Toward the Advanced LIGO optical configuration investigated in 40meter prototype

Aspen winter conference

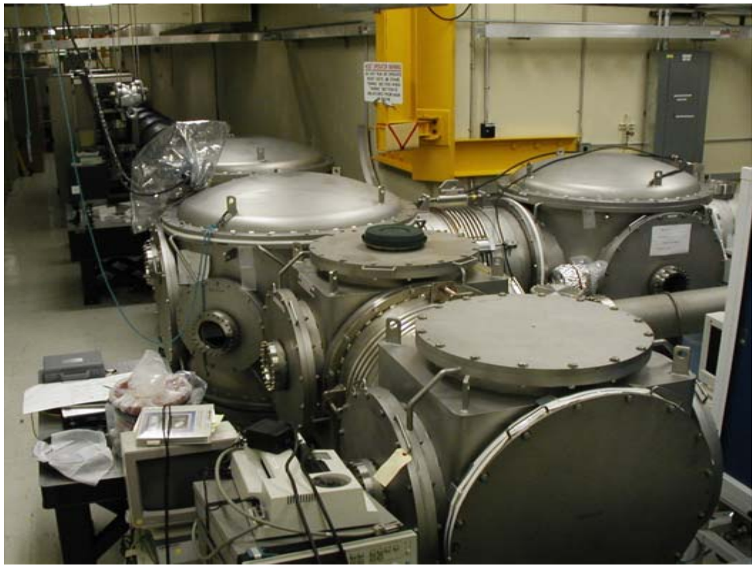
Jan. 19, 2005

O. Miyakawa, Caltech
and the 40m collaboration

Caltech 40 meter prototype interferometer

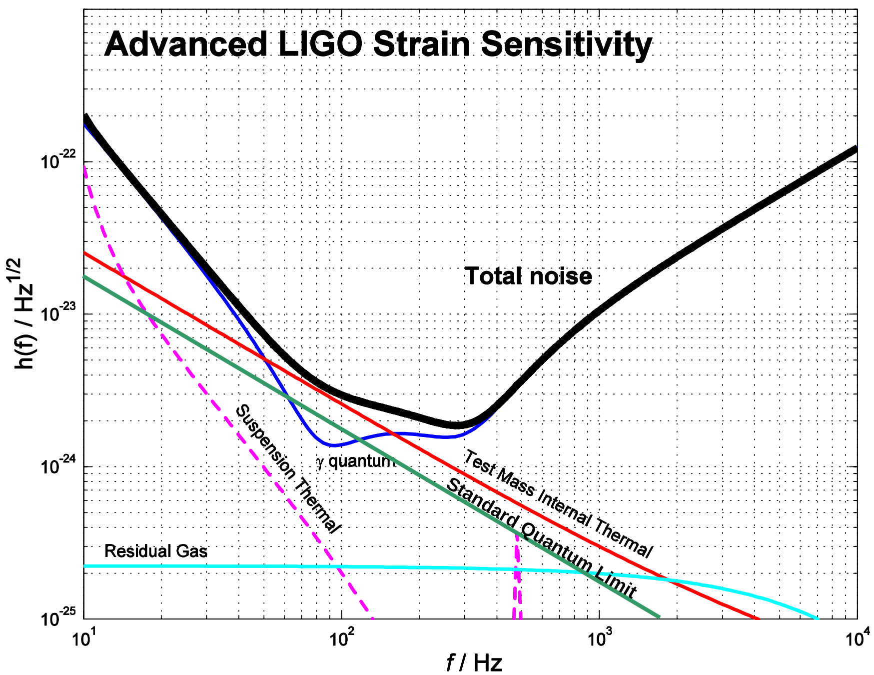
Objectives

- Develop **lock acquisition procedure** of detuned Resonant Sideband Extraction (RSE) interferometer, as close as possible to Advanced LIGO optical design
- Characterize noise mechanisms
- Verify optical spring and optical resonance effects
- Develop DC readout scheme
- Extrapolate to AdLIGO via simulation
- etc.

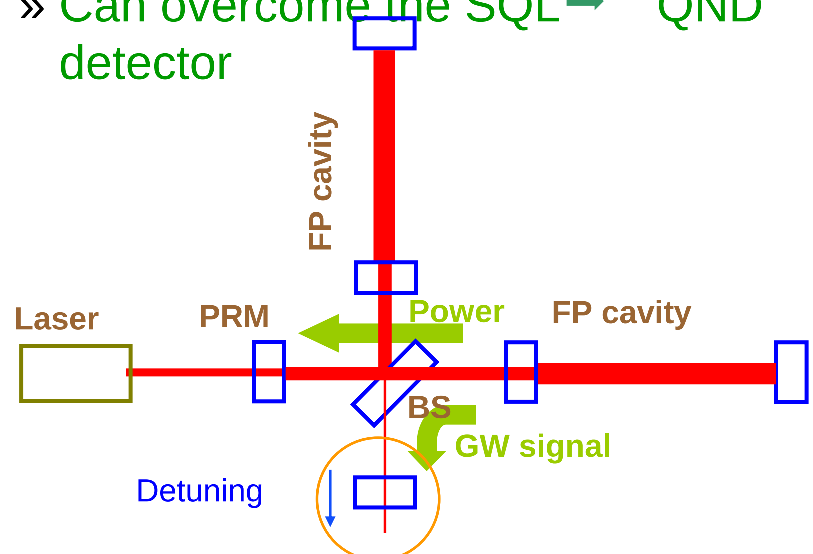


Advanced LIGO optical configuration

- LIGO:Power recycled FPMI
  - » Optical noise is limited by Standard Quantum Limit (SQL)



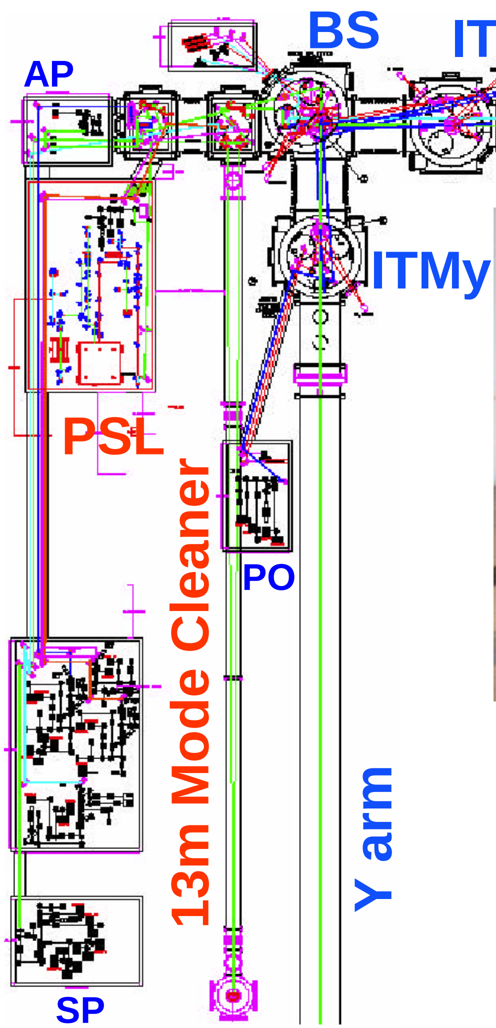
- AdvLIGO:GW signal enhancement using Detuned RSE
  - » Two dips by optical spring, optical resonance
  - » Can overcome the SQL ➡ QND detector

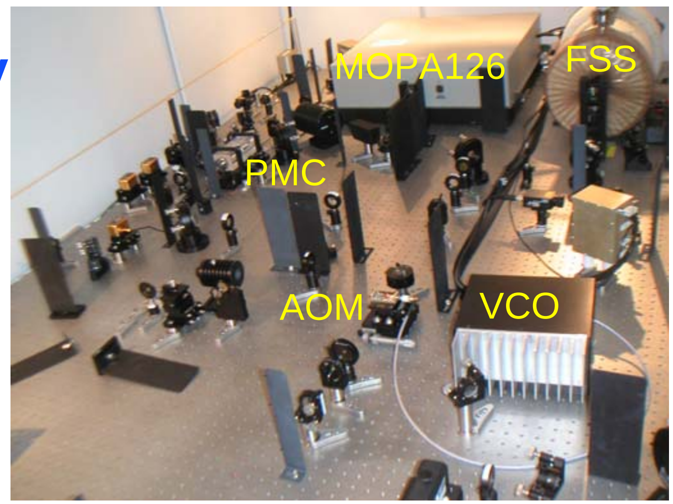


Differences between AdvLIGO and 40m prototype

- **100 times shorter cavity length**
- **Arm cavity finesse at 40m chosen to be = to AdvLIGO**
  - » **Storage time is x100 shorter.**
- **Control RF sidebands are 33/166 MHz instead of 9/180 MHz**
  - » **Due to shorter PRC length.**
- **LIGO-I 10-watt laser, negligible thermal effects**
  - » **180W laser will be used in AdvLIGO.**
- **Noisier seismic environment in town**
  - » **>$1x10^{-6}$m at 1Hz**
- **Smaller stack, commercial active seismic isolation**
  - » **STACIS isolators in use on all test chambers, providing ~30 dB of isolation from 1-100 Hz.**
- **LIGO-I single pendulum suspensions are used**
  - » **AdvLIGO will use triple (MC, BS, PRM, SRM) and quad (ITMs, ETMs) suspensions.**

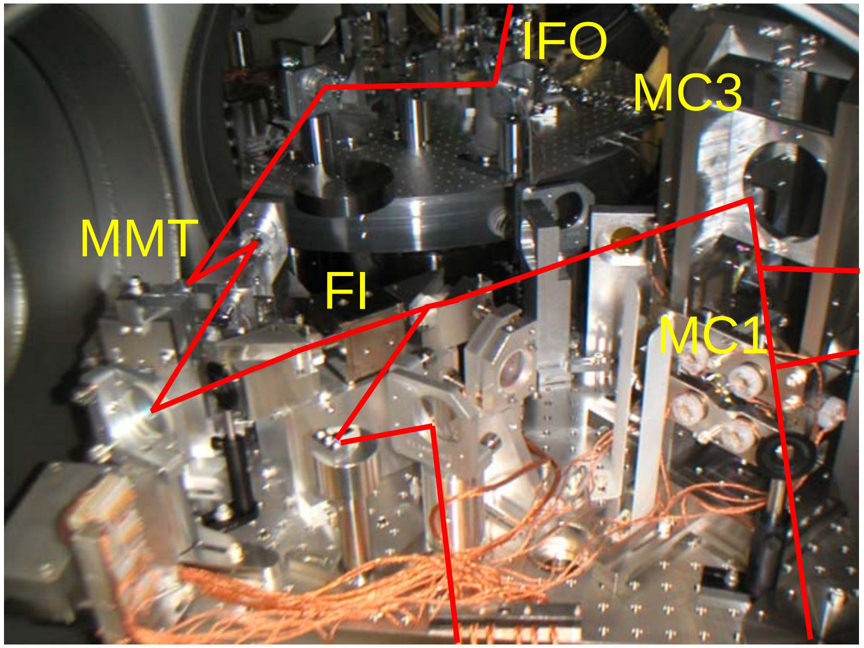
Pre-Stabilized Laser(PSL) and 13m Mode Cleaner(MC)

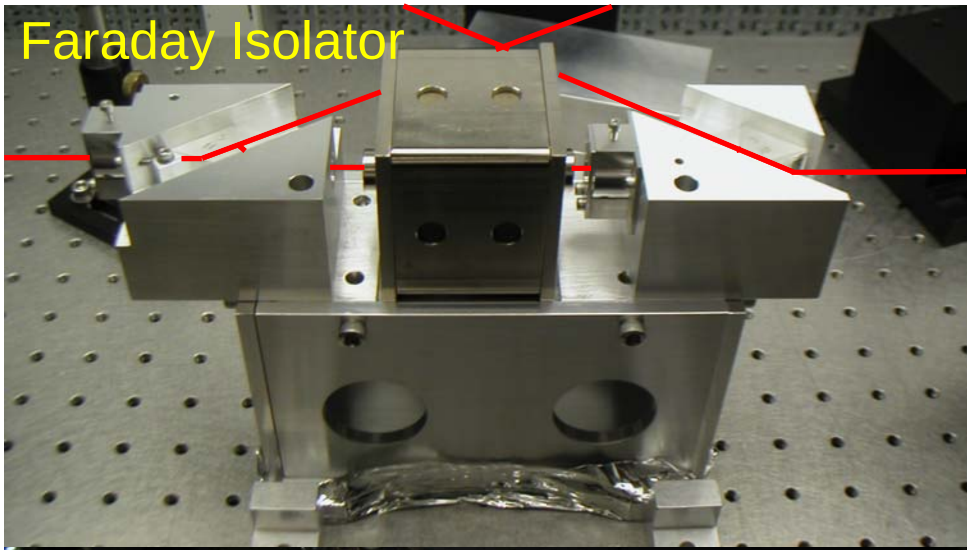


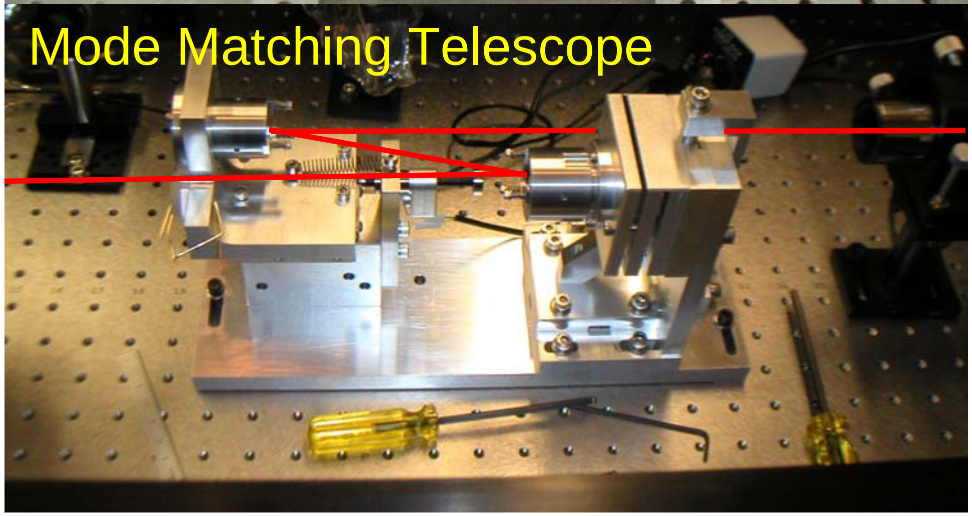


- 10W MOPA126
- Frequency Stabilization Servo (FSS)
- Pre-Mode Cleaner (PMC)
- 13m Mode Cleaner with digital controlled suspension
- Good noise performance and stable operation

