# Optical Springs at the 40m

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for the 40m Team

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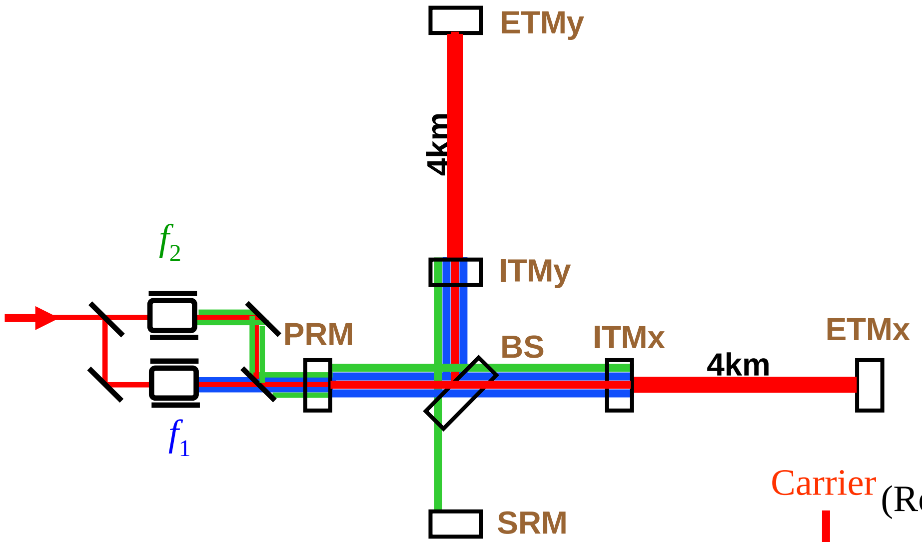
# Caltech 40 meter prototype interferometer

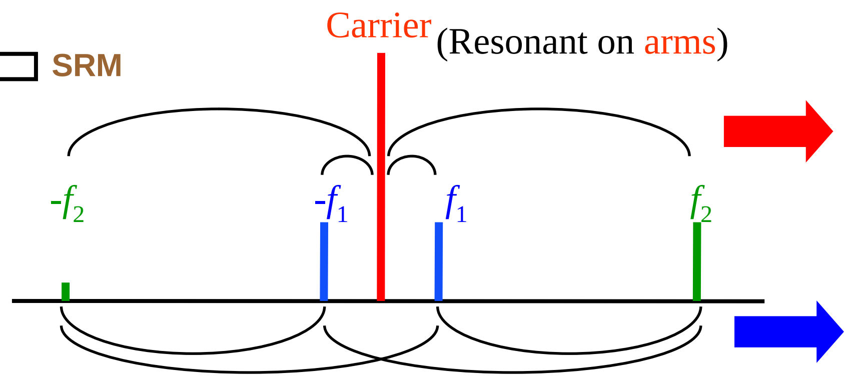
## An interferometer as close as possible to the Advanced LIGO optical configuration and control system

- Detuned Resonant Sideband Extraction (DRSE)
- Power Recycling
- Suspended mass
  - Single pendula
- Digital controls system
- Same cavity finesse as AdLIGO baseline design
  - 100x shorter storage times.

# 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

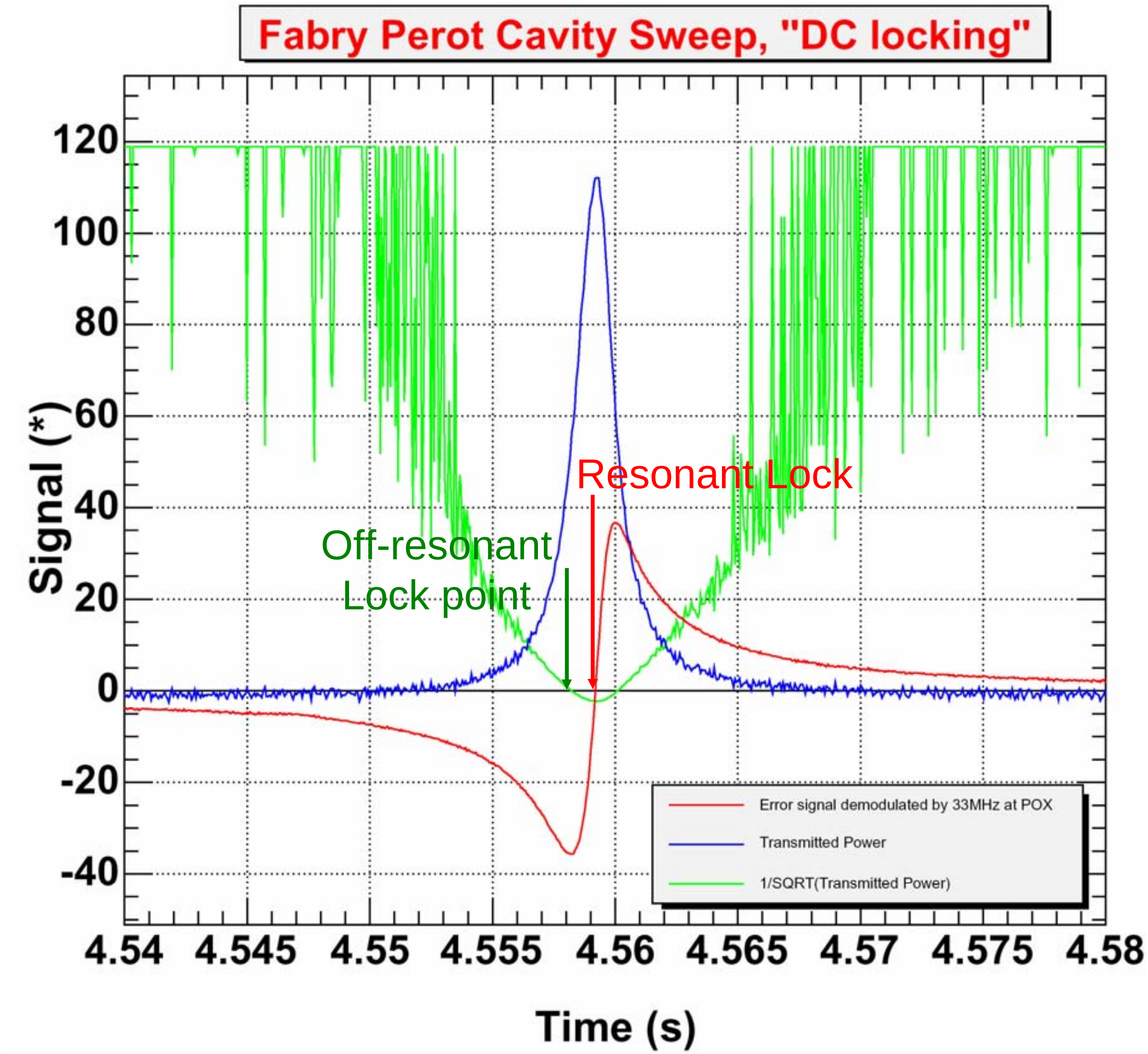
- Double demodulation
- Central part information

- 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.

# The Story So Far

To understand why we saw the optical springs in the way we have, it helps to know the story of Lock Acquisition at the 40m.

