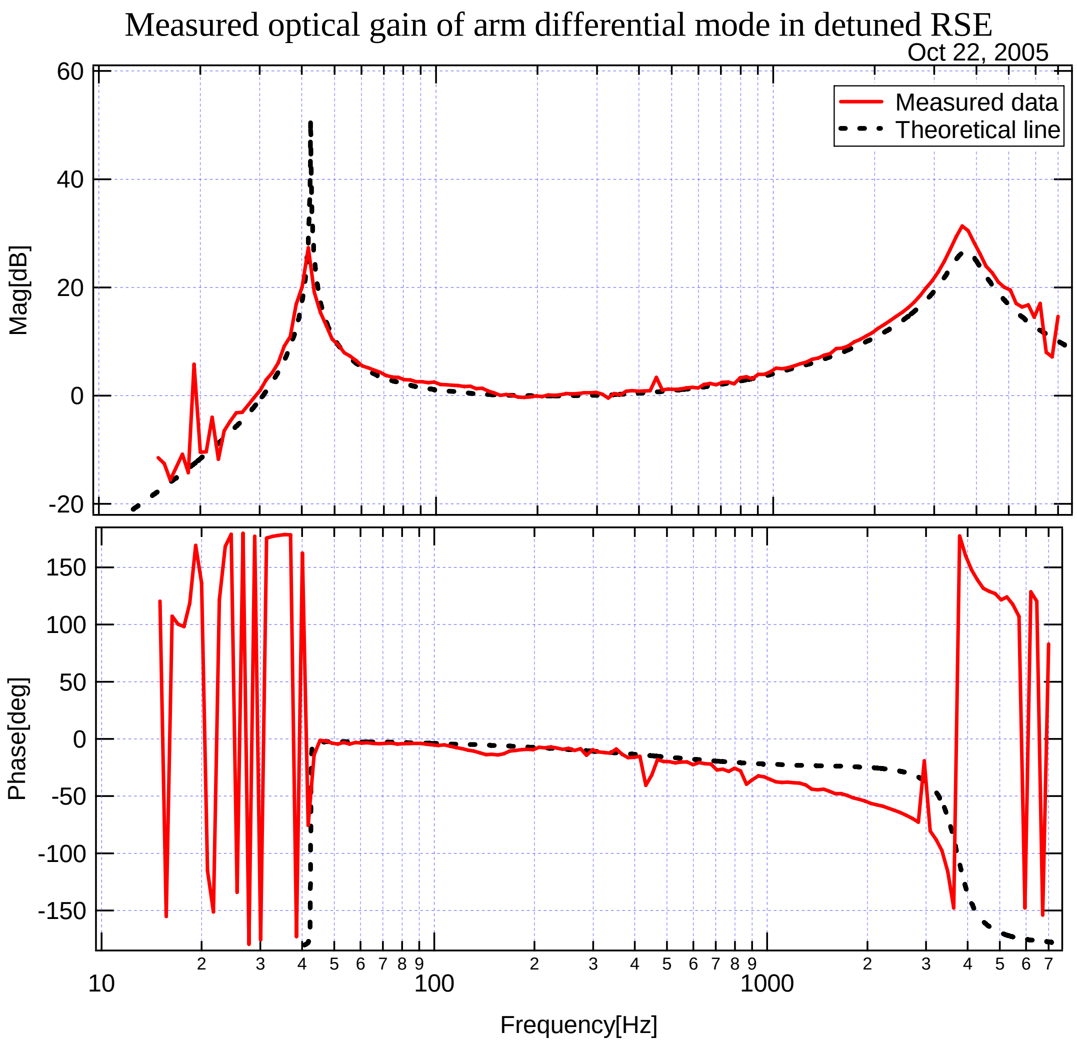
- Radiation pressure

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

- Spring constant

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

Optical spring and Optical resonance in differential arm mode of detuned RSE

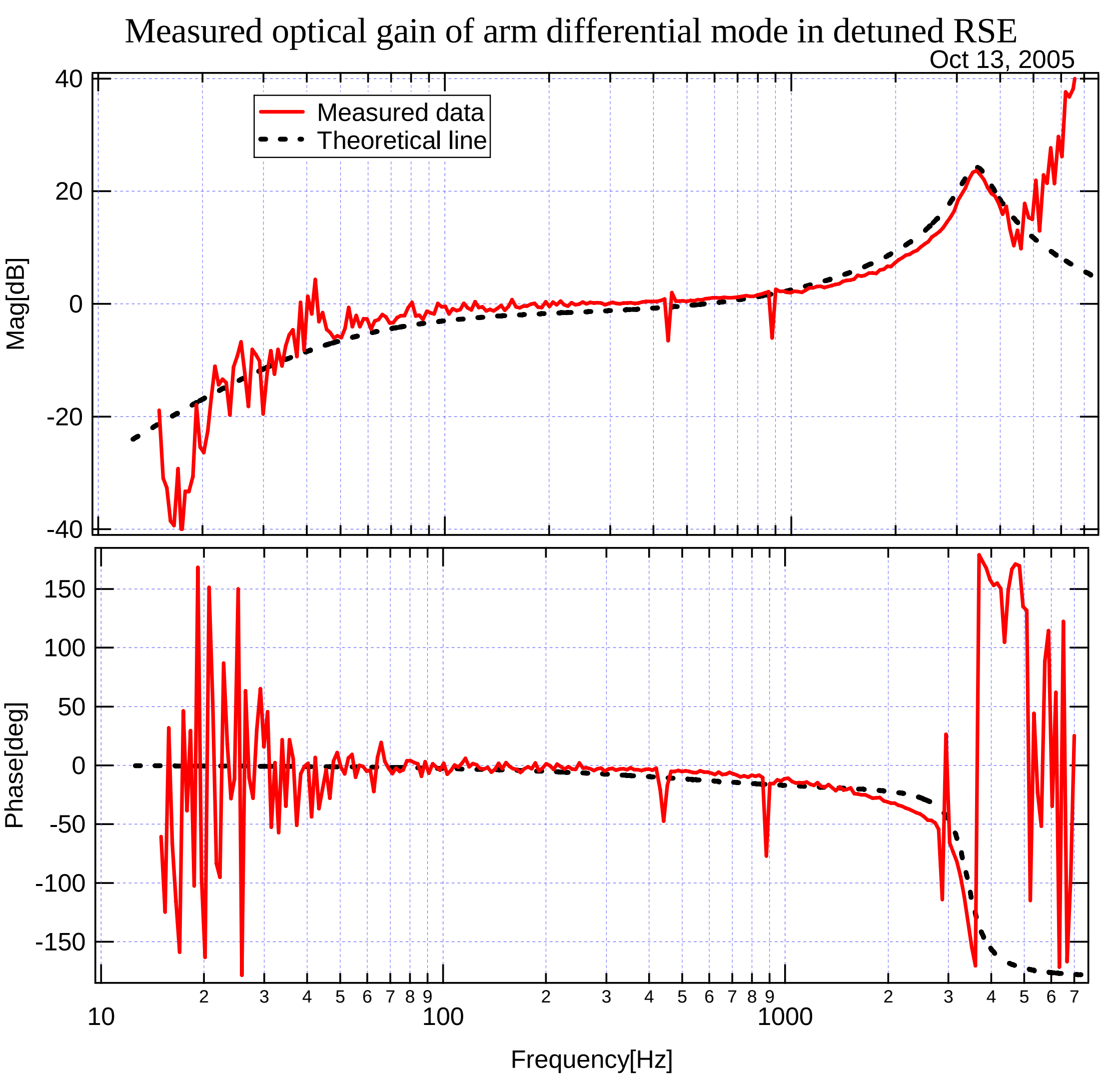


- Optical gain of *L*- loop
  DARM_IN1/DARM_OUT divided by pendulum transfer function

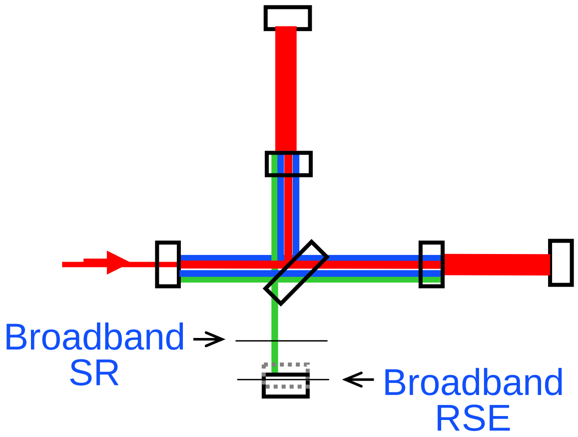
- Optical spring and optical resonance of detuned RSE were measured.
- Frequency of optical spring depends on cavity power, mass, detuning phase of SRC.
- Frequency of optical resonance depends on detuning phase of SRC.