In-vacuum Faraday Isolator and In-vacuum Mode Matching Telescope

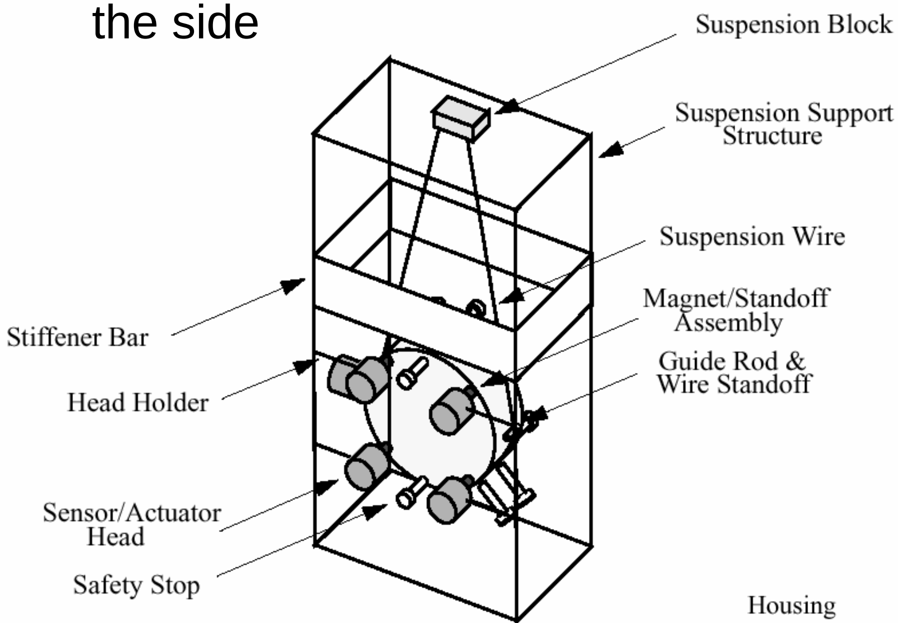


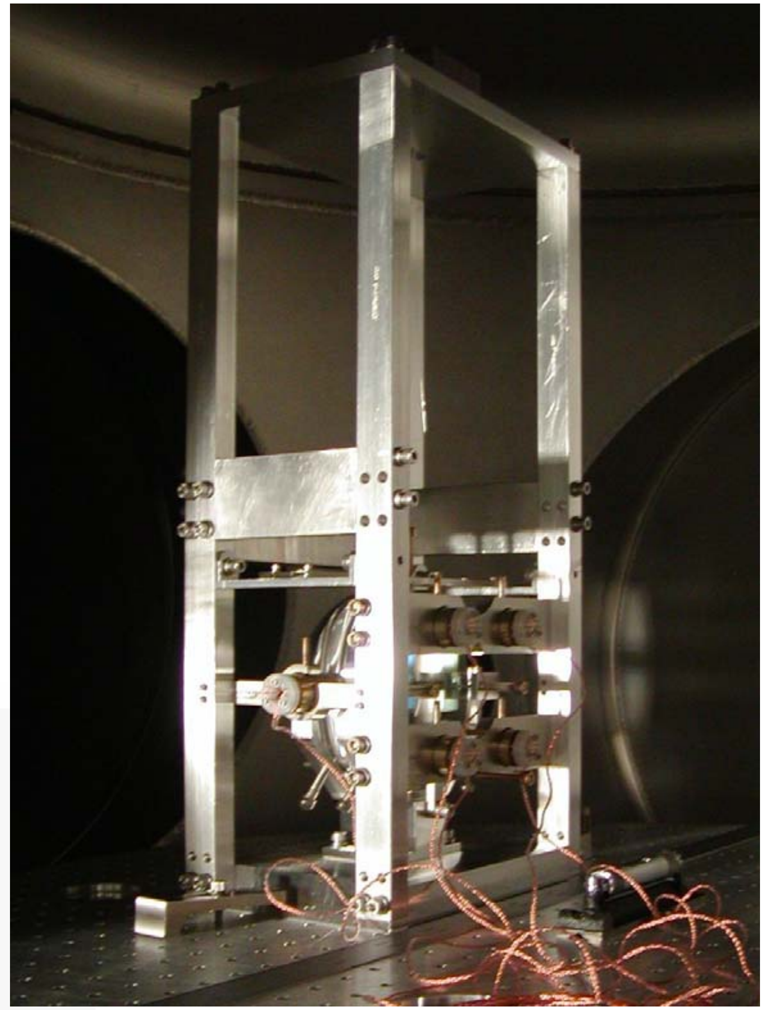




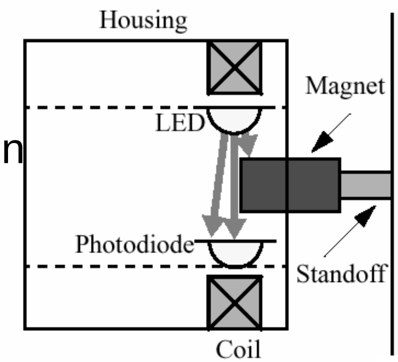
LIGO-I type single suspension

- 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



STACIS Active seismic isolation

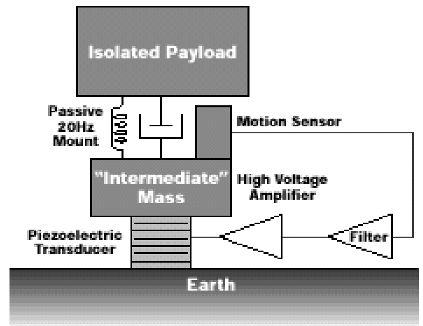
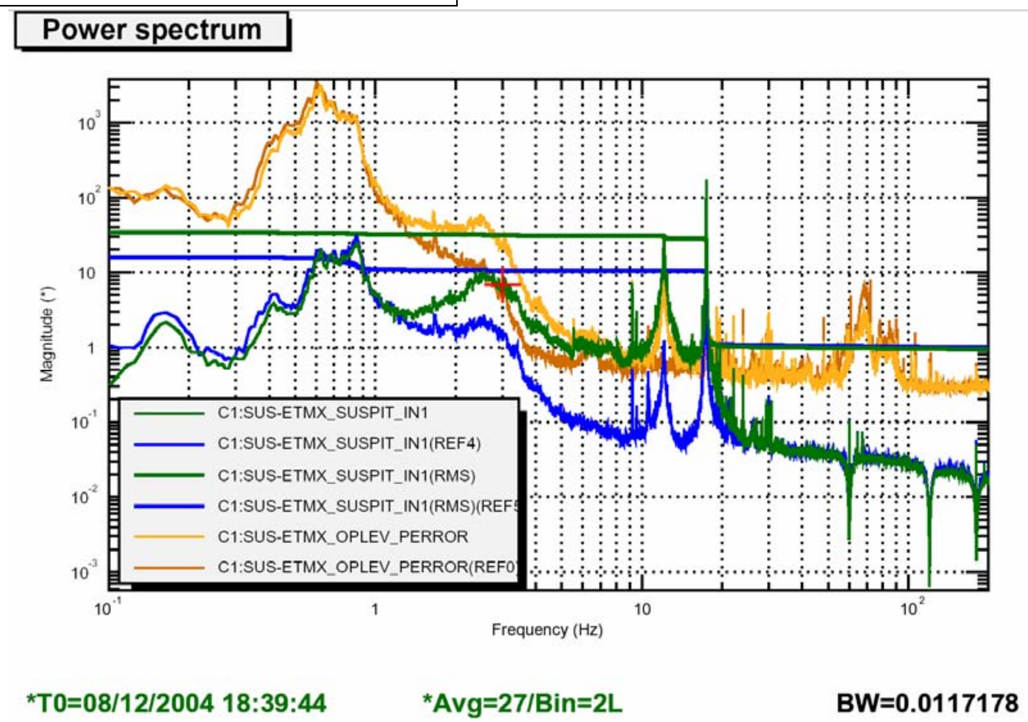
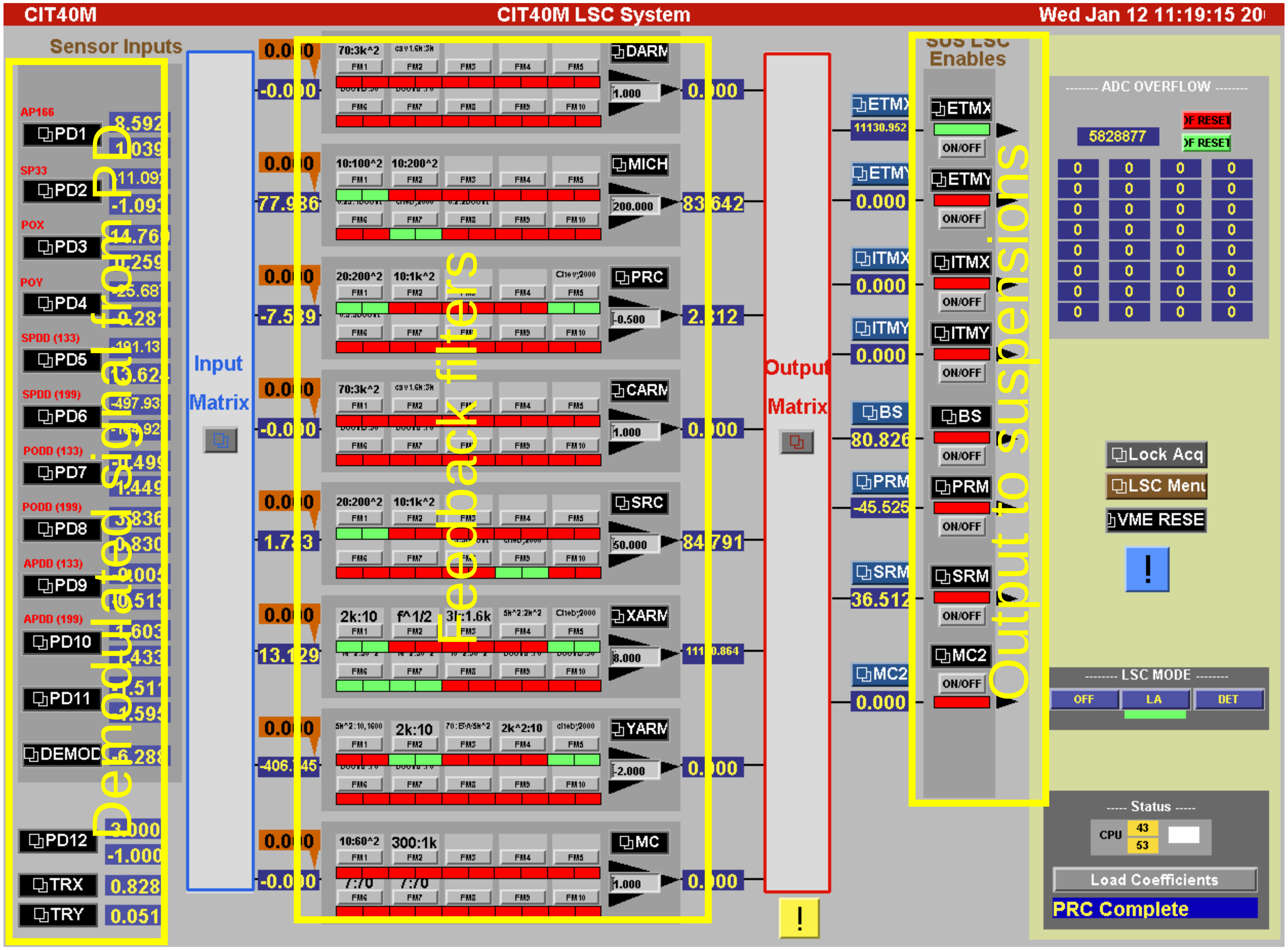


Figure 18

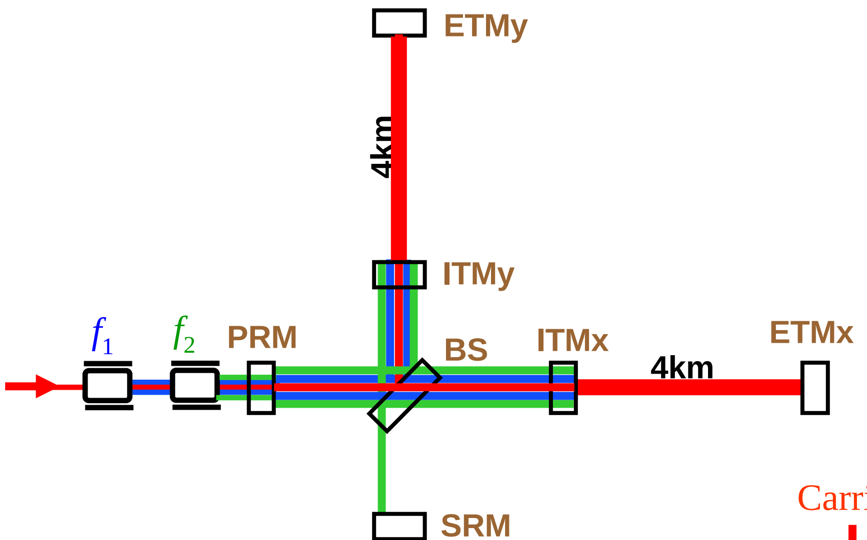
- One set of 3 for each of 4 test chambers
- 6-dof stiff PZT stack
- Active bandwidth of 0.3-100Hz,
- 20-30dB of isolation
- passive isolation above 15 Hz.