# 40m Lock Acquisition part I:
# Off-resonant lock scheme for a single cavity

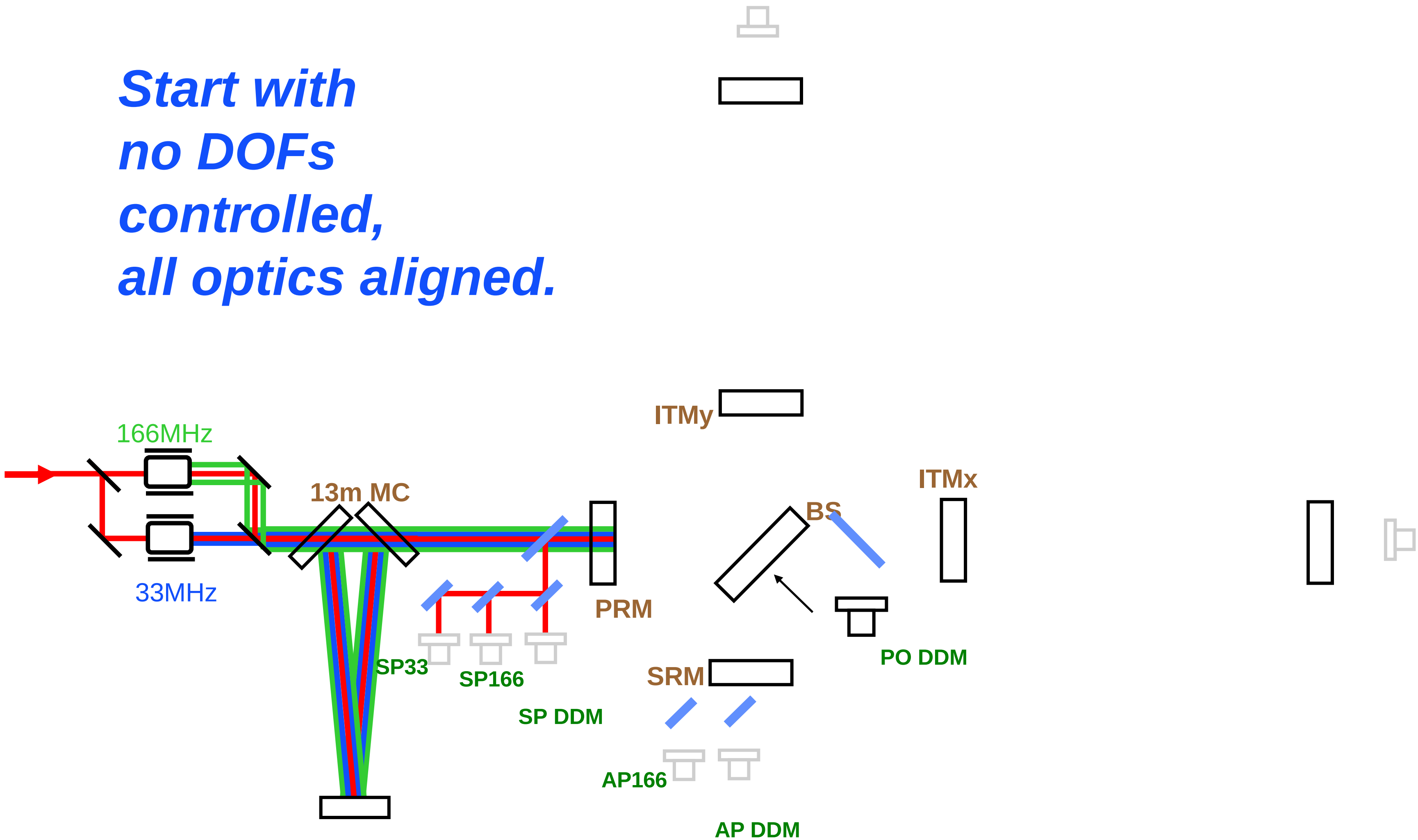



Transmitted light is used as

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

# 40m Lock acquisition procedure

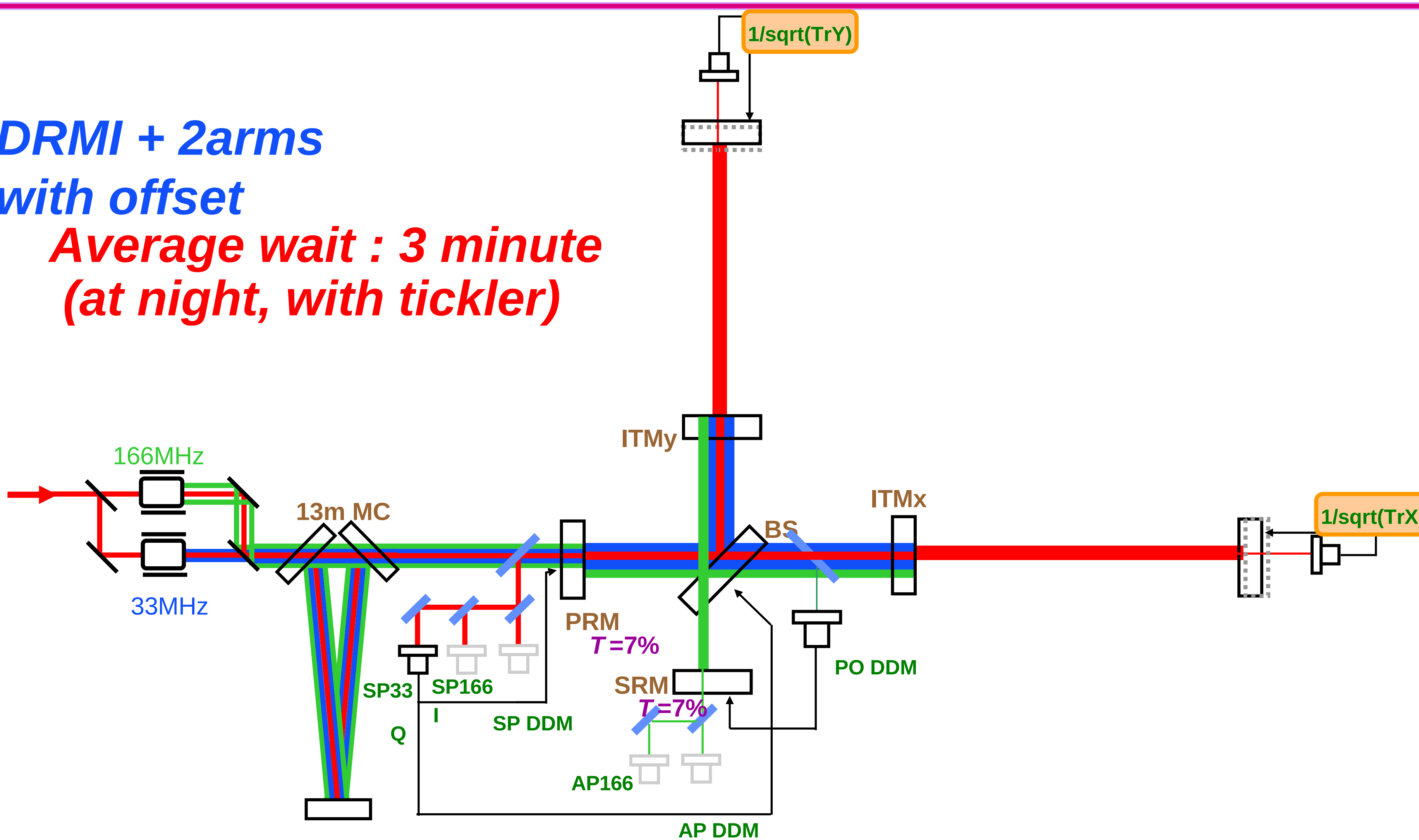
***Start with no DOFs controlled, all optics aligned.***