- Theoretical line was calculated using A. Buonanno and Y.Chen's equations.

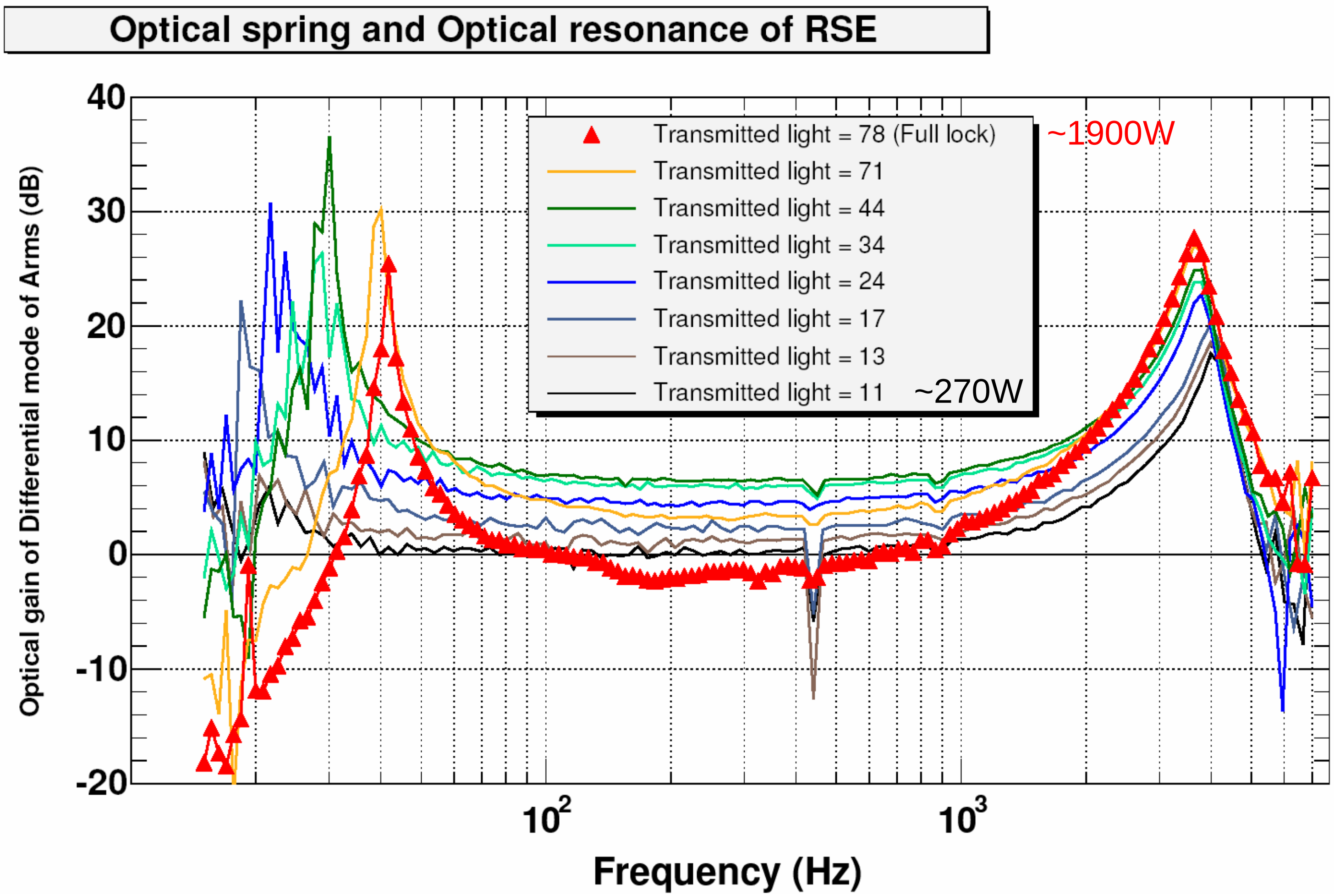
Positive spring constant