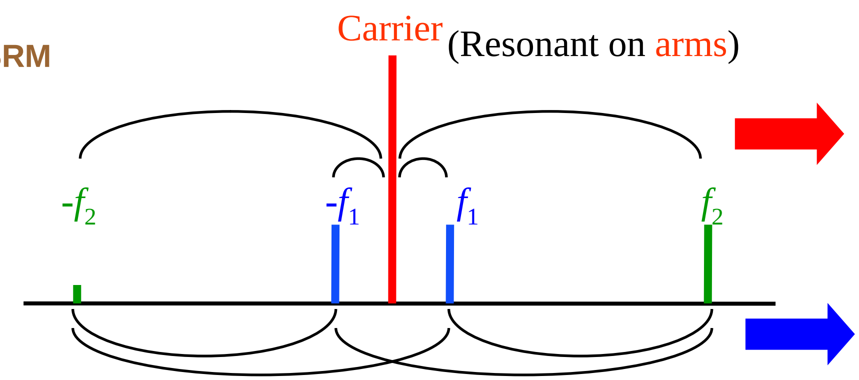
Digital control system



Signal extraction for AdvLIGO



- Two modulations are used to separate high finesse, 4km long arm cavity signals from Central part (Michelson, PR, SR) signals.
- Only + f_2 is resonant on SRC
- Unbalanced sidebands of +/-f_2 make error signal of Central part

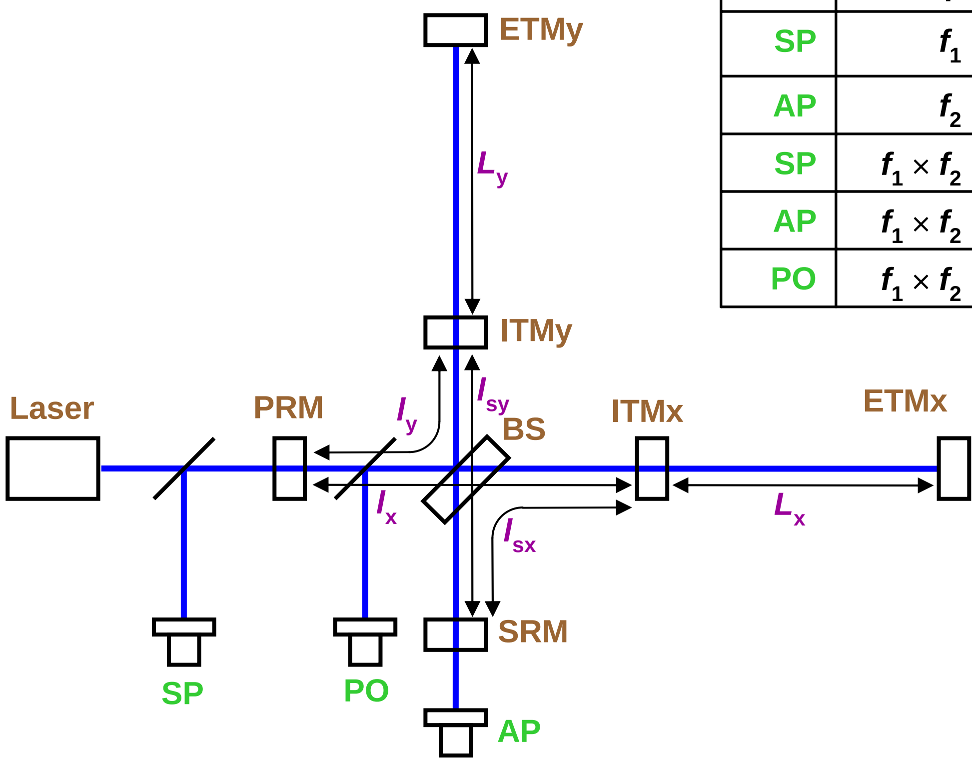


- Single demodulation
- Arm information

- Double demodulation
- Central part information

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

5 DOF for length control



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 : $L_- = L_x - L_y$

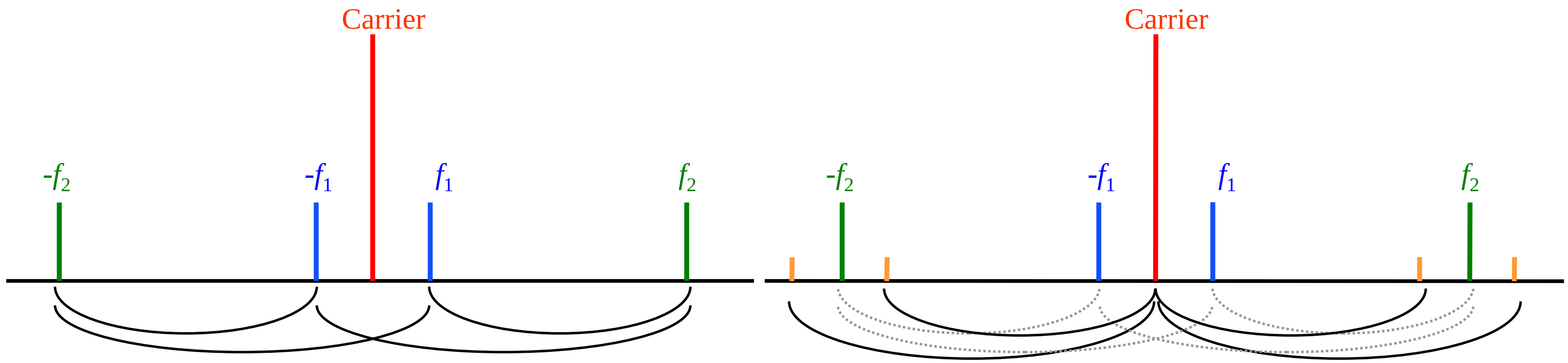
Power recycling cavity : $l_+ = (l_x + l_y) / 2$

Michelson : $l_- = l_x - l_y$

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

Disturbance by sidebands of sidebands

Original concept | Real world

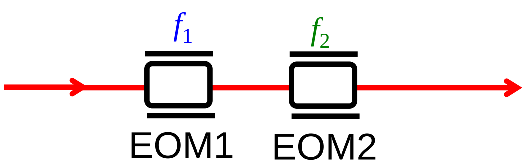


- Sidebands of sidebands are produced by two series EOMs.
- Beats between carrier and f_2 +/- f_1 disturb central part.

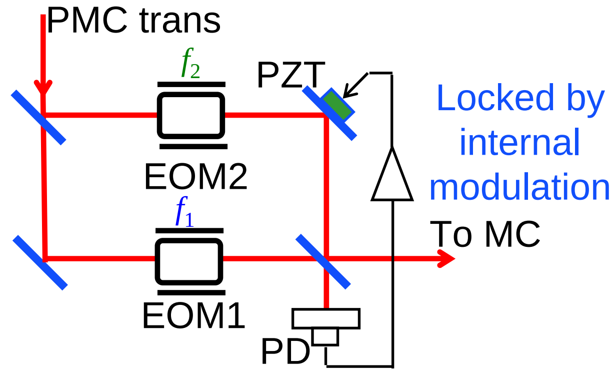
Port	Dem. Freq.	L_+	L_-	l_+	l_-	l_s
SP	f_1	1	-1.4E-8	-1.2E-3	-1.3E-6	-6.2E-6
AP	f_2	1.2E-7	1	1.4E-5	1.3E-3	6.5E-6
SP	$f_1 \times f_2$	7.4	-3.4E-4	1	-3.3E-2	-1.1E-1
AP	$f_1 \times f_2$	-5.7E-4	32	7.1E-1	1	7.1E-2
PO	$f_1 \times f_2$	3.3	1.7	1.9E-1	-3.5E-2	1

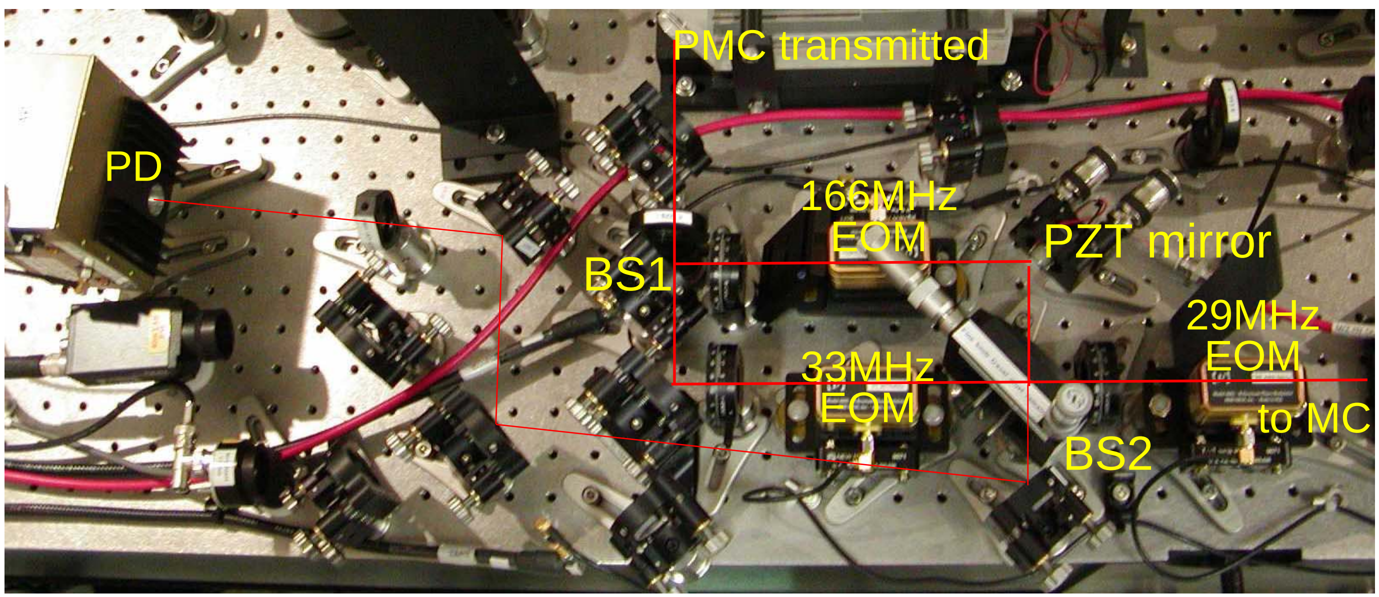
Mach-Zehnder interferometer on 40m PSL to eliminate sidebands of sidebands

Series EOMs
with sidebands of sidebands



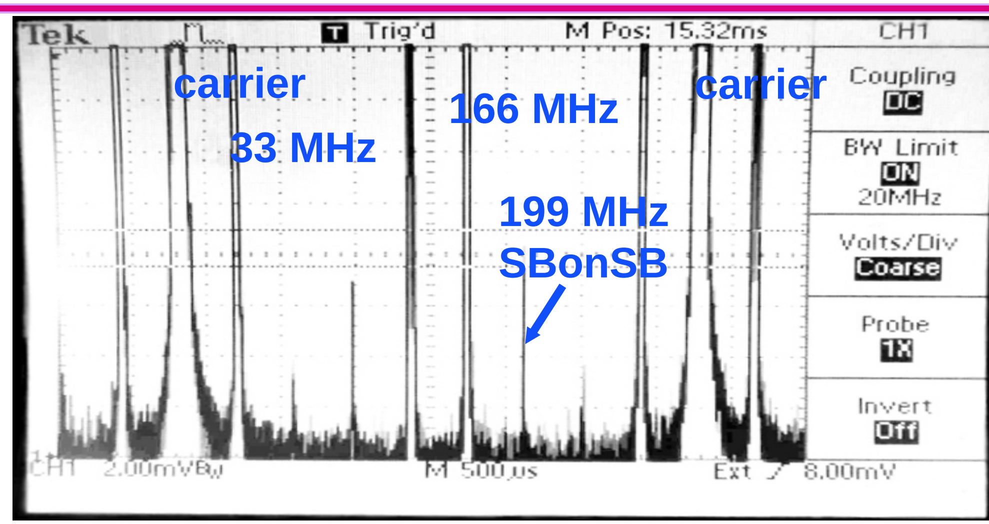
Mach-Zehnder interferometer
no sidebands of sidebands from beginning





MZ eliminates sidebands on sidebands

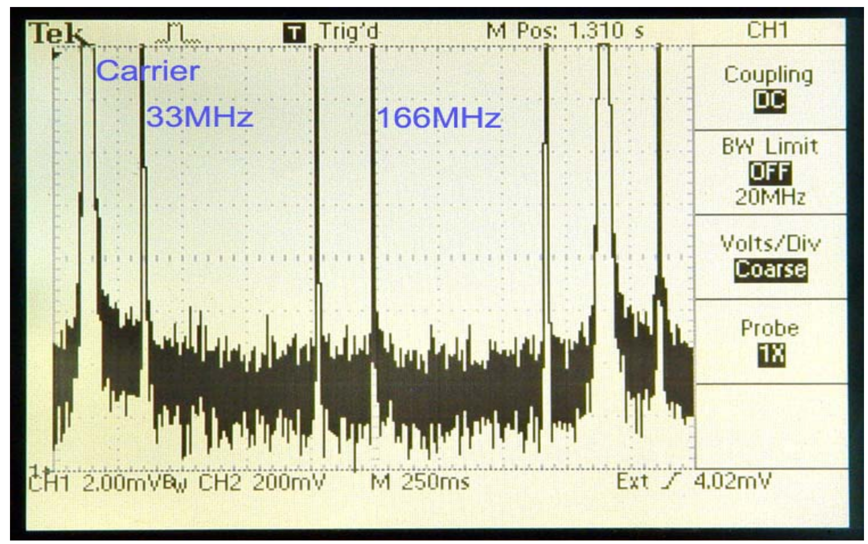
MCT light, series EOMs



parallel EOMs in MZ ifo

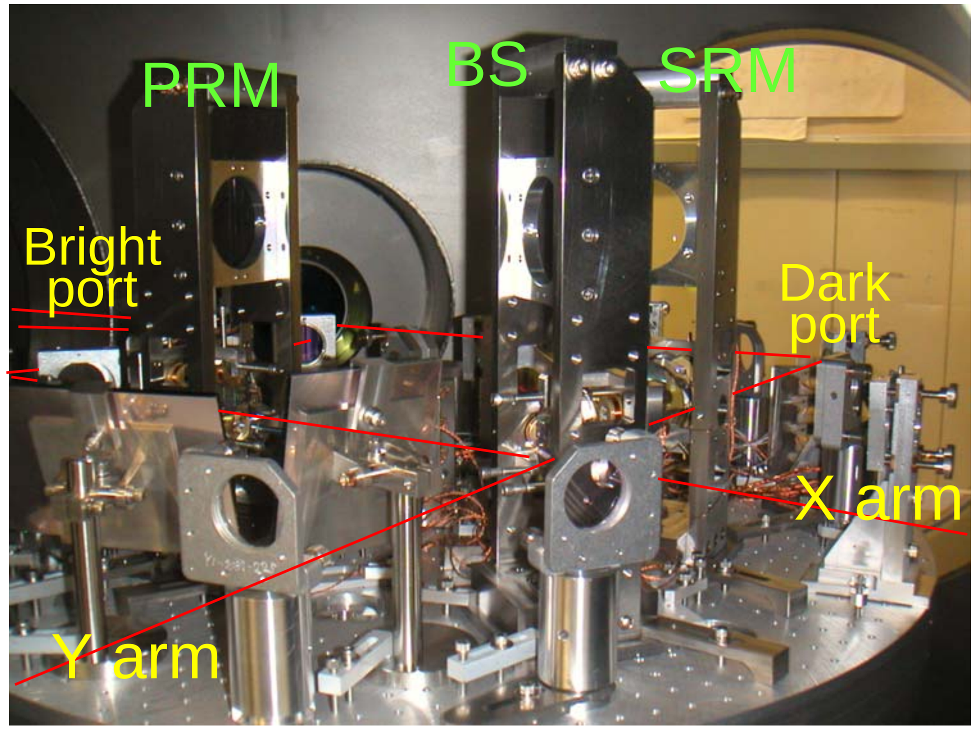
No sidebands on sidebands!