# 40m Lock acquisition procedure

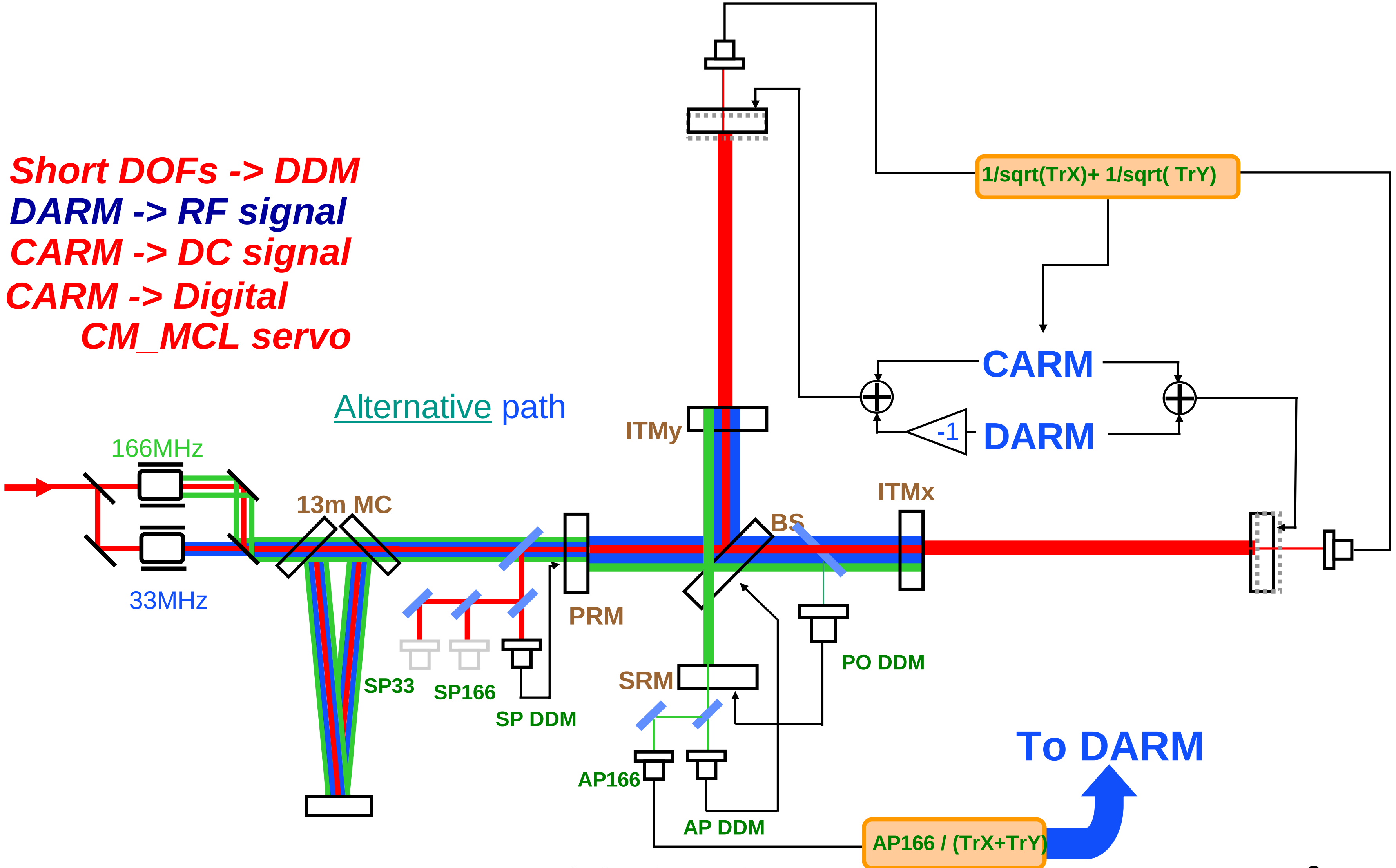
***DRMI + 2arms with offset***

***Average wait : 3 minute (at night, with tickler)***



# 40m Lock acquisition procedure

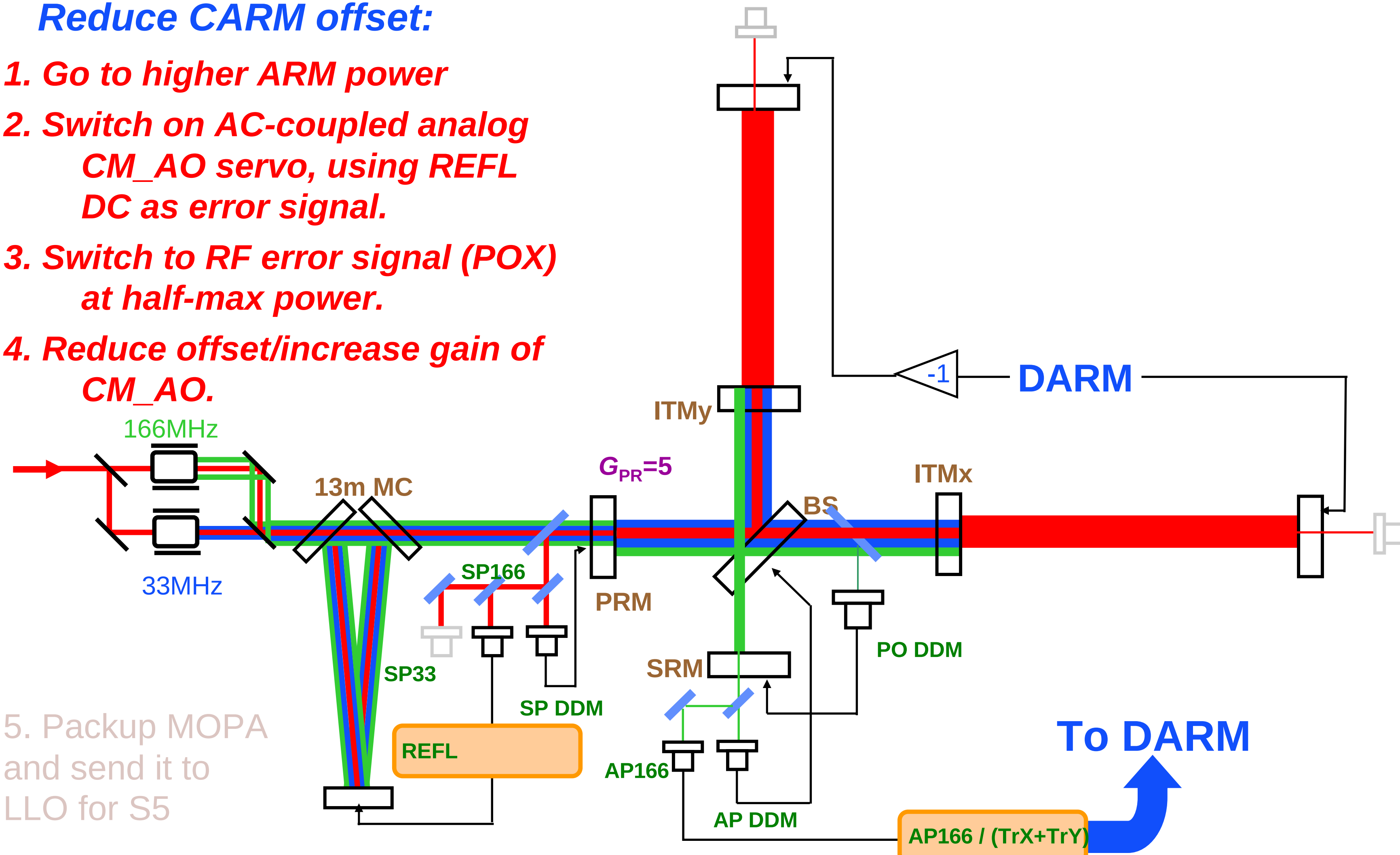
***Short DOFs -> DDM***
***DARM -> RF signal***
***CARM -> DC signal***
***CARM -> Digital CM_MCL servo***



# 40m Lock acquisition procedure

***Reduce CARM offset:***

1. ***Go to higher ARM power***
2. ***Switch on AC-coupled analog CM_AO servo, using REFL DC as error signal.***
3. ***Switch to RF error signal (POX) at half-max power.***
4. ***Reduce offset/increase gain of CM_AO.***




5. Packup MOPA and send it to LLO for S5

# Optical spring in detuned RSE

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

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

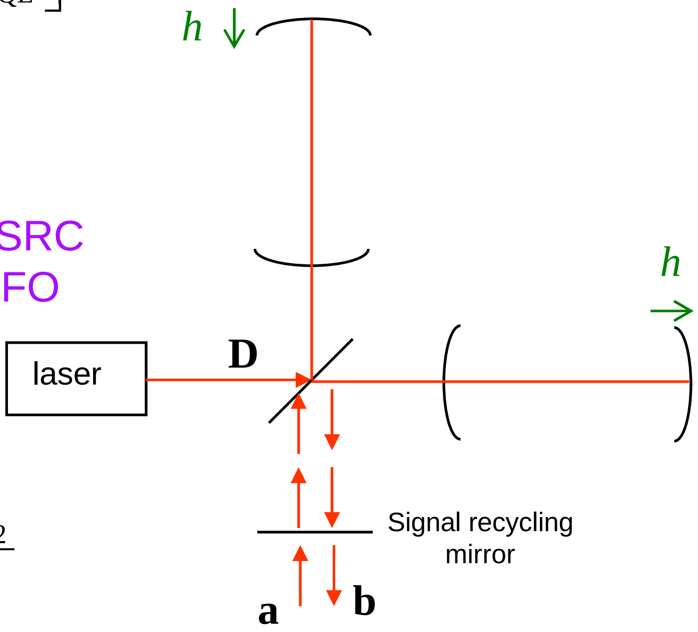
**a** :input vacuum
**b** :output
**D** :
*M* :
*h* :strain

$h_{\mathrm{SQL}}$:standard quantum limit
$\tau$: transmissivity of SRM
$\kappa$: coupling constant
$\Phi$: GW sideband phase shift in SRC
$\beta$: GW sideband phase shift in IFO

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

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

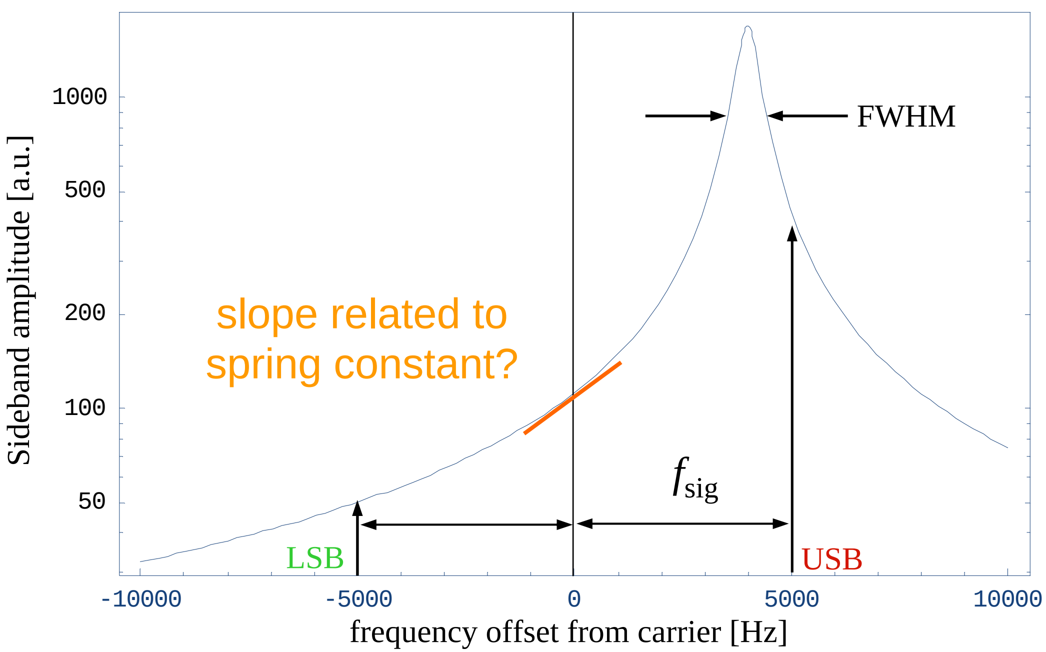
$\zeta$: homodyne phase




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

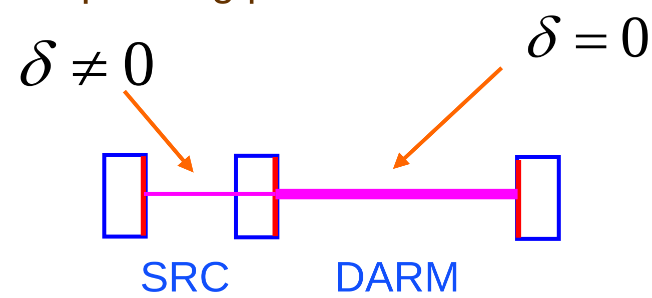
# Detune Cartoon

IFO DARM/CARM

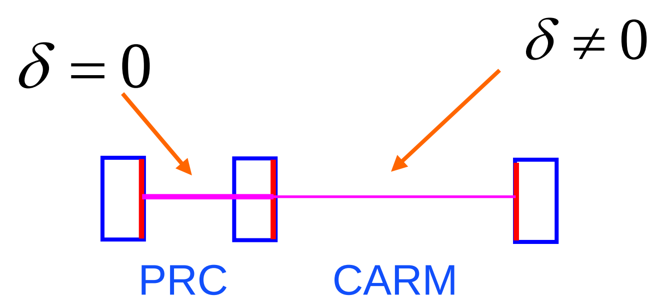



•Responses of GW USB and GW LSB are different due to the detuning of the signal recycling cavity.

