Impressions of CARM/ALS

J. Kissel, for the people way smarter than me.

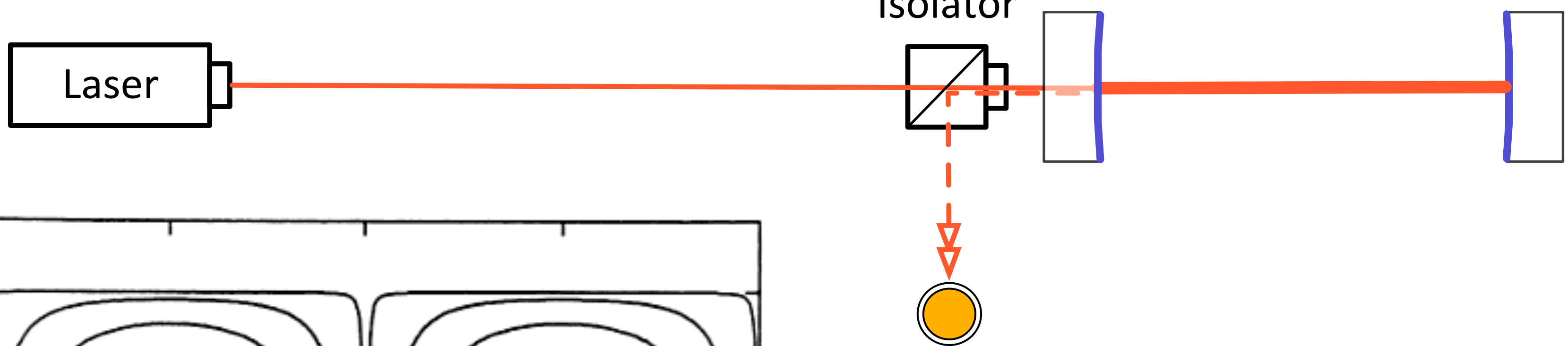
Primer

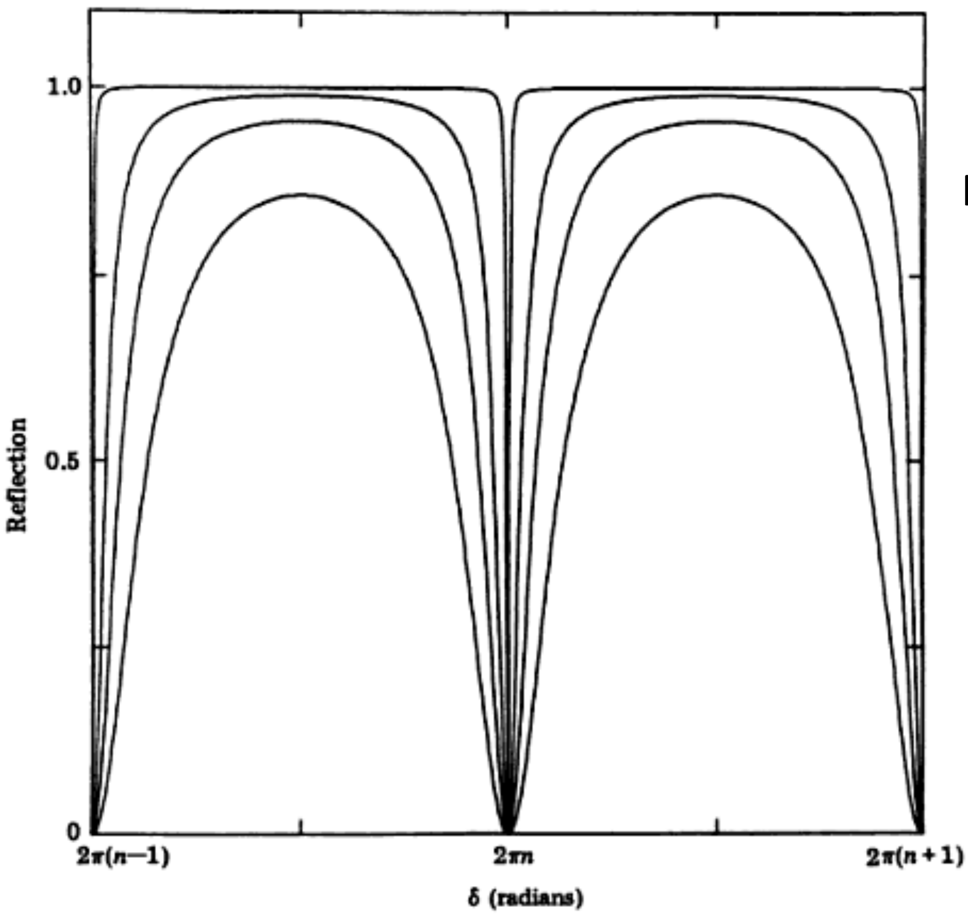
The development of CARM/ALS spans many decades, many people, and many subsystems, so documentation isn't always consistent and it's tough to find the big picture with everything included in one place. This is my attempt. It's too ambitious for one talk that I wrote in a day. Please also bare in mind

- I'm just getting to know this system
- This system is still under development
  - some documentation is out-of-date
  - two sites do things differently
- This presentation will not be perfect
- Go to references for guidance, they've done a better job.