(hard to directly compare because we can't turn the modulation depth up as high as we could before; but we can get up to Γ = 0.25 easily)



Important Milestones

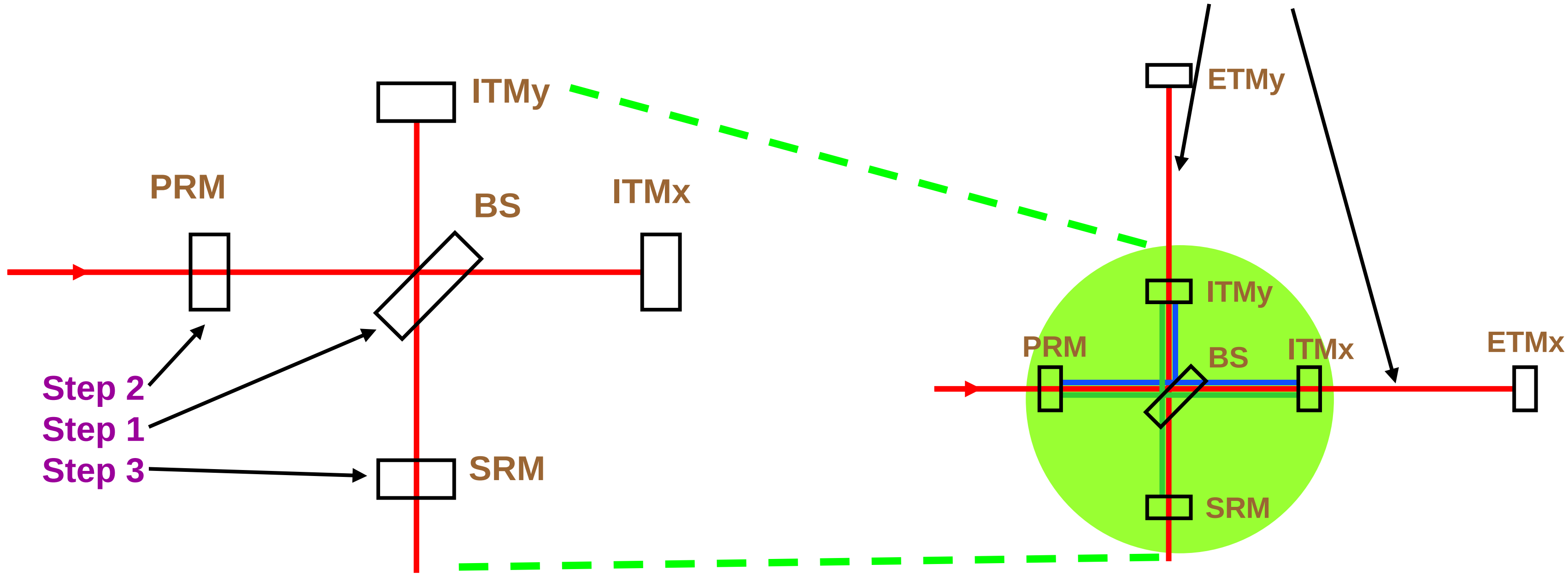
September, 2003
Four TMs and BS: installed
November 2003
FP Michelson locked
February 2004
Power Recycling Mirror (PRM) ,
Signal Extraction Mirror (SRM) installed
June 2004
Mach-Zehnder installed
August 2004
DRMI locked with carrier resonance
October 2004
DRMI locked with sideband resonance
November 2004
Off-resonant lock of arm cavities with DRMI



Lock Acquisition of Detuned RSE

1. lock central part

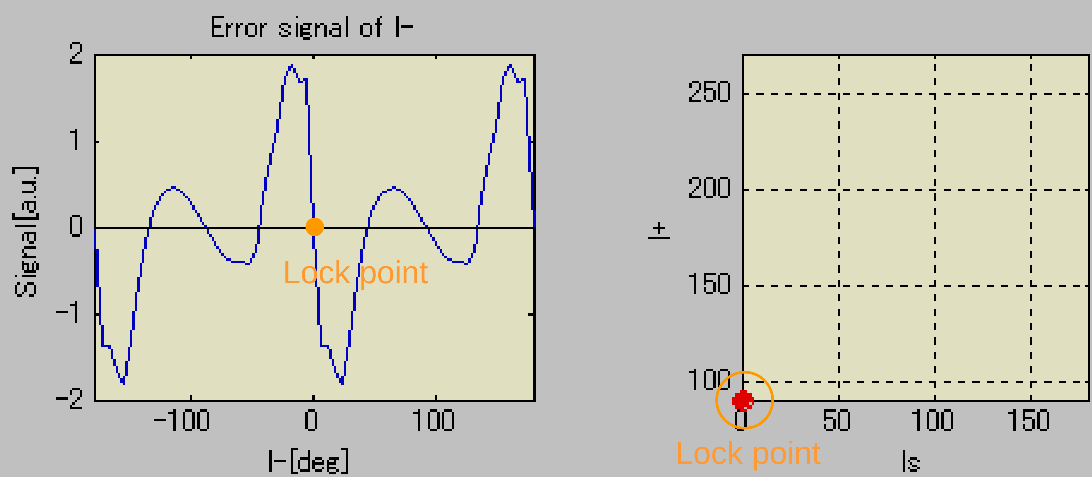
2. lock arm cavities



- Central part: not disturbed by carrier resonance on arm cavity (but disturbed by sidebands resonance)
- Lock acquisition — After lock:
  - l_- : dither @ 1200 Hz → DDM@AP
  - l_+ : 33MHz@SP → DDM@SP
  - l_s : DDM@PO → DDM@PO

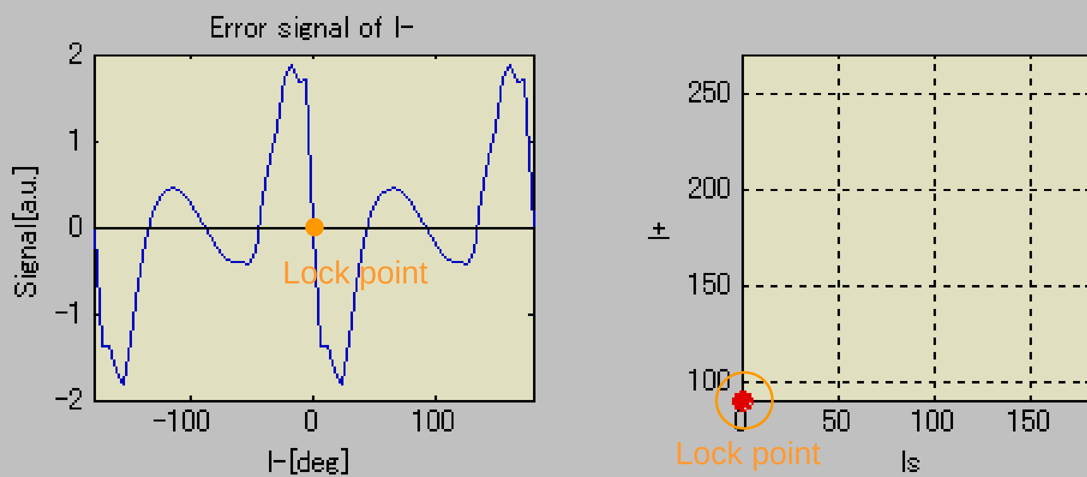
- Arm cavities: not disturbed by locked central part
- Lock each arm cavity independently
- Switch control servo to common/differential control

l_- signal with double demodulation



- Good l_- signal when l_+ and l_s is locked
- No good l_- signal once l_+ and l_s start moving

l_- signal with double demodulation



- Good l_- signal when l_+ and l_s is locked
- No good l_- signal once l_+ and l_s start moving

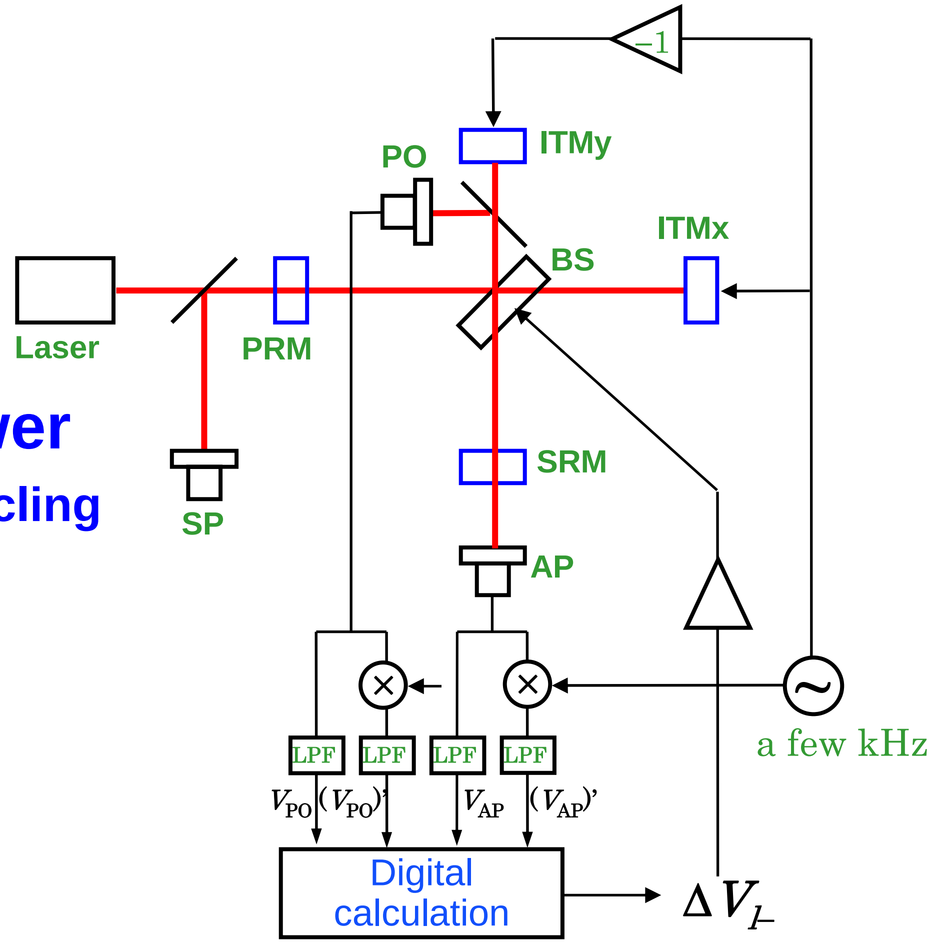
Looking for good signal for lock acquisition

- Unfortunately, no way to lock central part directly using the original double demodulation

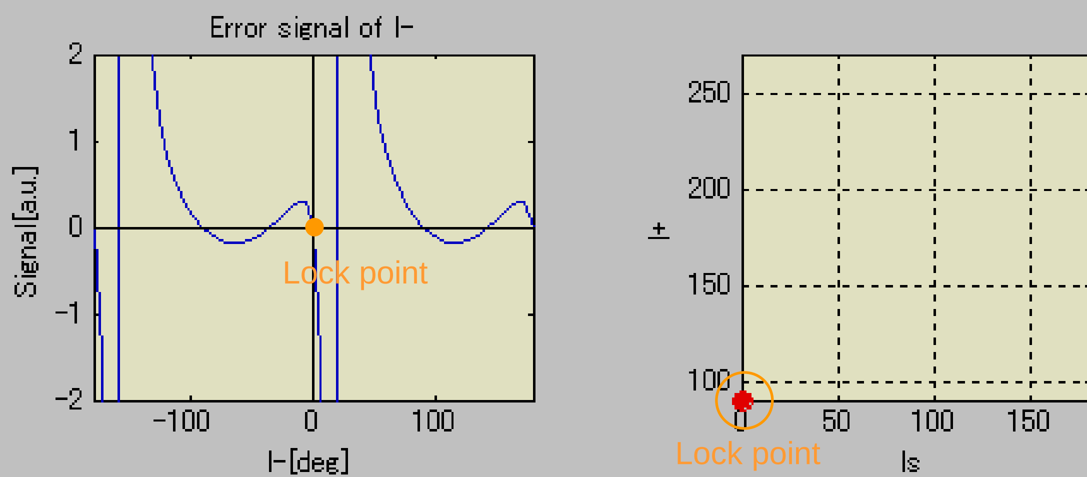
- **Dither locking for l_- signal**
- **Divide signal by inside power**
  - » **Good cancellation of power recycling**

$$\Delta V_{l_-} = \frac{d}{d\,l_-}\left(\frac{V_{AP}}{V_{PO}}\right)$$

$$= \frac{V'_{AP}\,V_{PO} - V_{AP}\,V'_{PO}}{V_{PO}^{\;2}}$$



l_- signal with dither



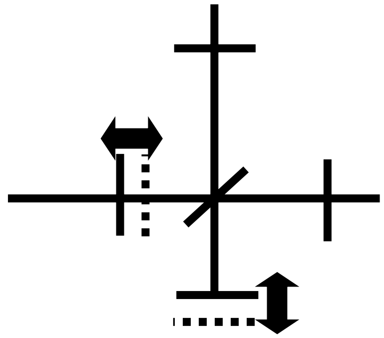
- Dither on ITMx, ITMy with 1kHz
- Error signal is calculated digitally as follows;