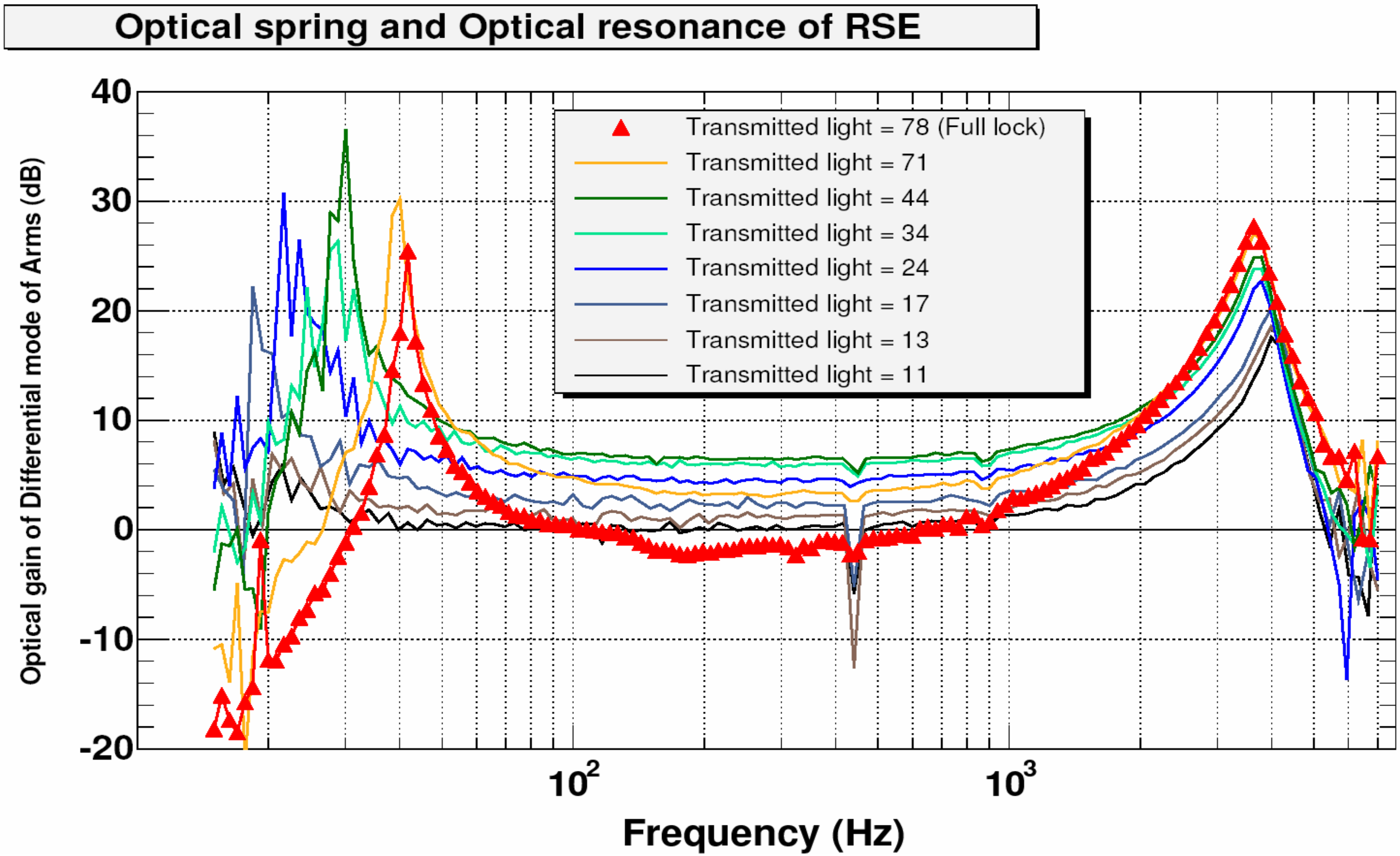
•IFO Differential Arm mode is detuned from resonance at operating point