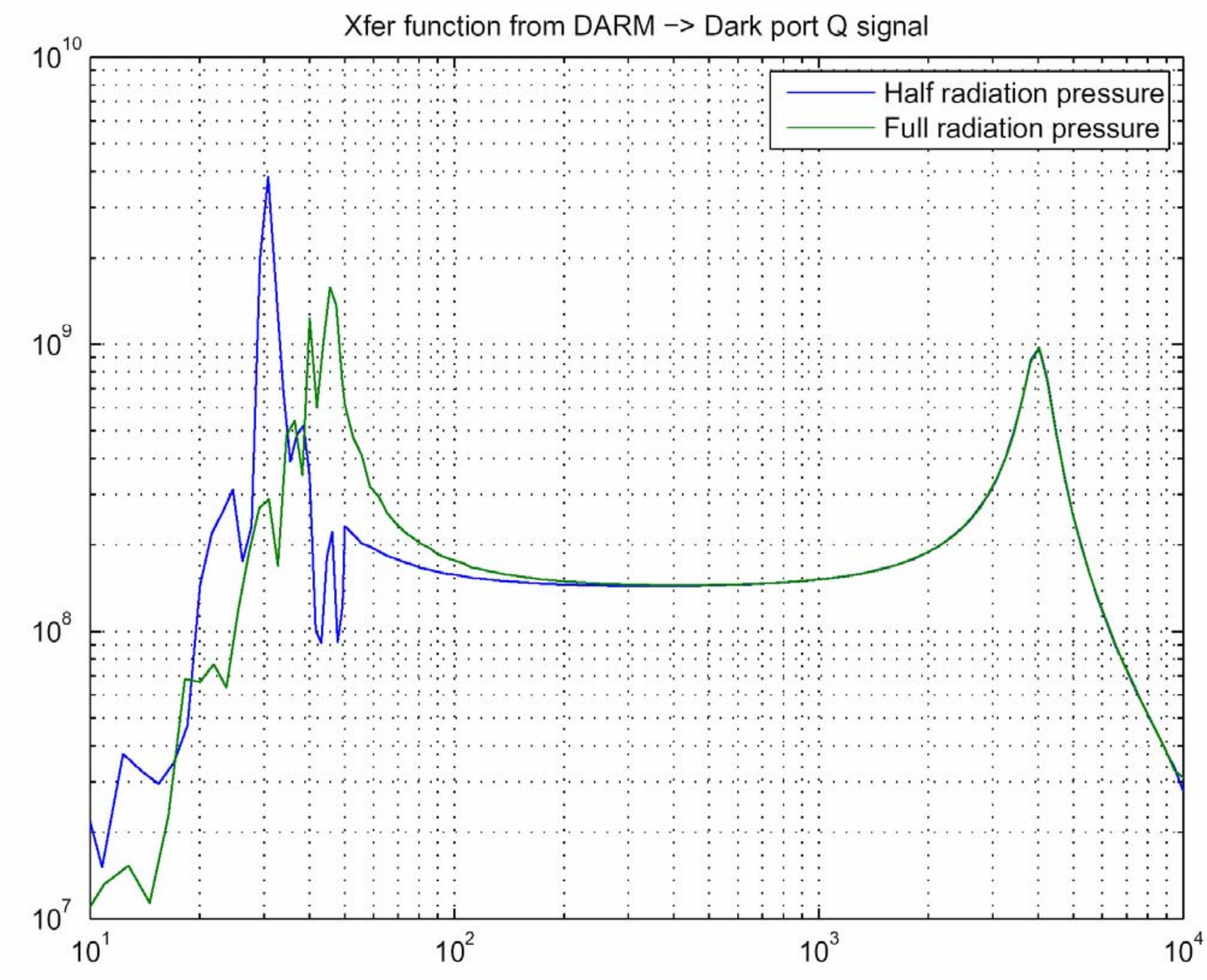
- SRM is locked at opposite position from anti-resonant carrier point(BRSE).
- Optical spring disappeared due to positive spring constant.