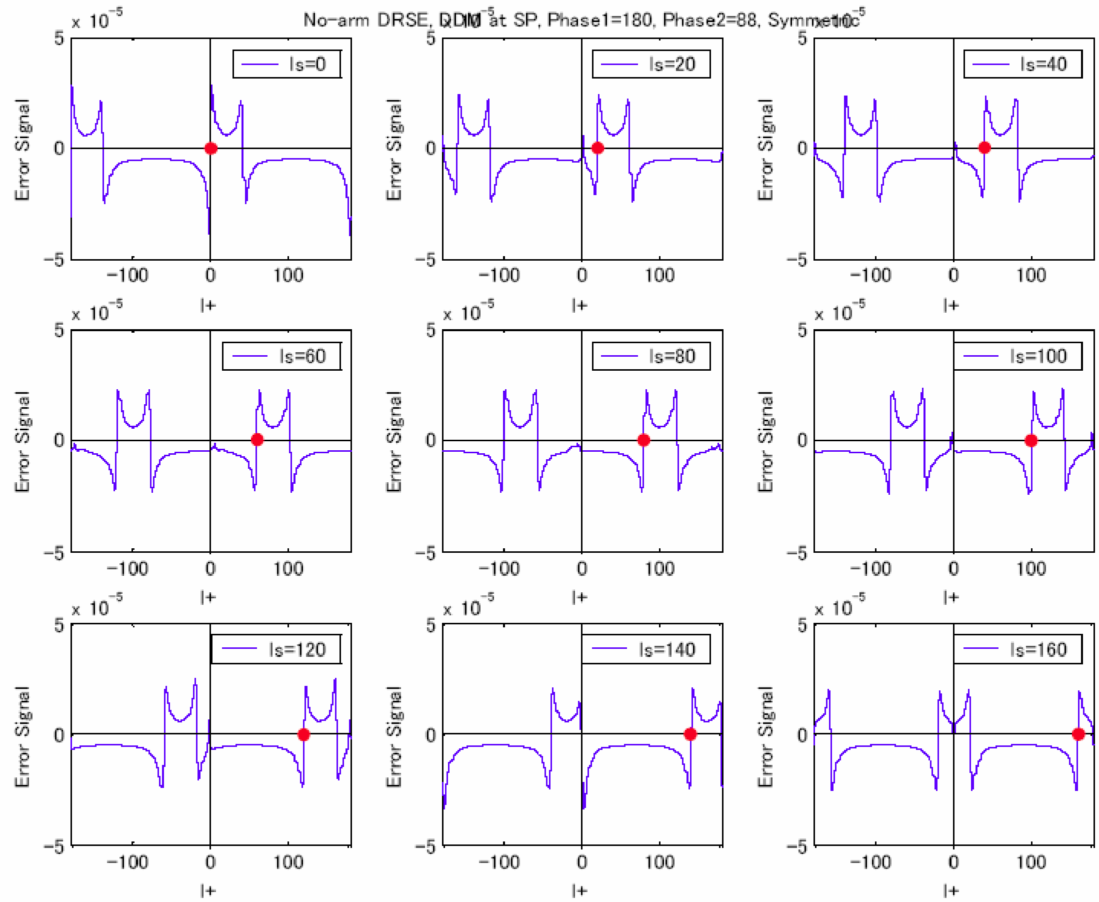
$$\Delta V_{l_-} = \frac{d}{d\, l_-}\left(\frac{V_{AP}}{V_{PO}}\right) = \frac{V'_{AP}\, V_{PO} - V_{AP}\, V'_{PO}}{{V_{PO}}^2}$$

- l_- signal does not depend on l_+ at all
- l_- dither locking signal gain depends on l_s, but polarity of signal is always the same

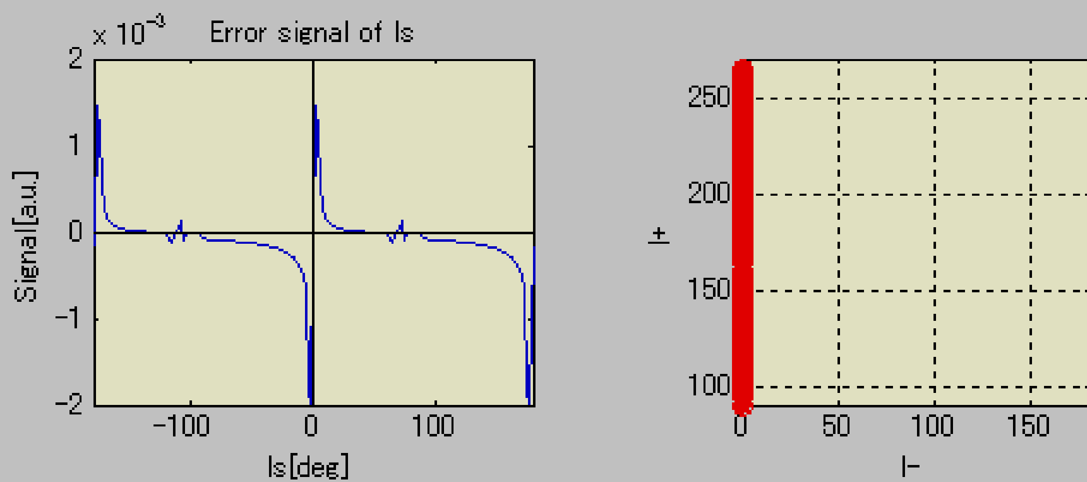
Lock l+ with DDM at SP

- With l- dither-locked, there's always a good l+ signal, for all values of ls.
- The locking point may not be at l+ = 0° !
- The PRM follows the swinging of the SRM; this signal keeps the combined cavity locked.
- Then, once ls is locked, we'll recover l+ = 0°.





I_s signal with I_- and I_+ lock



- Good I_s signal can be extracted once I_+ is locked to zero-crossing point

DRMI lock with Unbalanced sideband by detuned cavity

August 19, 2004

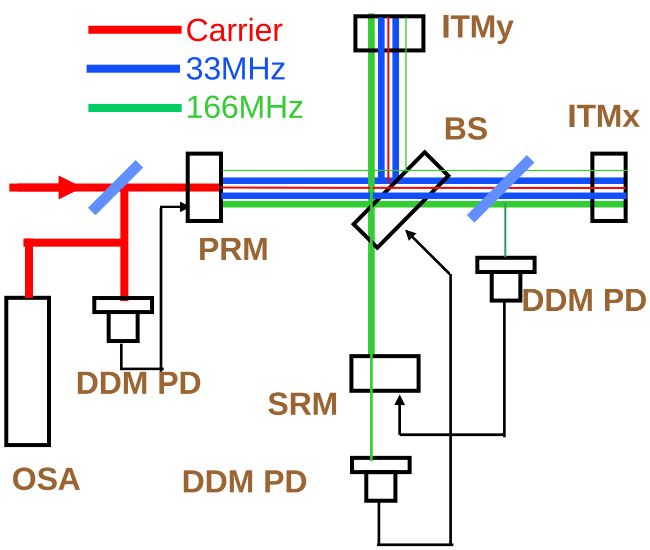
- **DRMI locked with carrier resonance (like GEO configuration)**

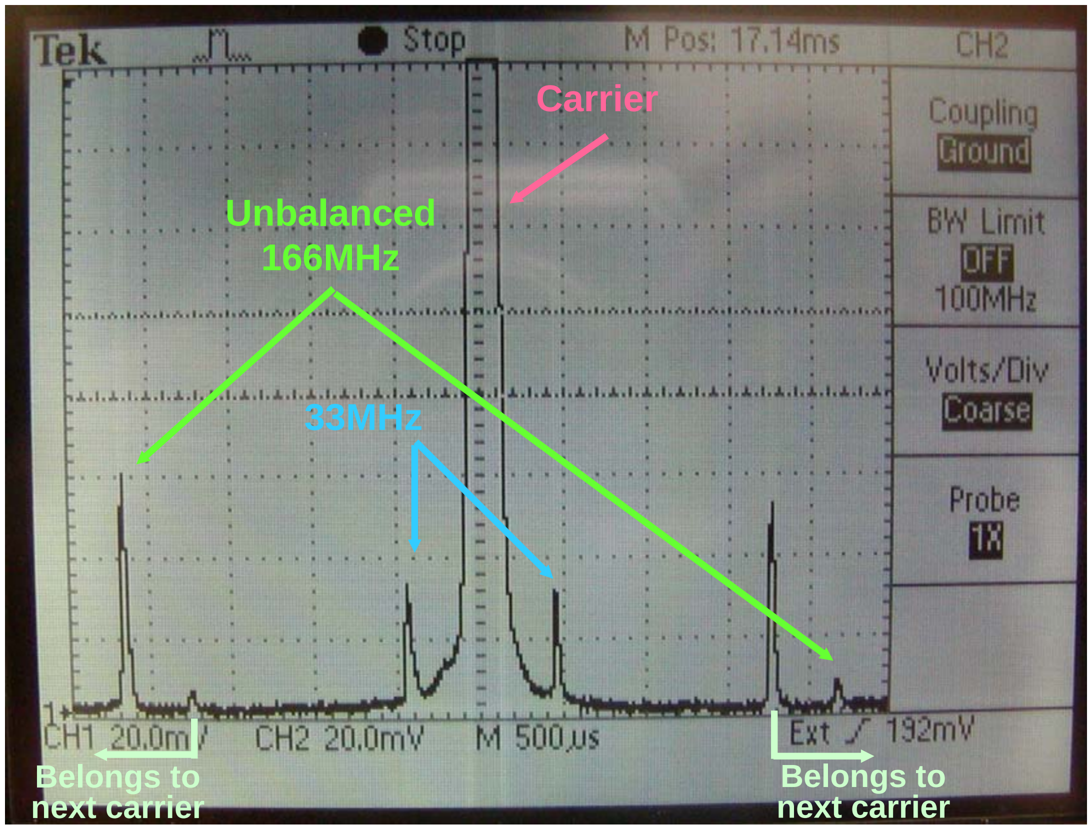
November 9, 2004

- **DRMI locked with sideband resonance (Carrier is anti resonant preparing for RSE.)**

November 16, 2004

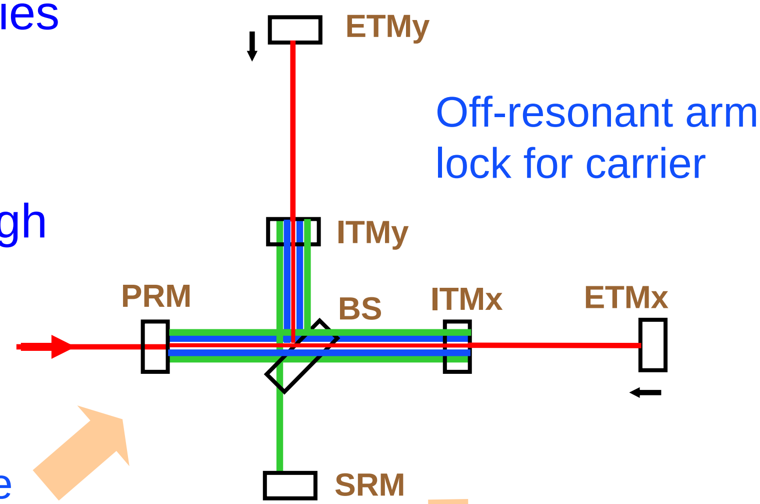
- **Switched to DDM control**
- **Can be locked with DDM directly**
- **Longest lock: 2.5 hours**
- **Typical lock acquisition time ~10sec**