•IFO Common Arm mode is detuned from resonance at intial locking point

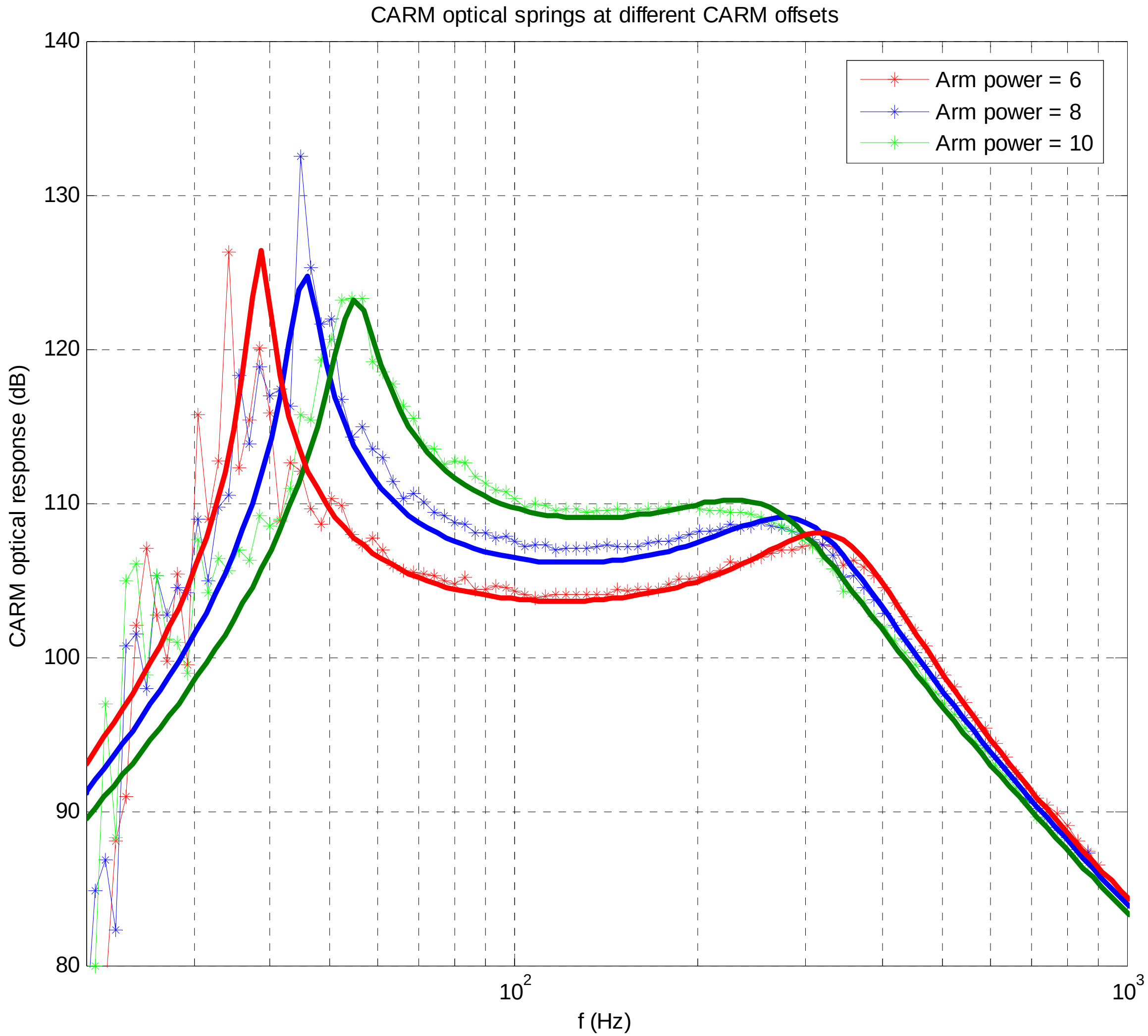


# DARM TFs as CARM offset is reduced

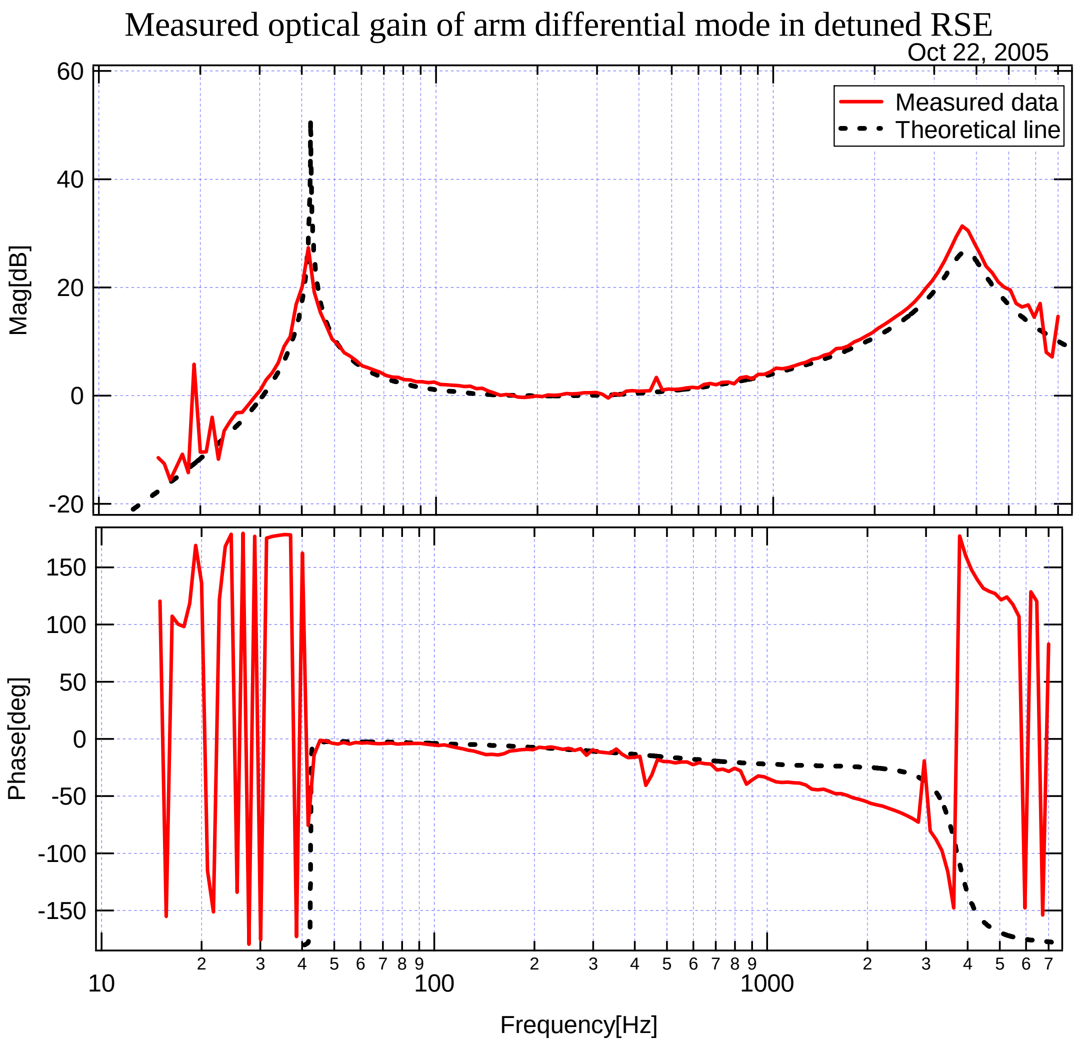


# CARM optical springs

- Solid lines are from TCST
- Stars are 40m data
- Max Arm Power is ~80
- Also saw CARM anti-springs, but don't have that data



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

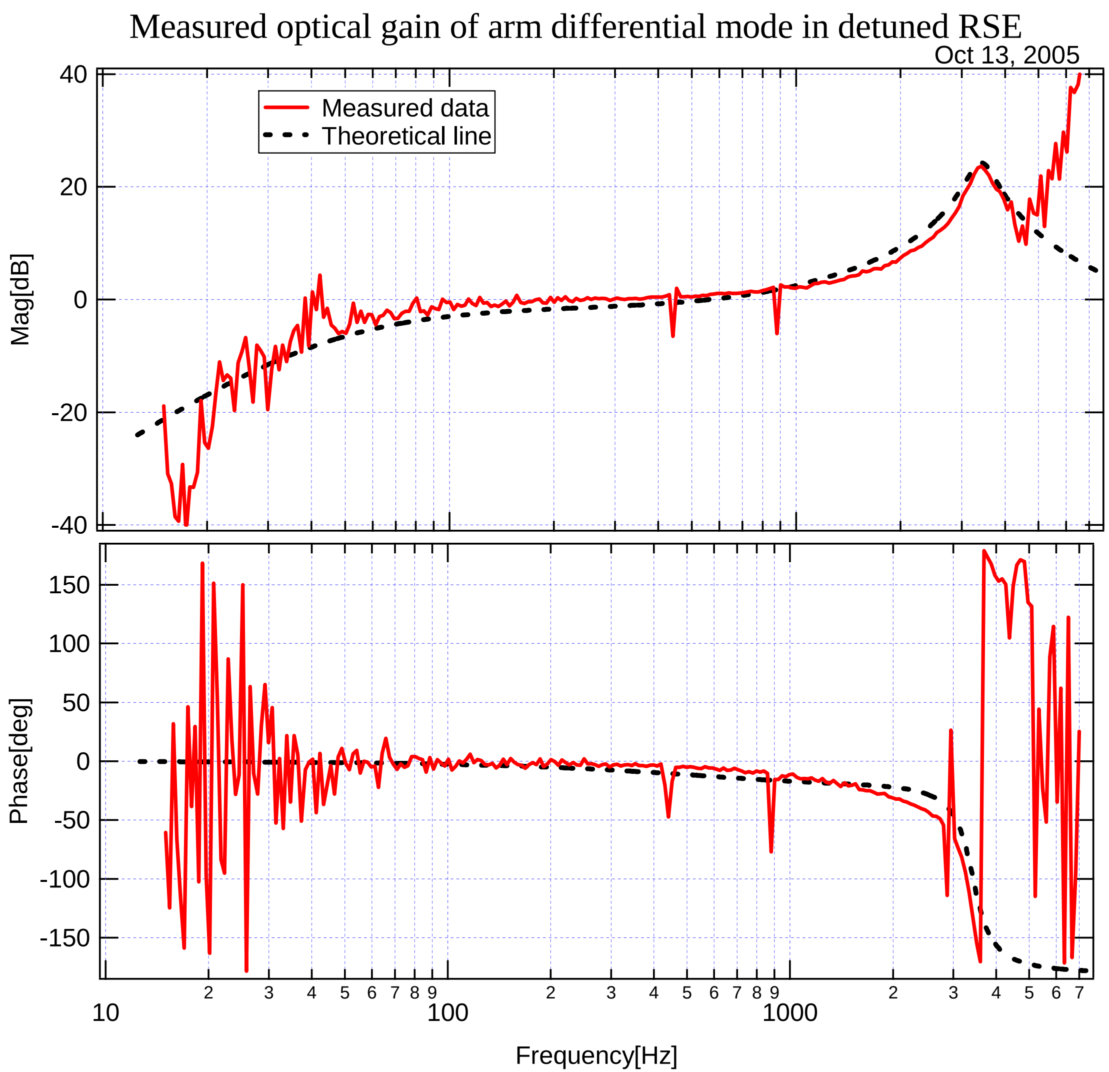



- Optical gain of *L*- loop
  DARM_IN1/DARM_OUT divided by pendulum transfer function

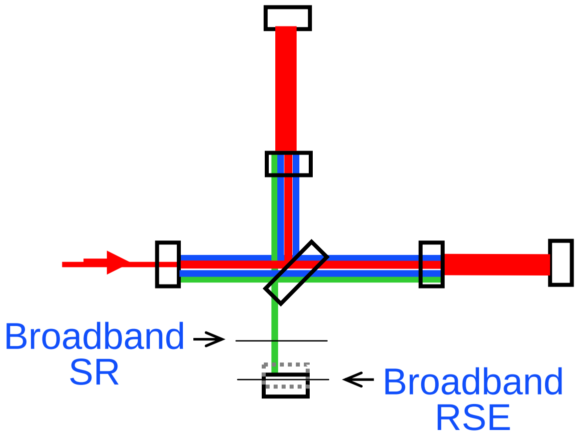
- Optical spring and optical resonance of detuned RSE were measured.
- Frequency of optical spring depends on cavity power, mass, detuning phase of SRC.
- Frequency of optical resonance depends on detuning phase of SRC.

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

# Positive spring constant



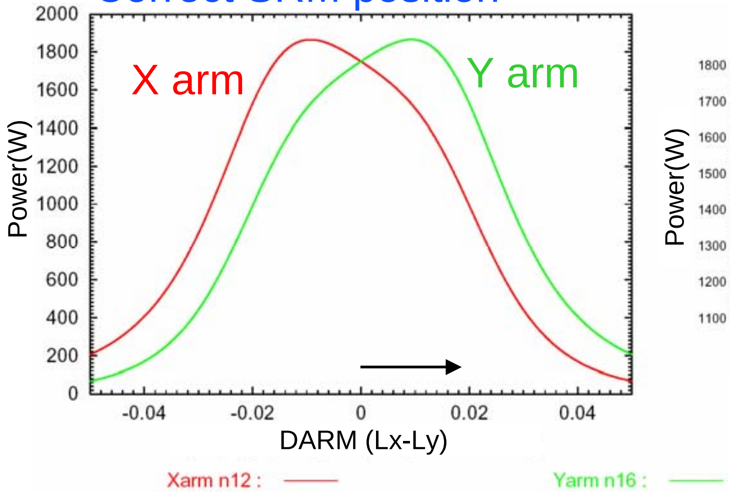

- SRM is locked at opposite position from anti-resonant carrier point(BRSE).
- Optical spring disappeared due to positive spring constant.



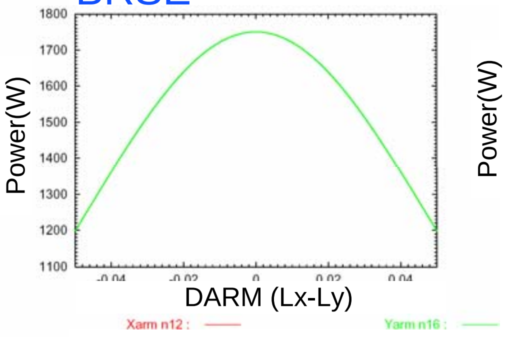
# Simple picture of optical spring in detuned RSE

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

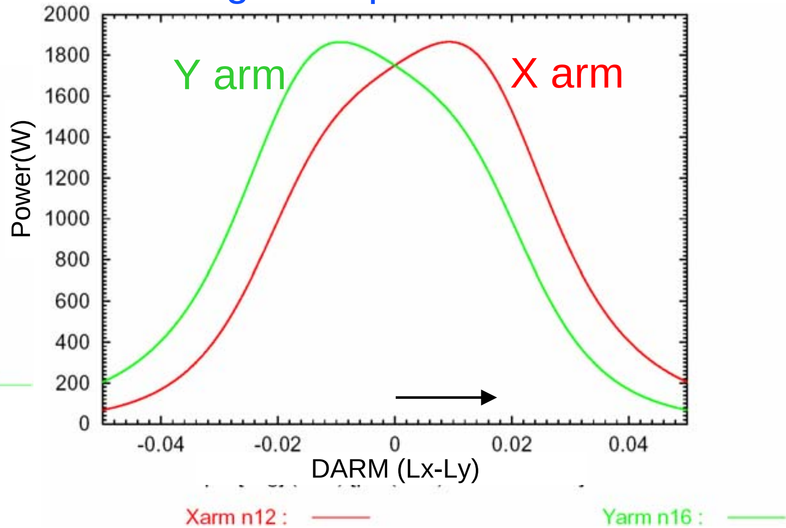
Correct SRM position




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)

# Relationship between the CARM and DARM springs at the 40m

- With the 40m Lock Acquisition scheme, we only see a CARM spring if there’s also a DARM spring.
- Details tomorrow

•Using the DC-locking scheme for the arms, there are, prima facie, four locking points corresponding to the four possible gain combinations, but only two will acquire lock.