Frequency sweep of optical spring



Optical spring in E2E



- Calculated by time domain simulation

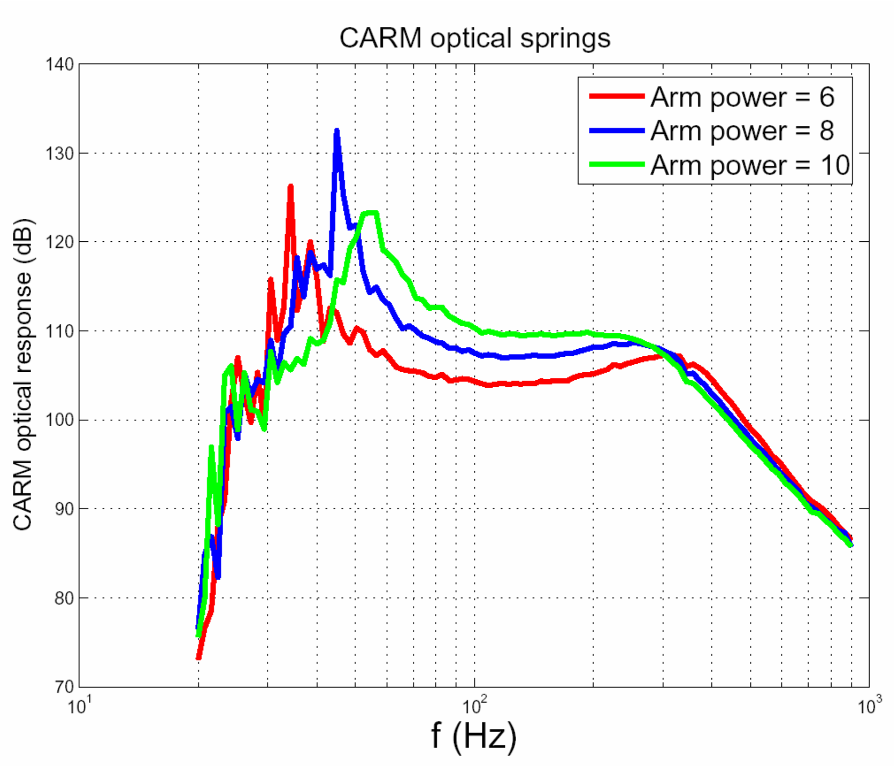
- No length control
- Lock lasts ~0.7sec, so statistics at low frequency is not good.
- Simple length control required

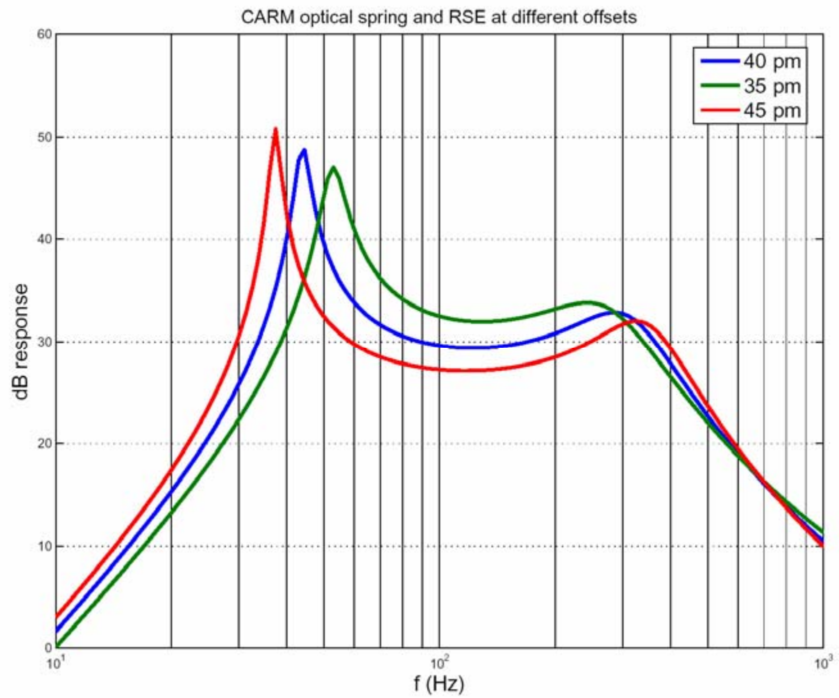
- Calculation time ~5min using DRMI summation cavity

How much power inside arm?

	Design	Measured(estimated)
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	Over coupled	Under coupled
Input power	0.1W	1W
Power in one arm	560W	1900W
Optical spring	23Hz	41Hz

CARM optical spring





Mode healing at Dark Port?