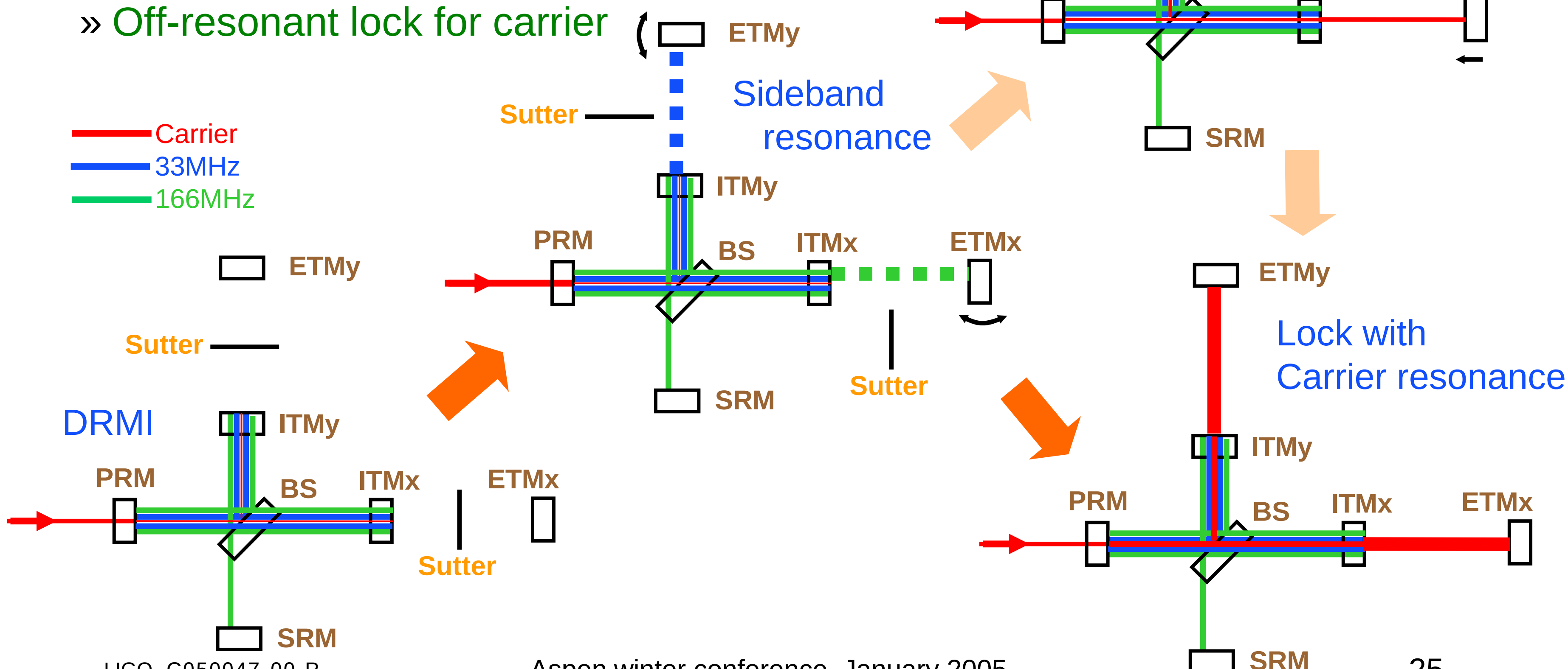




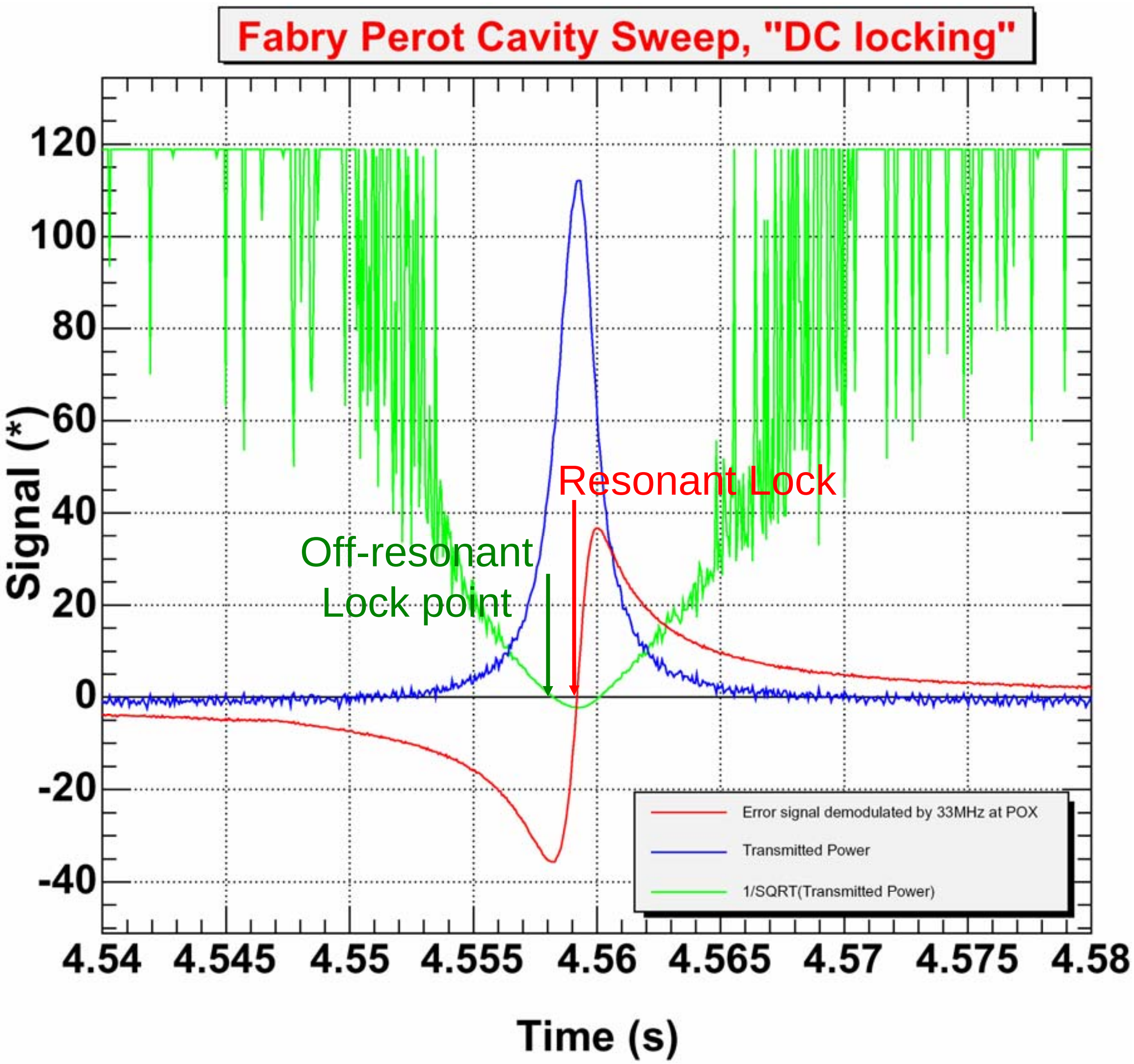
Trial of Arm lock with DRMI

1. Disturbance of sideband resonance on arm cavities
   » Gain and amplitude limitter on DRMI control
2. Slow digital sampling rate
3. Coupling between X-arm and Y-arm signal through carrier resonance on Michelson part
   » Off-resonant lock for carrier





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 Michelson part when arm cavity is locked.

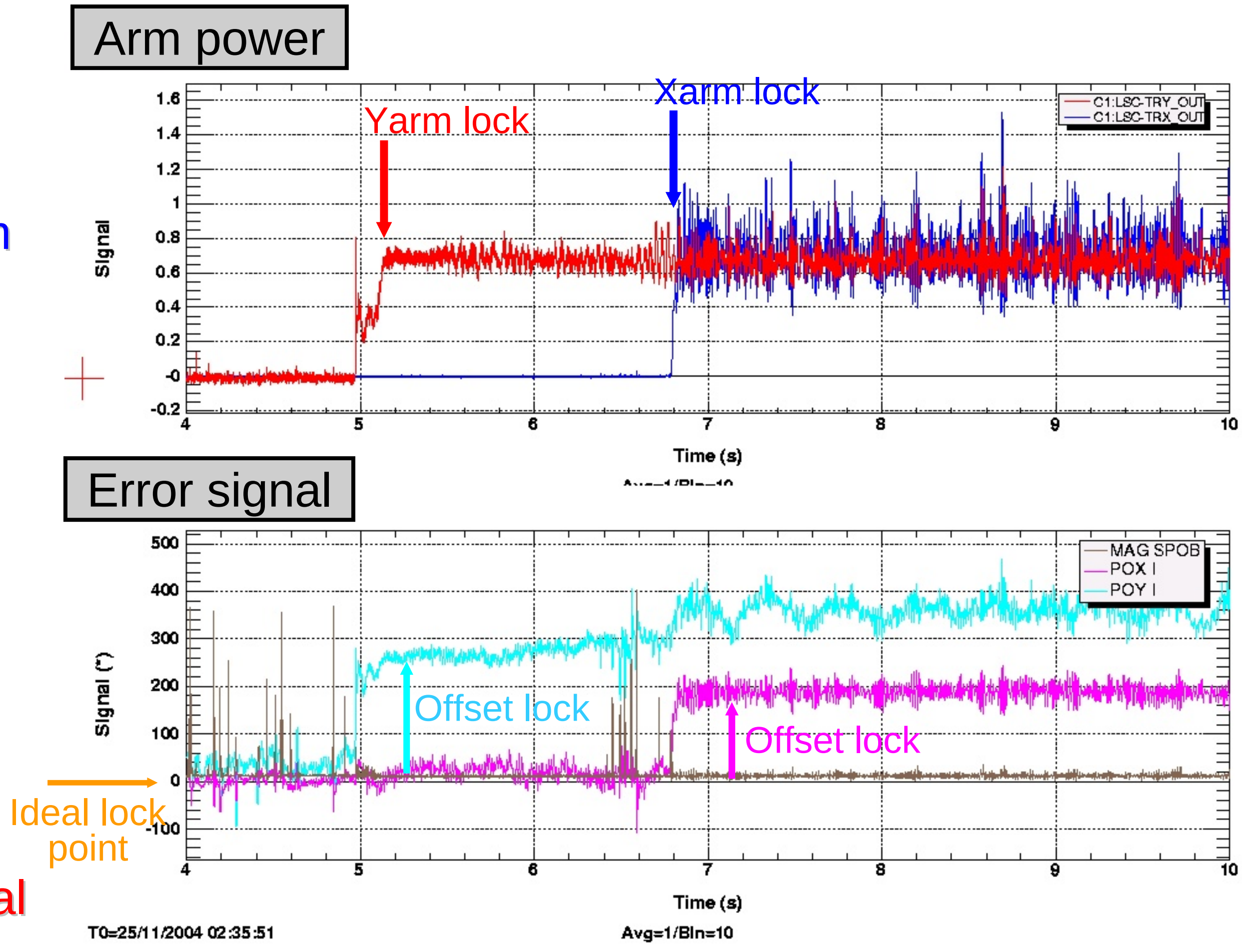
Off resonant Arm lock with DRMI

November 25, 2004

- Both arms locked with DRMI
- Off-resonant carrier on arm cavities
- Last < 1 min
- Locked only 2 times

DRMI with single arm lock

- Not so difficult
- Last ~10 min
- Lock acquisition time ~1 min
- Reducing offset starts oscillation caused by optical lever servo, under investigation



Summary

- Optical configuration for AdvLIGO being developed at 40m prototype interferometer
- Stable operation of PSL and MC
- Locking of FPMI with digital LSC system (misaligned PRM, SRM), measurement of displacement noise
- Sidebands of sidebands: eliminated by M-Z interferometer
- Guided locking of DRMI using Dither-locking with carrier/sideband resonance
- Locking of DRMI with DDM with sideband resonance
- Off-resonant locking of both arms with DRMI (not perfect but very close to final configuration)

Hope we succeed in locking full RSE very soon!

40m vs. Ad-LIGO

40m

Table 4: Length sensing signals. ⊗ means double demodulation.

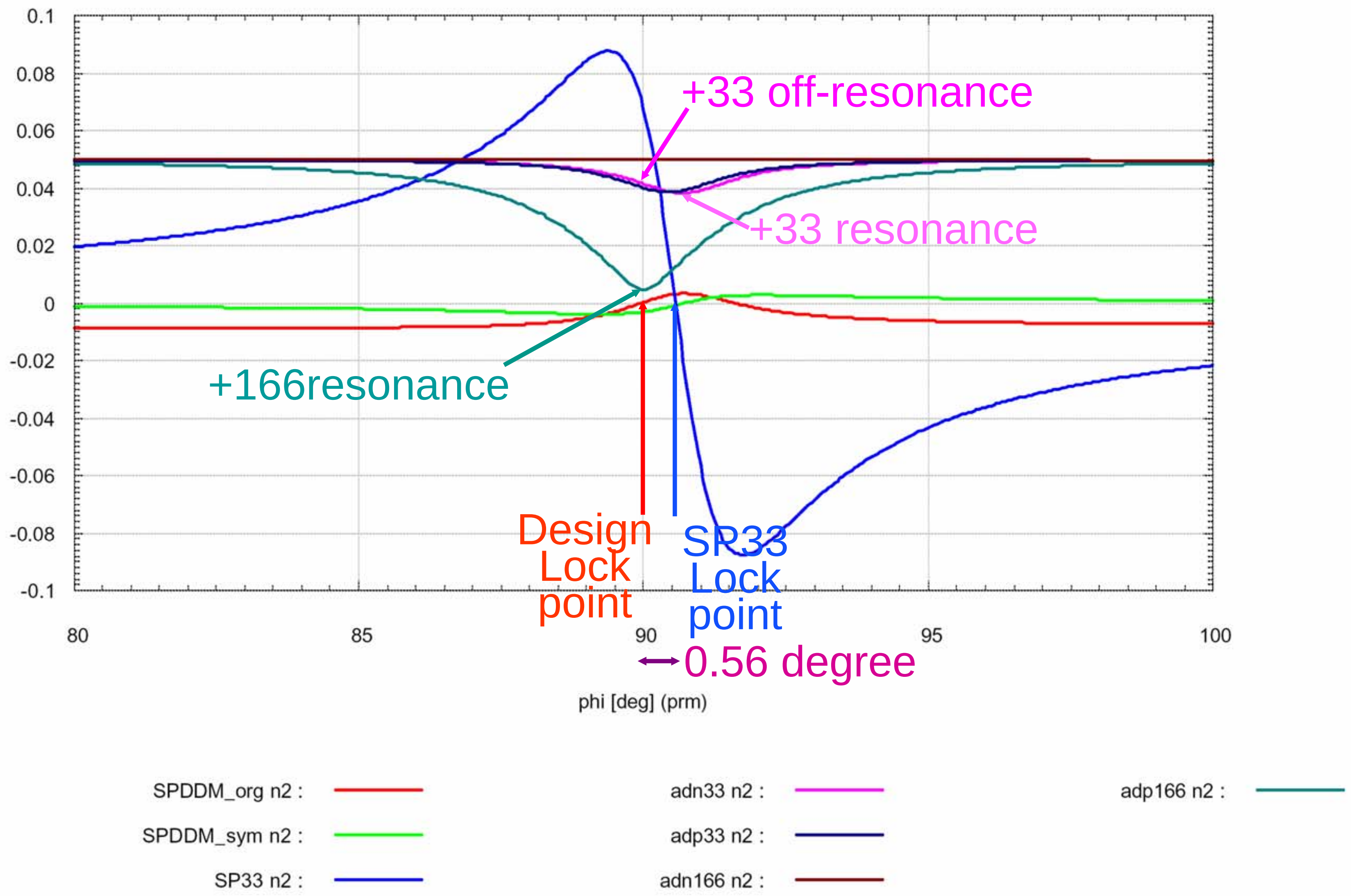
Signal	L_+	L_-	l_+	l_-	l_s	
SP, f_1	**15.2**	0.000	-0.062	0.064	-0.001	
AP, f_2	0	**1.69**	0	0.002	0	
SP, $f_2 - f_1$	-0.0003	0.0001	**0.214**	0.029	0.039	x6
AP, $f_2 \otimes f_1$	0	0	0.0025	**-0.0034**	-0.0004	x1.5
PO, $f_2 - f_1$	0.005	-0.004	1.000	-0.277	**-2.980**	x3

Table 5: Length sensing signals for Advanced LIGO. ⊗ means double demodulation. These numbers agree, up to an overall constant, with the table Peter Fritchel showed at the August 2000 LSC meeting (LIGO-G000225).