Correct SRM position

| Xarm | Yarm | DARM | CARM |
|---|---|---|---|
| + | + | x | x |
| - | - | 0 | + |
| + | - | x | x |
| - | + | + | - |

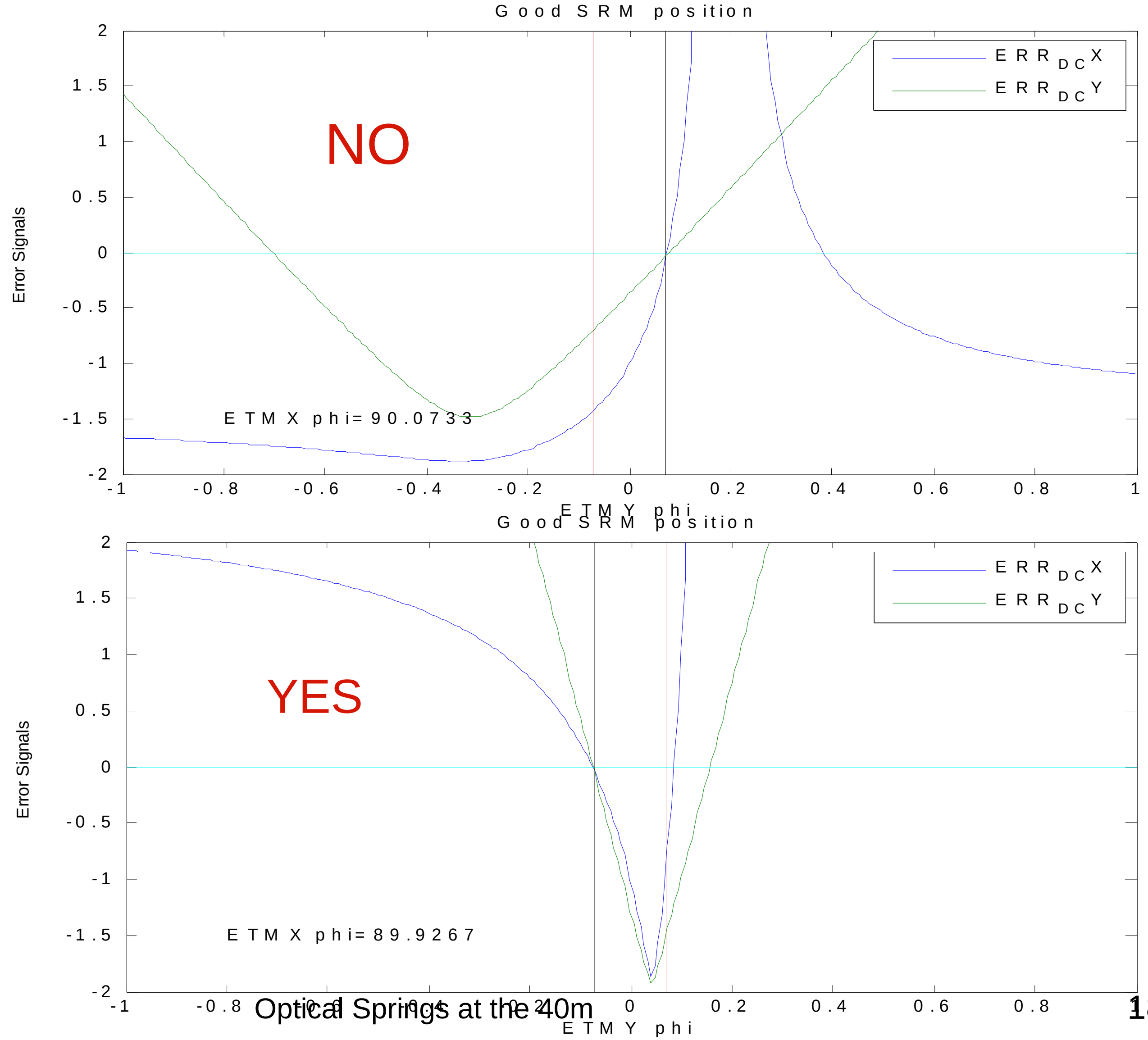
Incorrect SRM position

| Xarm | Yarm | DARM | CARM |
|---|---|---|---|
| + | + | 0 | - |
| - | - | x | x |
| + | - | - | + |
| - | + | x | x |

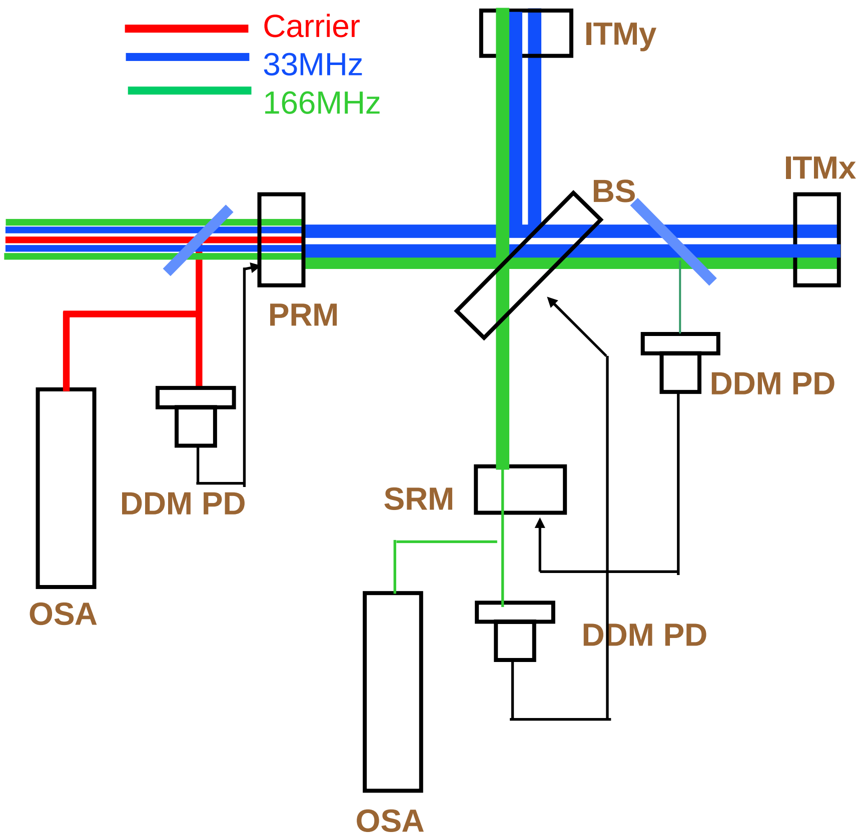
# Will it lock?

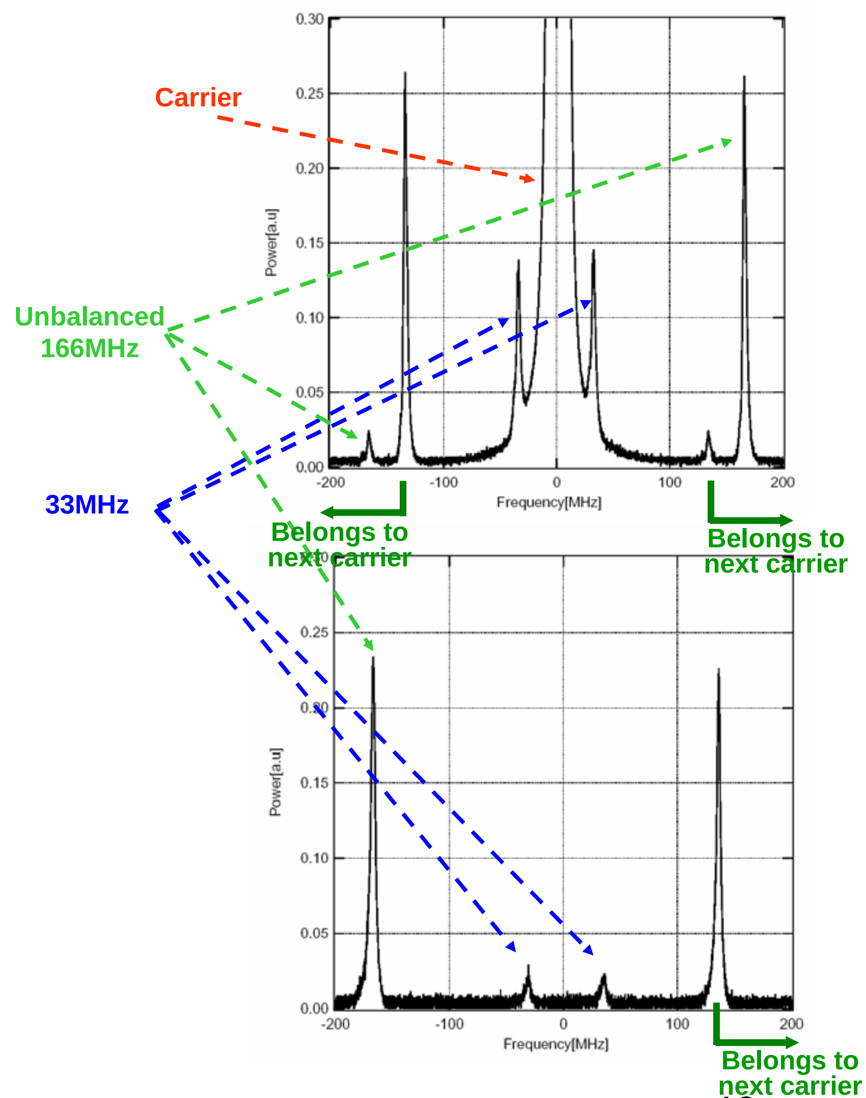
- x-axis: EY position
- y-axis: signal
- blue: X err
- green: Y err
- black: DARM
- red: CARM