Negative spring constant with optical spring

Positive spring constant with no optical spring

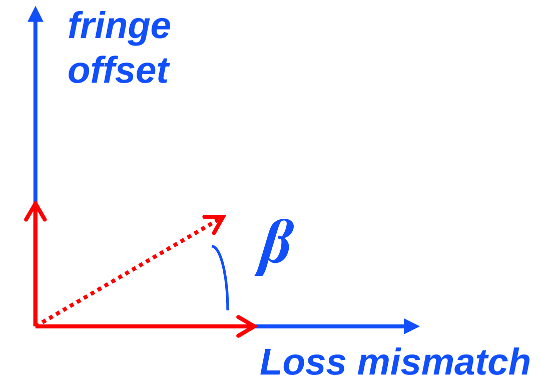
- Repeatable
- The same alignment quality
- Under investigation.

Next step

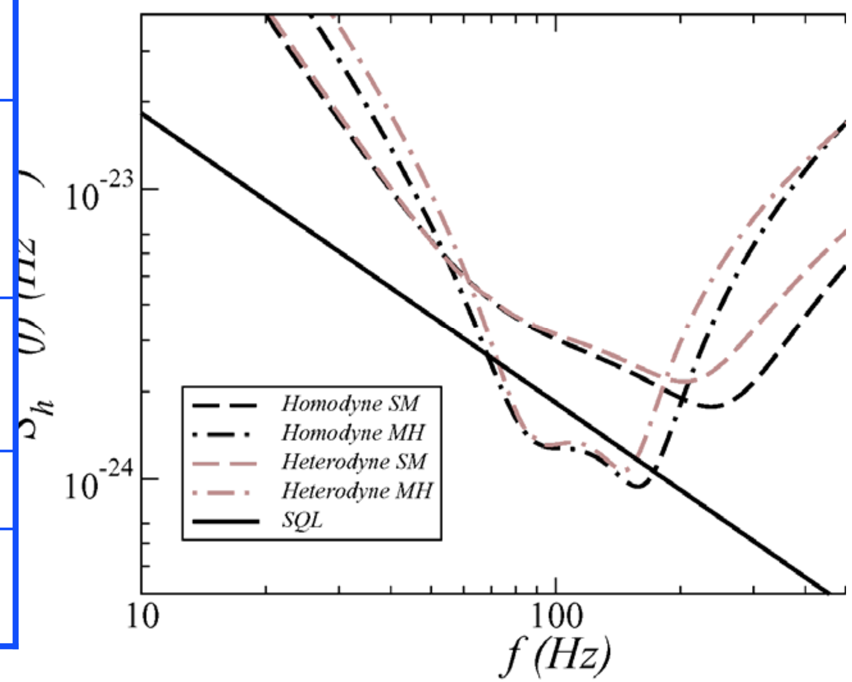
- Stable operation and noise hunting
- E2E simulation for AdLIGO
- DC readout
- Squeezer
- Alignment control with wave front sensors
- Cleaning arms
- Narrow-band operation
- LF RF modulation scheme
- Etc.