Ad-LIGO

Signal	L_+	L_-	l_+	l_-	l_s	
SP, f_1	**1890**	0.00	-1.94	0.11	0.00	
AP, f_2	0	**-1500**	0	-1.88	0	
SP, $f_2 - f_1$	-0.11	-0.01	**19.5**	-0.11	8.66	x2
AP, $f_2 \otimes f_1$	0.000	0.001	-0.031	**0.242**	0.005	x6
PO, $f_2 - f_1$	-0.42	-0.01	8.84	5.81	**245**	x17

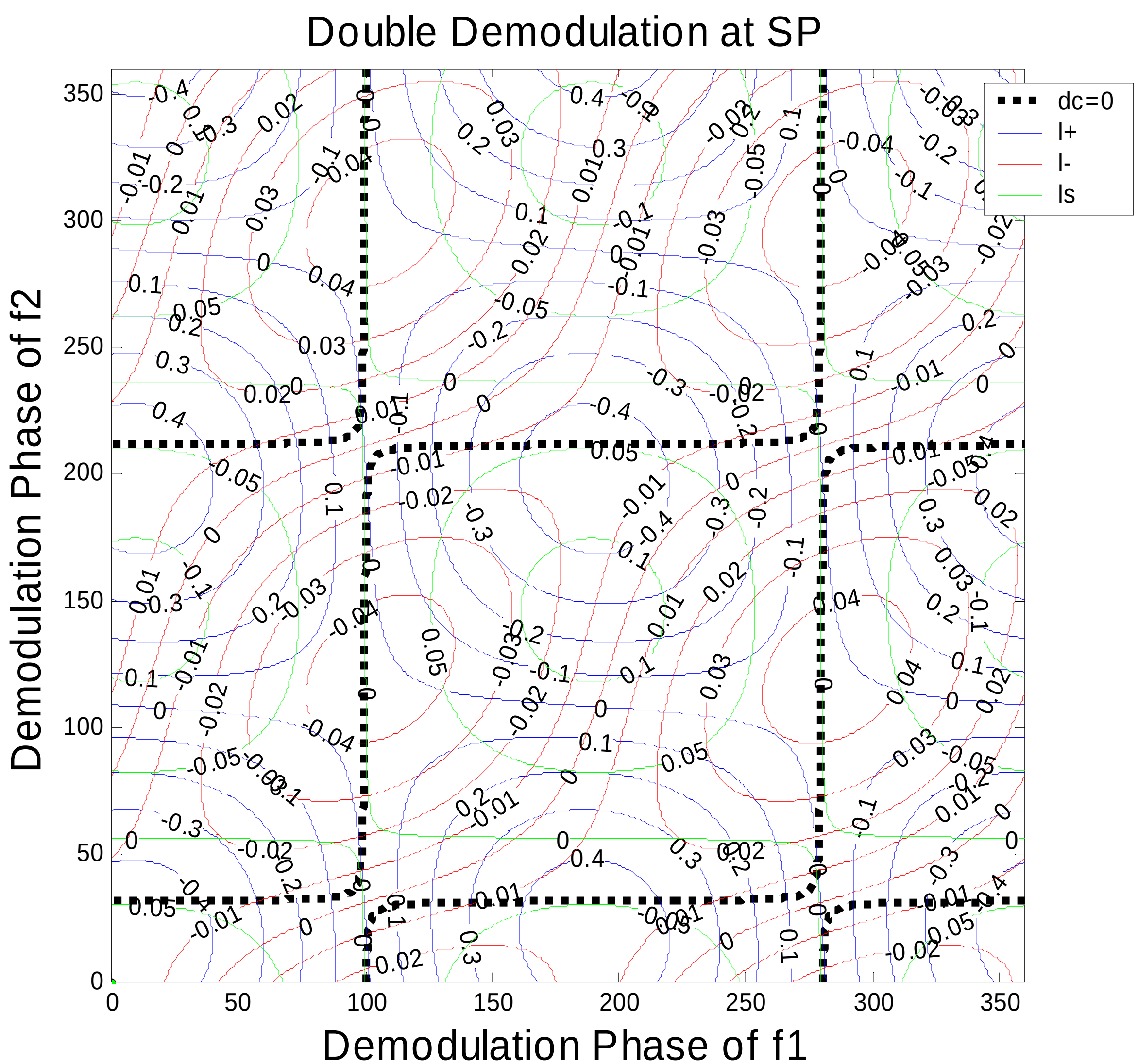
SP33,DDM,+/-33M,+/-166M@SP



Original design (no offset)

+33 : off-resonant
-33 : off-resonant
+166: resonant
-166 : anti-resonant

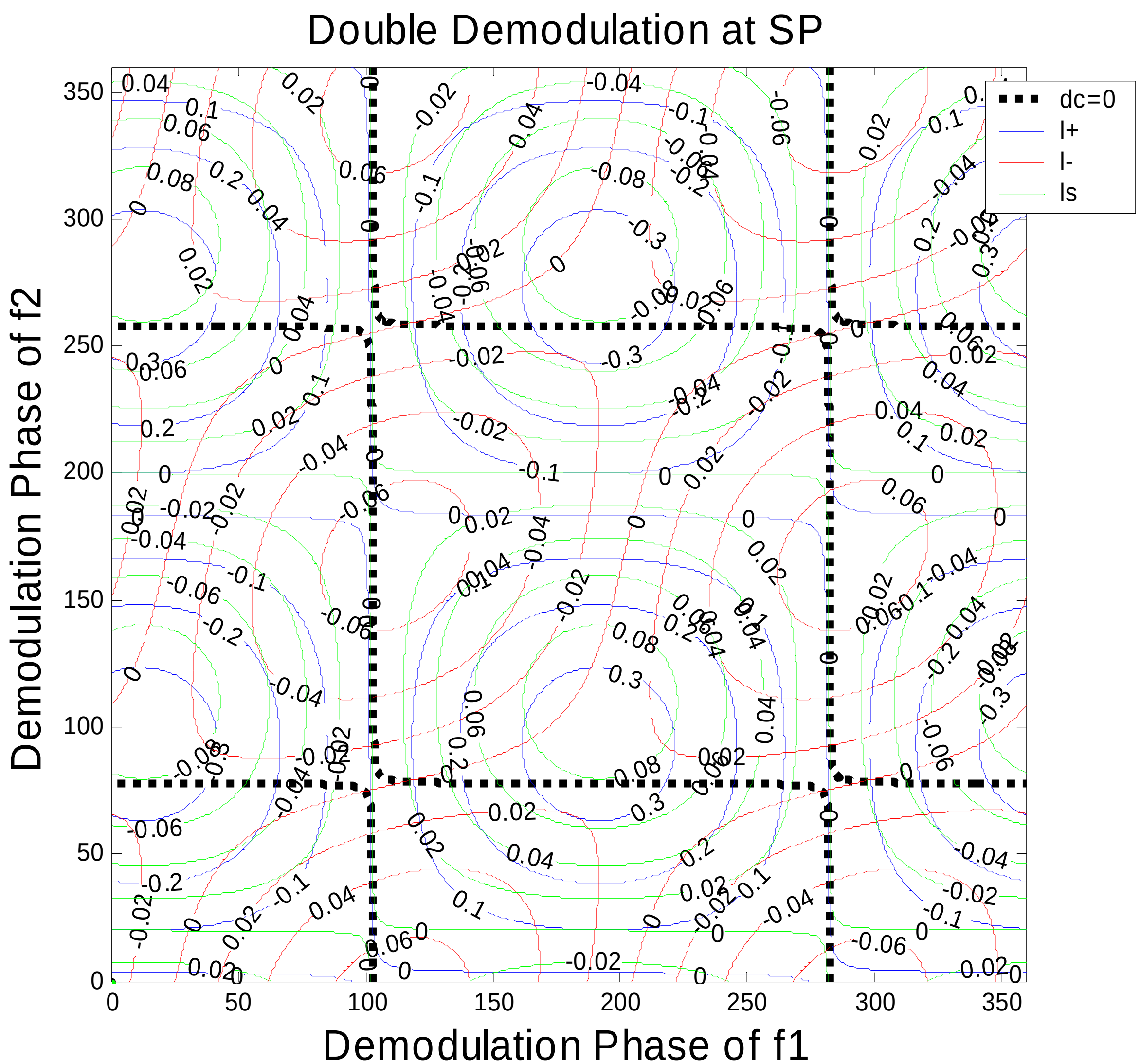
- I_+ and I_s plot separated
- Difficult



I_+ +0.56 degree

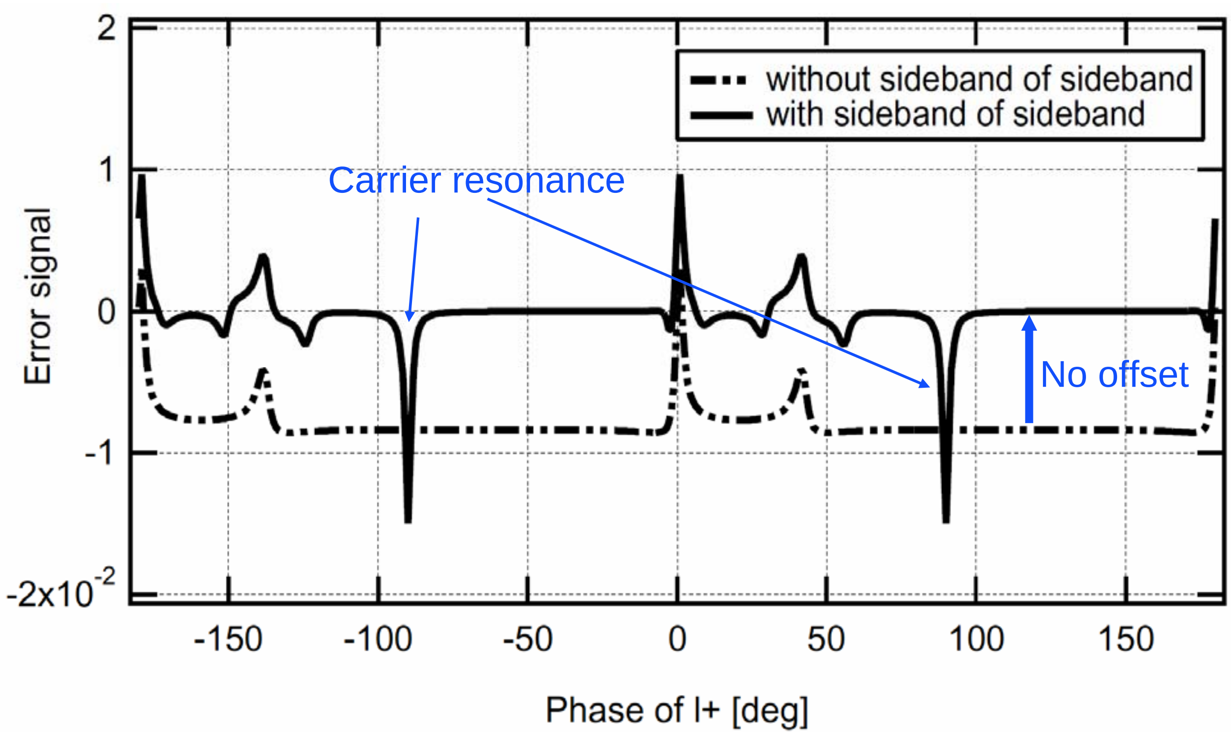
+33 : resonant
-33 : resonant
+166: off-resonant
-166 : anti-resonant

- I_+ and I_s plot overlapping
- DC line changed
- Difficult



Double demodulation signal of I_+

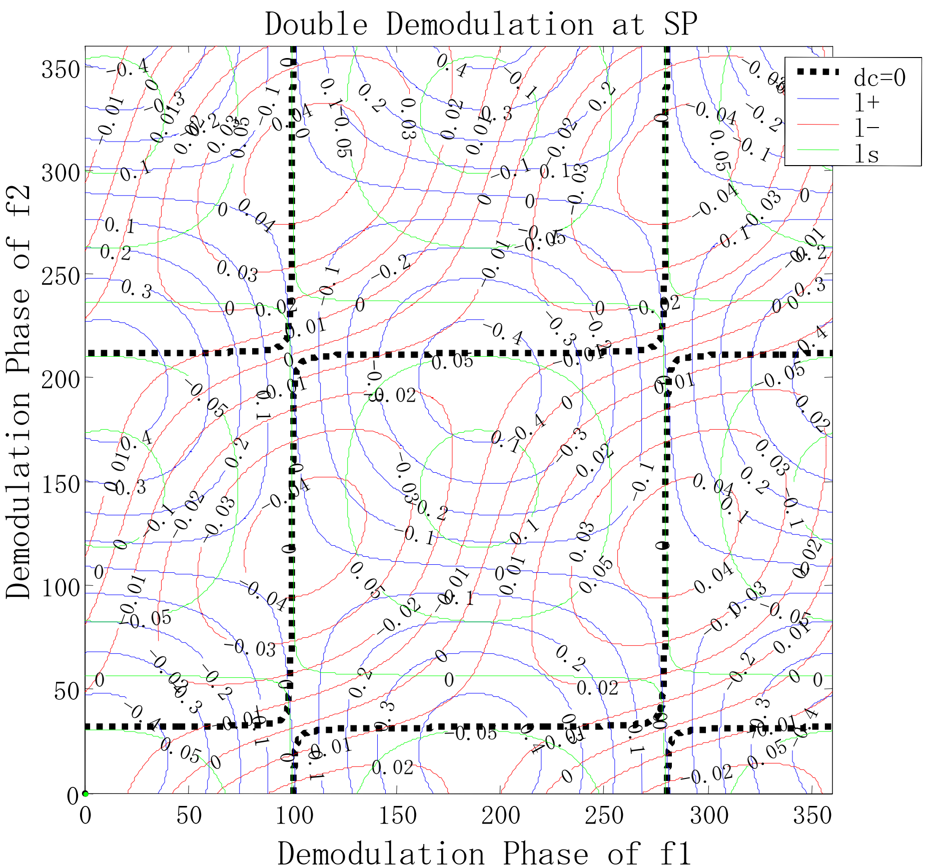
- What we expected
  - » Big offset when cavity is not locked
  - » No disturbance of carrier
- What we have seen
  - » No offset
  - » Big disturbance of carrier