modeled with FINESSE



# DRMI lock using double demodulation with unbalanced RF sideband in SRC

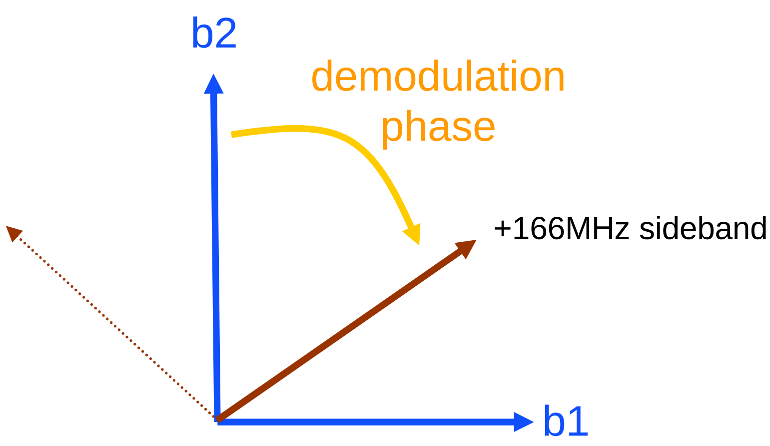


# Unbalanced Sideband Detection

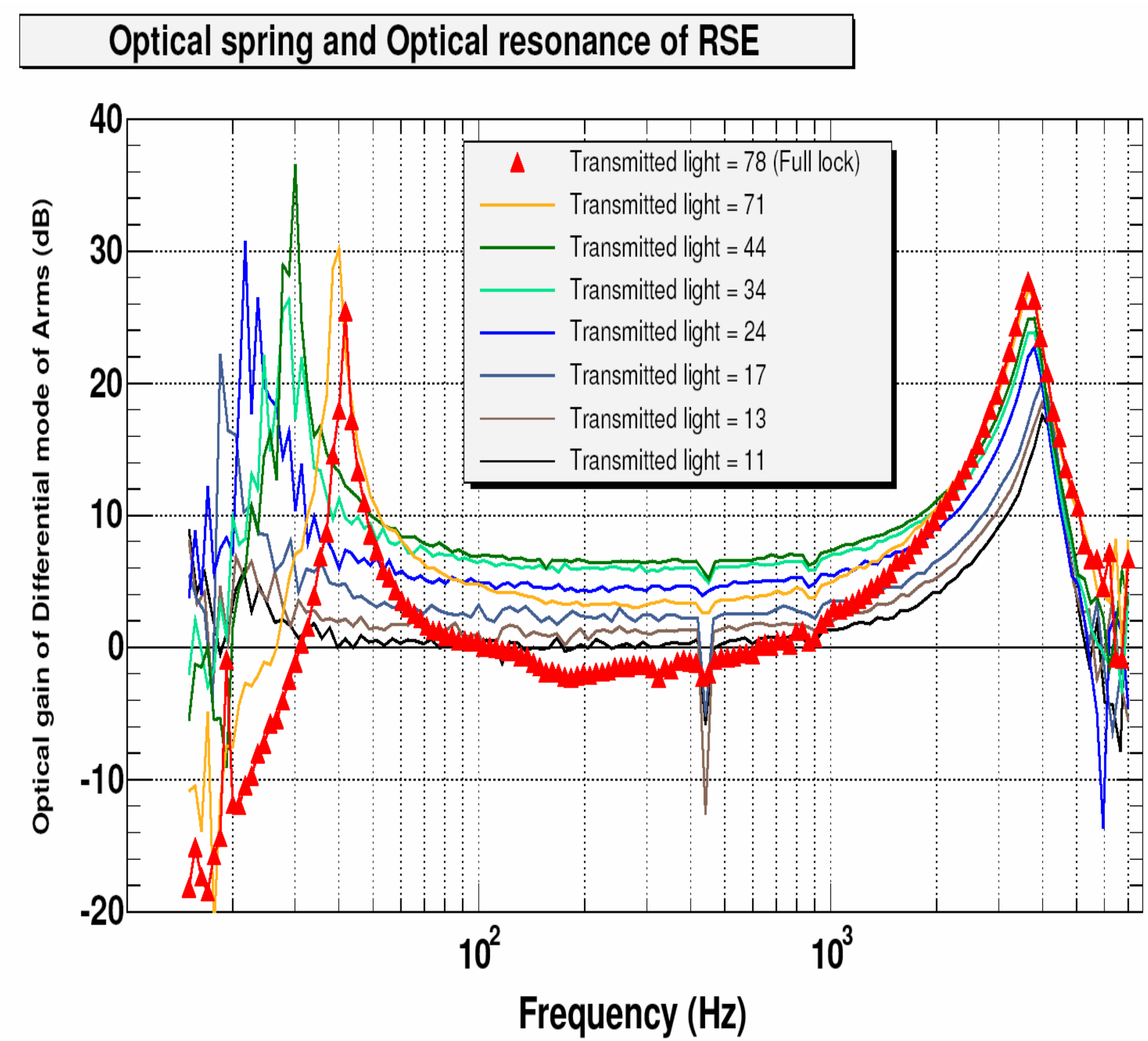
❖Can not be used to circumvent the standard quantum limit, due to heterodyne noise

❖Can be used to change the measurement quadrature, and thus reshape the GW response




- Kentaro Somiya "Photodetection method using unbalanced sidebands for squeezed quantum noise in a gravitational wave interferometer" *PHYSICAL REVIEW D* 67,122001 2003
- A. Buonanno, Y. Chen, N. Mavalvala, "Quantum noise in laser-interferometer gravitational-wave detectors with a heterodyne readout scheme" *PHYSICAL REVIEW D* 67,122005 2003

# Changing the DARM quadrature

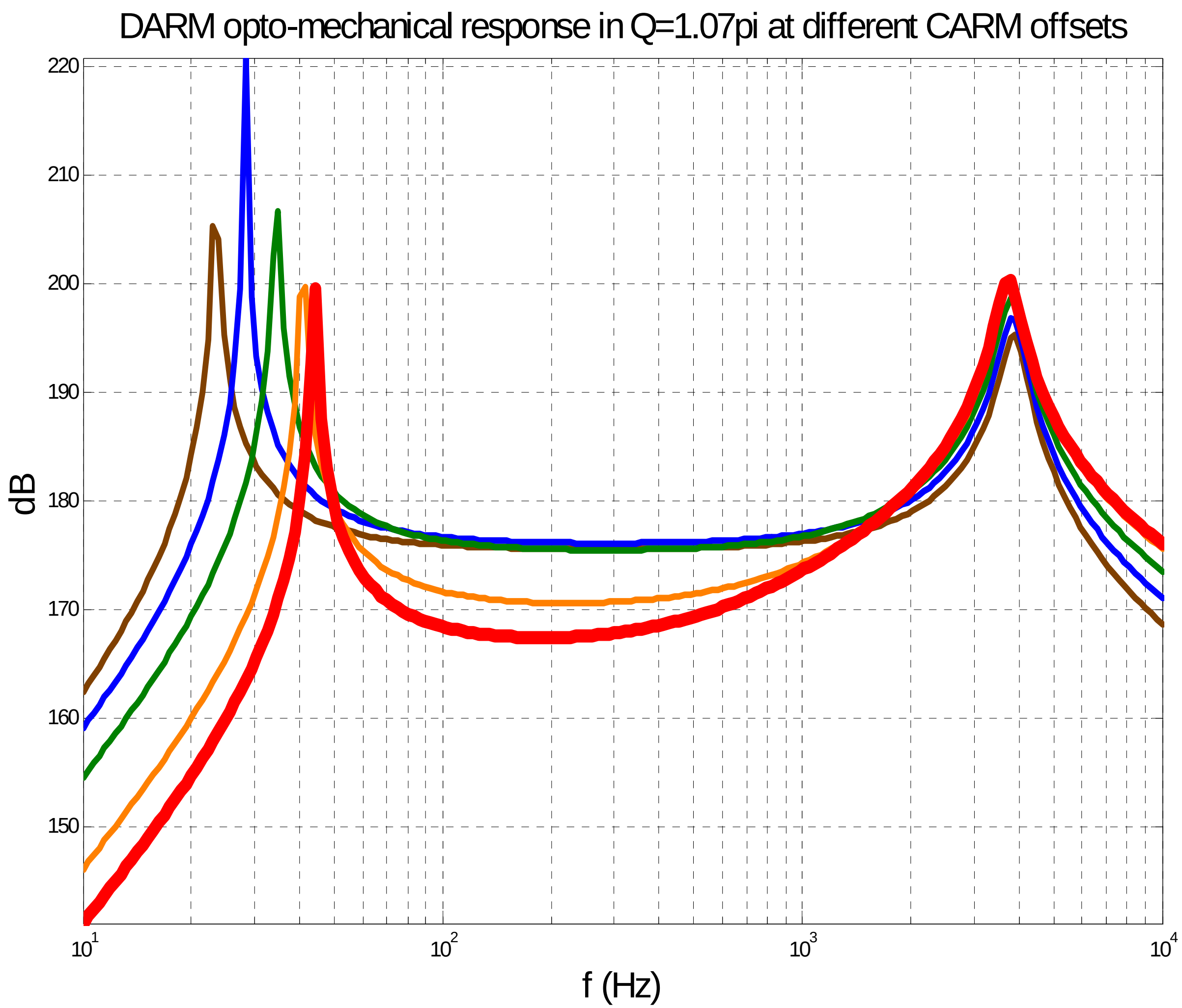



Story:

1. Lock IFO with CARM offset
2. Handoff DARM to RF
3. Adjust RF demodulation phase
4. Reduce CARM offset
5. This changes the quadrature of the signal. As we are not compensating for this by adjusting the demod phase, the shape of the response changes.

May also be some overall gain change due to imperfect normalization

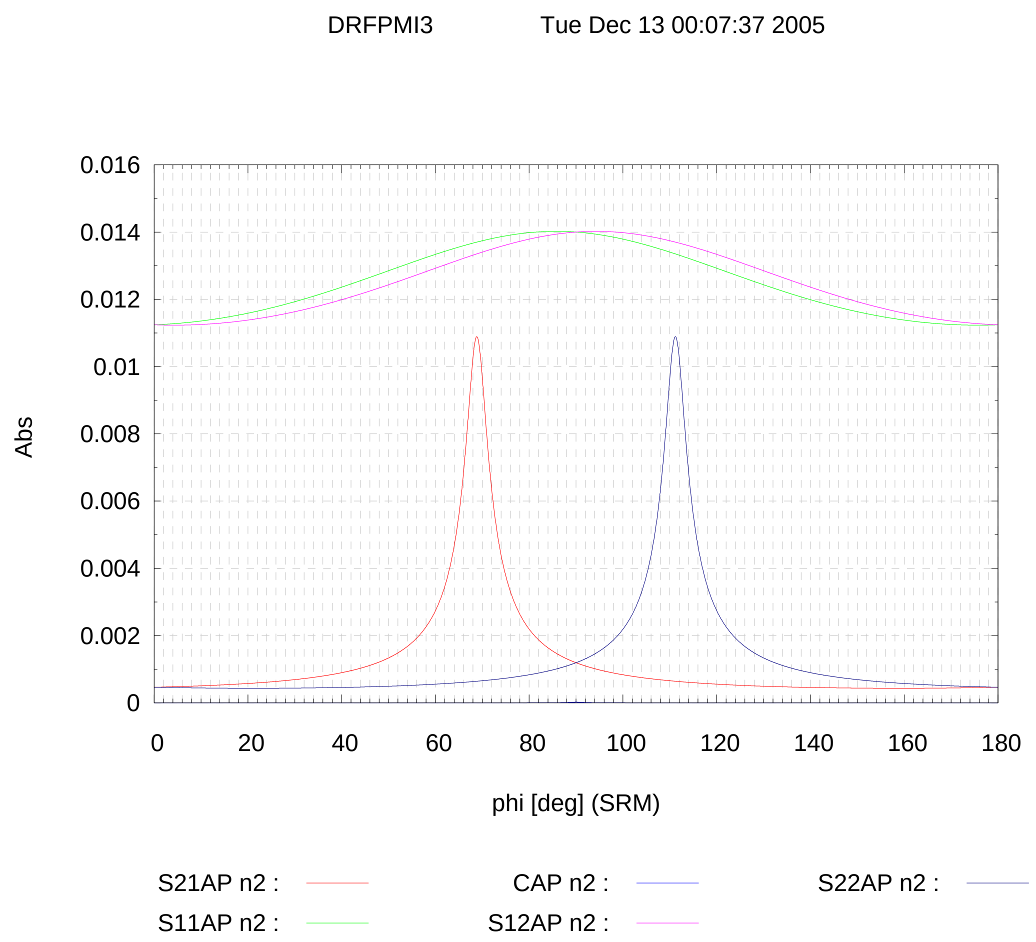
# Optickle Results




- GW response in a single, chosen quadrature at multiple CARM offsets

# Why is the correct SRM position harder to lock?

- The correctly detuned SRC doesn't lock as easily as the oppositely tuned SRC
- True for both full IFO and just the DRMI (though less noticeable on DRMI)
- For full IFO, lock time goes from 1 to 5 minutes.
- Have we just not tuned-it-up it right yet?



# Mode healing/injuring at Dark Port

Negative spring constant
with optical spring

Carrier power at DP is 10x smaller

Positive spring constant
with no optical spring

- Repeatable
- The same alignment quality

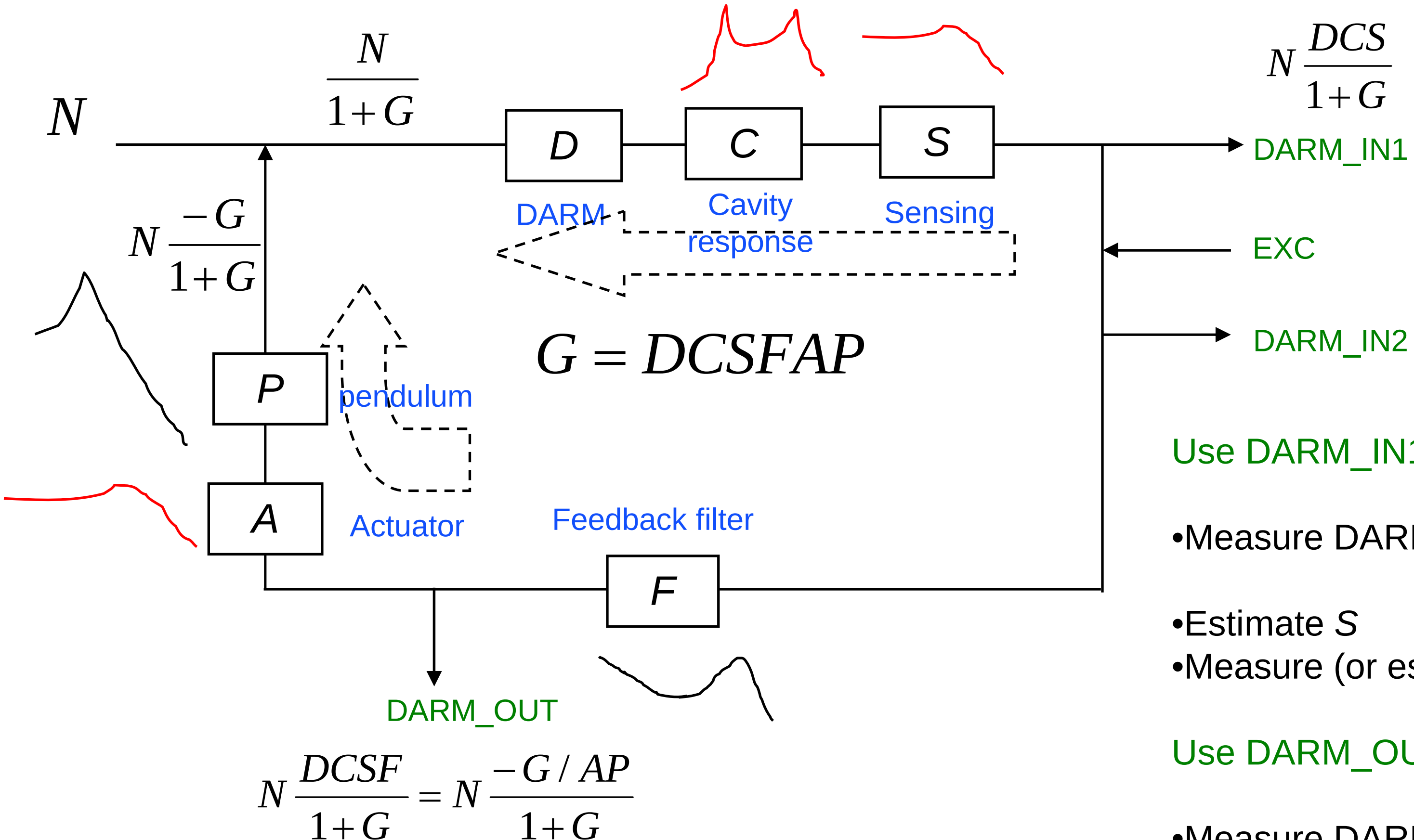
# Compensating the resonances

Compensation Filters for the various resonances:

UGFs ~ 250Hz

| | Optical | Opto-mechanical |
|---|---|---|
| DARM | 4kHz >> UGF<br>no compensation<br>AdLIGO: 180 Hz ~ UGF | 40Hz < UGF<br>no compensation<br>AdLIGO: 70Hz? |
| CARM | 1kHz -> 100Hz ~ UGF<br>dynamic compensation | 0->100Hz ~ UGF<br>not coherently compensated |

# DARM loop: Calibration questions




Use DARM_IN1

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

Use DARM_OUT

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