GW readout, Systems

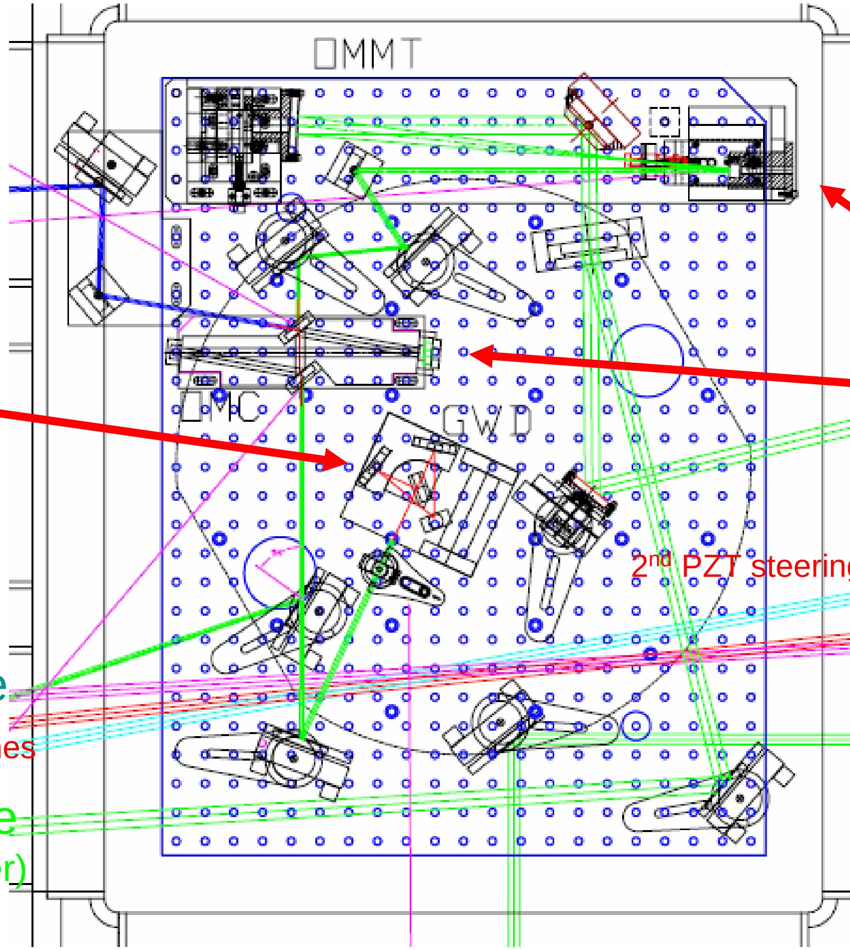
- DC rather than RF for GW sensing
  - » Requires Output Mode-Cleaner to reject RF
  - » Offset ~ 1 picometer from dark fringe can tune from 0 to 80 deg with 0-100 mW of fringe offset power



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



Output Optic Chamber



Existing in-vac seismically isolated optical table (OOC)

to OMCR beamline

Mike Smith has designed a compact, monolithic MMT, similar to our input MMT, using spherical mirrors.

Pair of DC PDs with in-vac electronics on monolithic base.

4-mirror monolithic OMC.

from SRM

2nd PZT steering mirror

PZT steering mirrors and their controls are duplicates of a pair that we have already installed and commissioned for steering from IMC to main IFO (in-vac); controls are fully implemented in the ASC system (by Rolf). Similar systems can be used for “LIGO I.V”.

to OMCT beamline

IMCR, IMCT, and SP beamlines

to AS RF beamline
(roughly 1/3 of AS power)

also a convenient path for autocollimator beam, for initial alignment in air

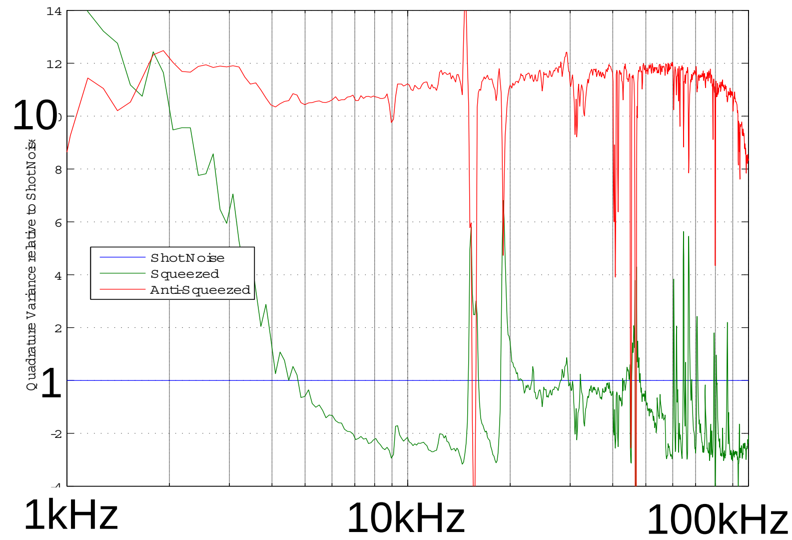
from PSL to IMC

Piezosystem Jena PSH 5/2 SG-V, PZT tilting mirror mount with strain gauge, and associated drivers and power supplies