Double Demodulation

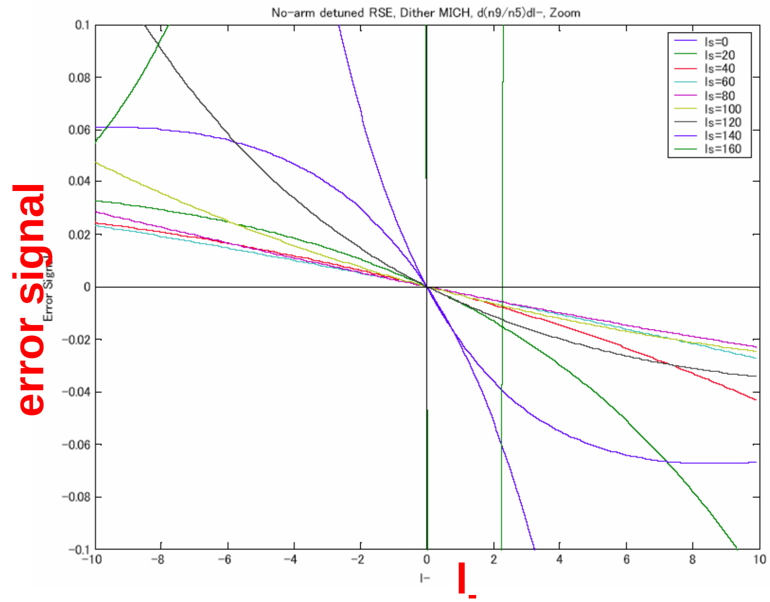
- Double Demodulation used for l_+, l_-, and l_s
- Demodulation phases optimized to suppress DC and to maximize desired signal

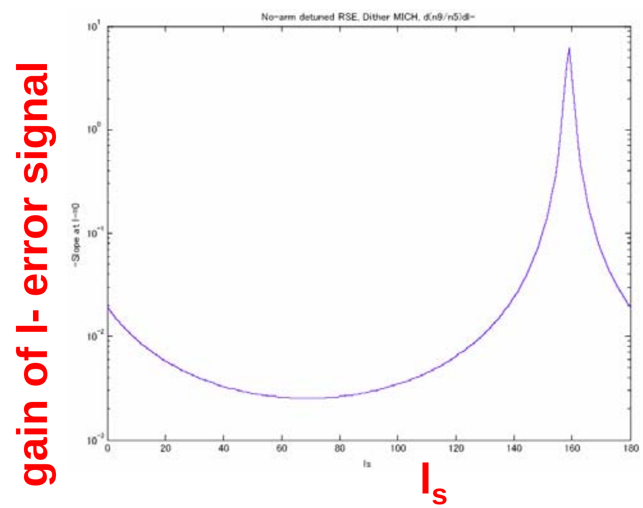
[S.Kawamura, “Signal Extraction Matrix of the 40m Detuned RSE Prototype”, LIGO-T040010-00-R (2004)]



Gain of dither locking signal

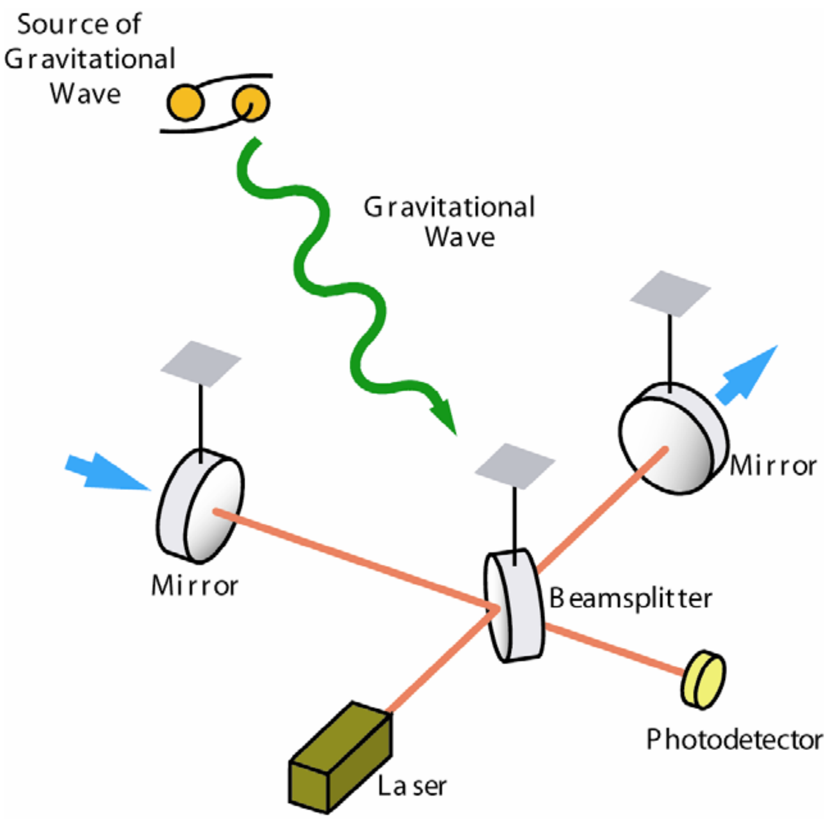
- l- dither locking signal gain depends strongly on ls
- But polarity of signal is always the same
- Can handle this with a limiter…
- l- dither locking signal doesn't depend on l+ at all!
- Signal is degraded by presence of RF sidebands… turn them down low (Γ<0.02) to acquire dither lock, then ramp them back up.



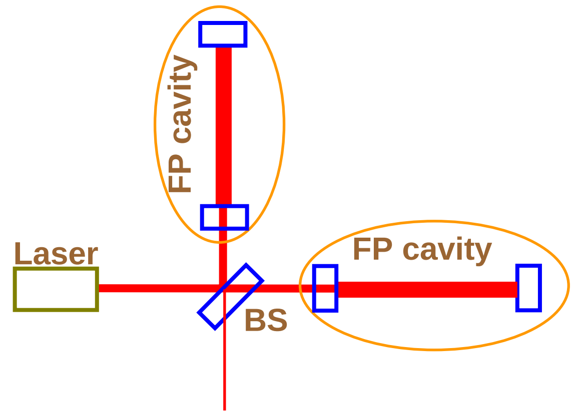


Optical configuration for Gravitational wave interferometer

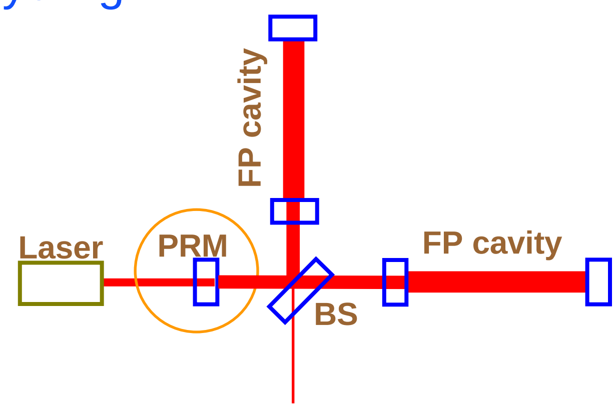
- Gravitational wave detection using Michelson interferometer



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

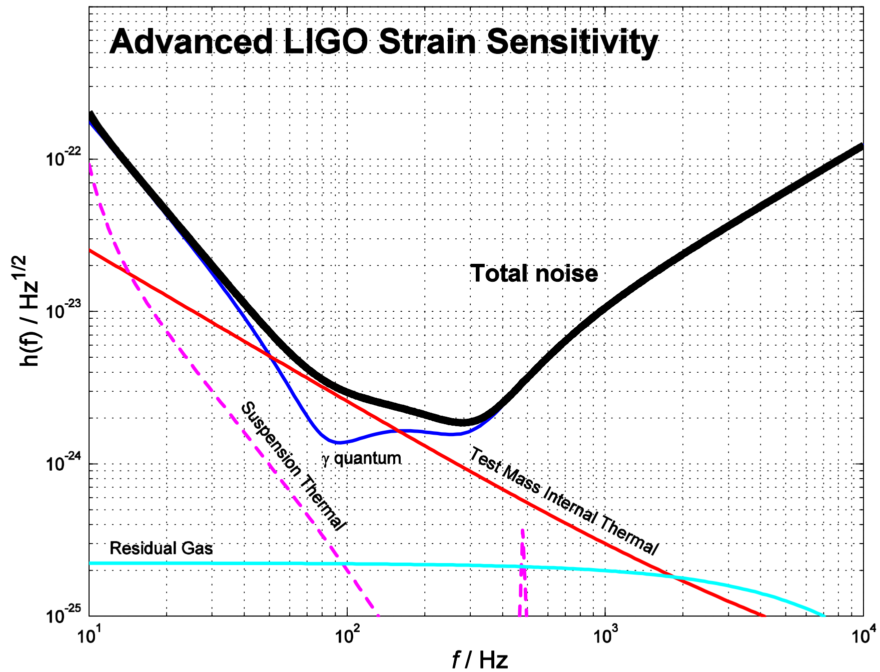


- Power enhancement using Power Recycling



Once we acquire full lock

- Measure in-lock transfer functions.
- Verify optical resonance and optical spring
- Begin noise characterization
- Operate at a different SEC tune?
- Begin work towards DC readout
  - » output mode cleaner
  - » offset locking of arms
  - » Tuning of homodyne phase



Contents

- Over view of 40meter prototype
- Signal extraction for Advanced LIGO
- Lock acquisition of Dual Recycled Michelson (DRMI)
- Off-resonant lock of arm cavities with DRMI

Dual Recycling Summation cavity for End to End model

Calculation time is determined by shortest cavity (Michelson) length.

$$\tau = \frac{L_{\mathrm{arm}}}{c} >> \frac{l_{\mathrm{Mi}}}{c}$$

Calculating many time steps at once in Michelson part

➡ Summation cavity

$$\left.\begin{aligned} E(t) &= \mathbf{M}\cdot E(t-\tau) \\ &= \mathbf{M}^2\cdot E(t-2\tau) \\ &\mathrm{M} \\ &= \mathbf{M}^N\cdot E(t-N\tau) \end{aligned}\right\}$$

N step

⬇

1 step

$$N = \frac{L_{\mathrm{arm}}}{l_{\mathrm{MI}}}$$

$$\mathbf{M} = \mathbf{M}_0 + \delta\mathbf{M}$$

$\mathbf{M}$: matrix for DR summation cavity

$$\mathbf{M}_0\cdot\delta\mathbf{M} \neq \delta\mathbf{M}\cdot\mathbf{M}_0$$

$\mathbf{M}$: scalar for PR summation cavity

$$\mathbf{M}_0\cdot\delta\mathbf{M} = \delta\mathbf{M}\cdot\mathbf{M}_0$$

- 400 times faster for LIGO
- 40 times faster for 40meter

40m Team

On the payroll: Ben Abbott, Osamu Miyakawa, Bob Taylor, Steve Vass, Alan Weinstein

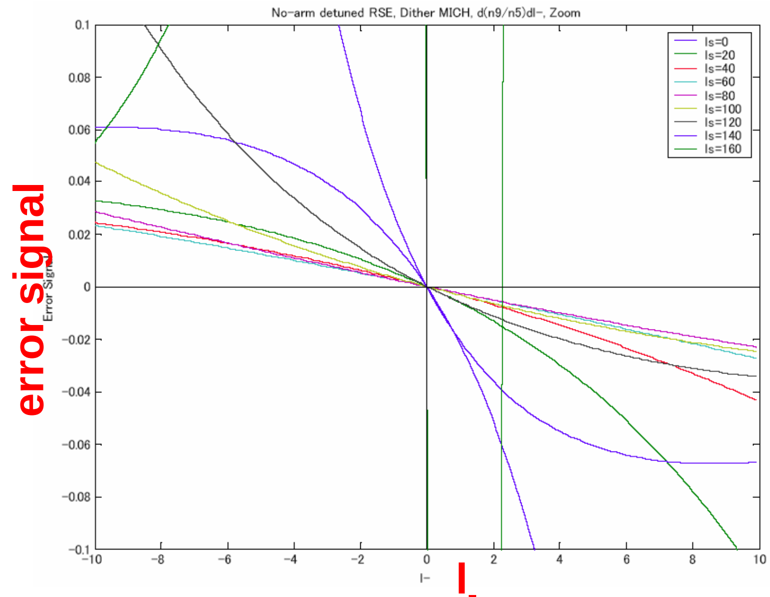
Grad students: Lisa Goggin, Rob Ward

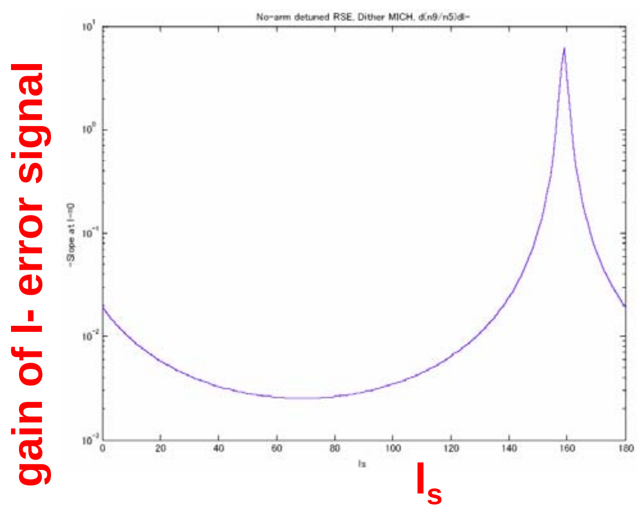
LIGO engineering support: Jay Heefner, Rolf Bork, Alex Ivanov, Flavio Nocera, Michael Smith, Lisa Bogue, many others

Visitors: Seiji Kawamura, Fumiko Kawazoe, Shihori Sakata, Bryan Barr, Sascha Schediwy, Kentaro Somiya, Rana Adhikari (Hartmut Grote of GEO arrives Oct 1)

Gain of dither locking signal

- l- dither locking signal gain depends strongly on ls
- But polarity of signal is always the same
- Can handle this with a limiter…
- l- dither locking signal doesn't depend on l+ at all!
- Signal is degraded by presence of RF sidebands… turn them down low (Γ<0.02) to acquire dither lock, then ramp them back up.





First lock of Dual recycled Michelson

Lock now:	Control later:
l_- : dither @AP	→ DDM@AP
l_+ : 33@SP	→ DDM@SP
l_s : DDM@SP	→ DDM@PO

l_s lock at -5.2 sec

l_- lock at -5.3 sec

l_+ lock at -5.6 sec

Control room