Mike Smith

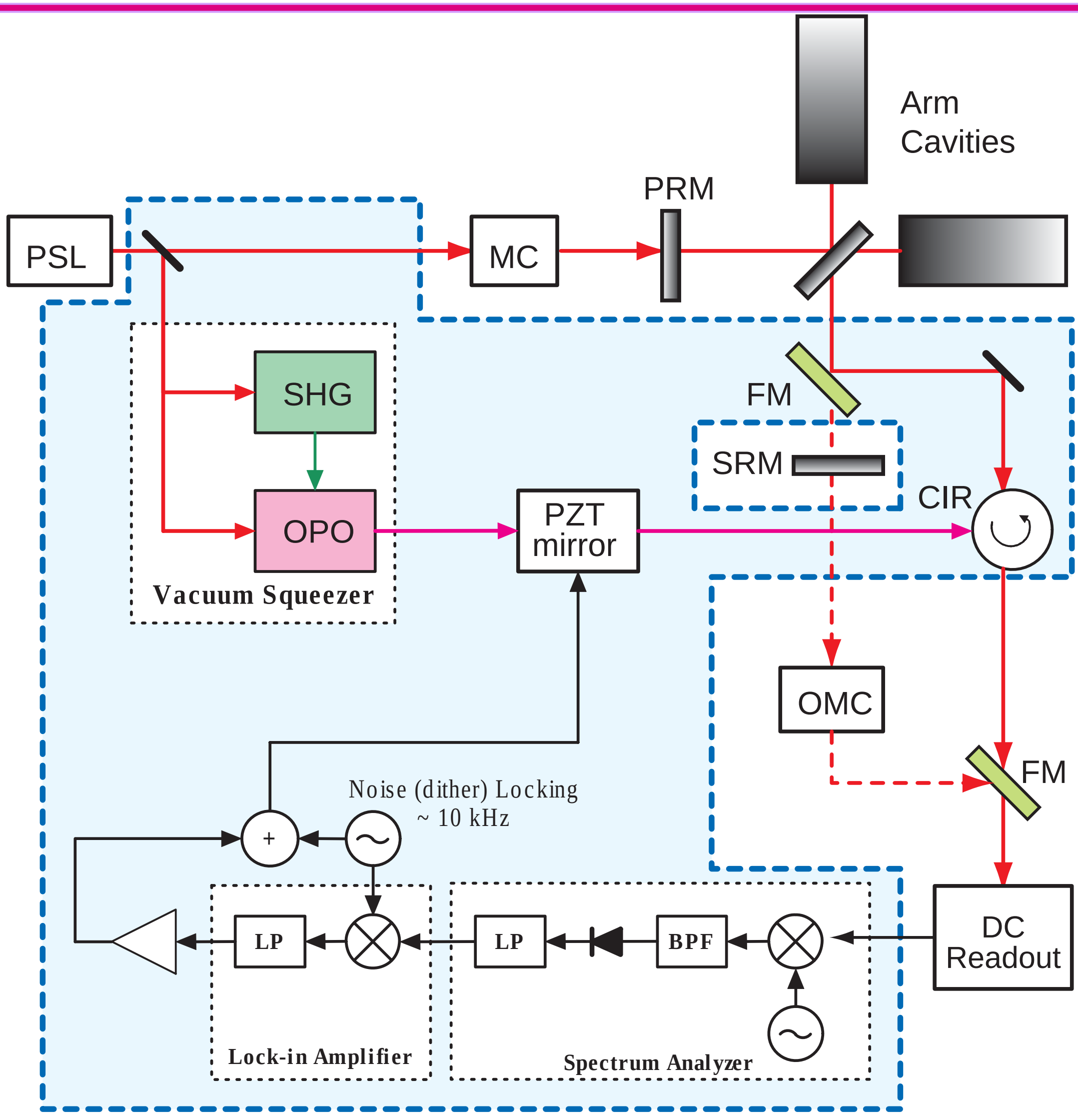
Squeezing Tests at the 40m

- 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

Interface to ongoing 40m experiments



Initial and Advanced LIGO

- Factor 10 better amplitude sensitivity
  - » (Reach)^3 = rate
- Factor 4 lower frequency bound
- NS Binaries: for three interferometers,
  - » Initial LIGO: ~20 Mpc
  - » Adv LIGO: ~300 Mpc
- BH Binaries:
  - » Initial LIGO: 10 M_o, 100 Mpc
  - » Adv LIGO : 50 M_o, z=2
- Stochastic background:
  - » Initial LIGO: ~3e-6
  - » Adv LIGO ~3e-9