Thanks for your patience.

Intro to Cavity "Locking"





Resonant cavity resonates, when cavity length is an integer number of laser wavelengths

$$2L = N\lambda$$

More reflective mirrors
= Tighter resonance condition

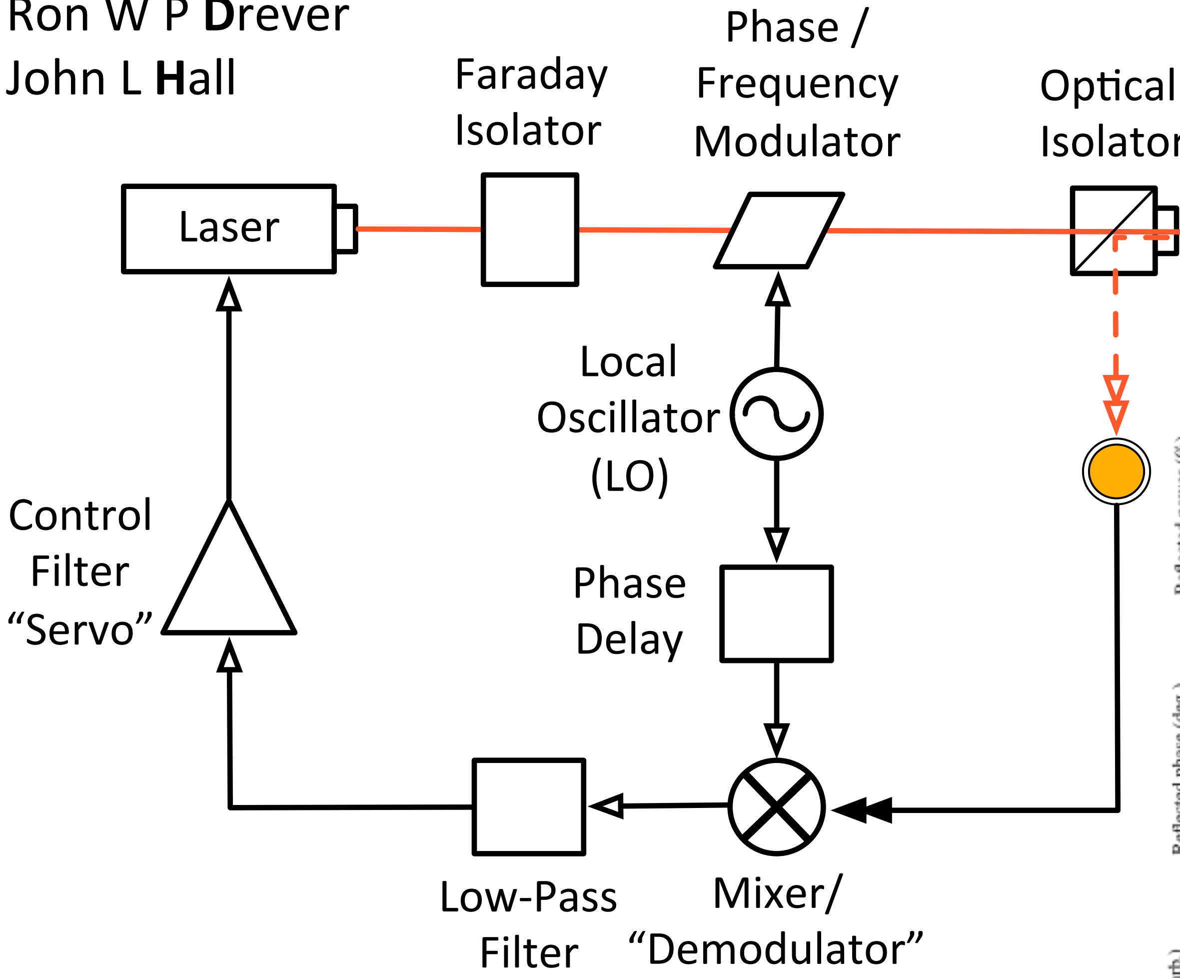
Equivalent noise sources to this system:
cavity length changes or
laser frequency/wavelength changes

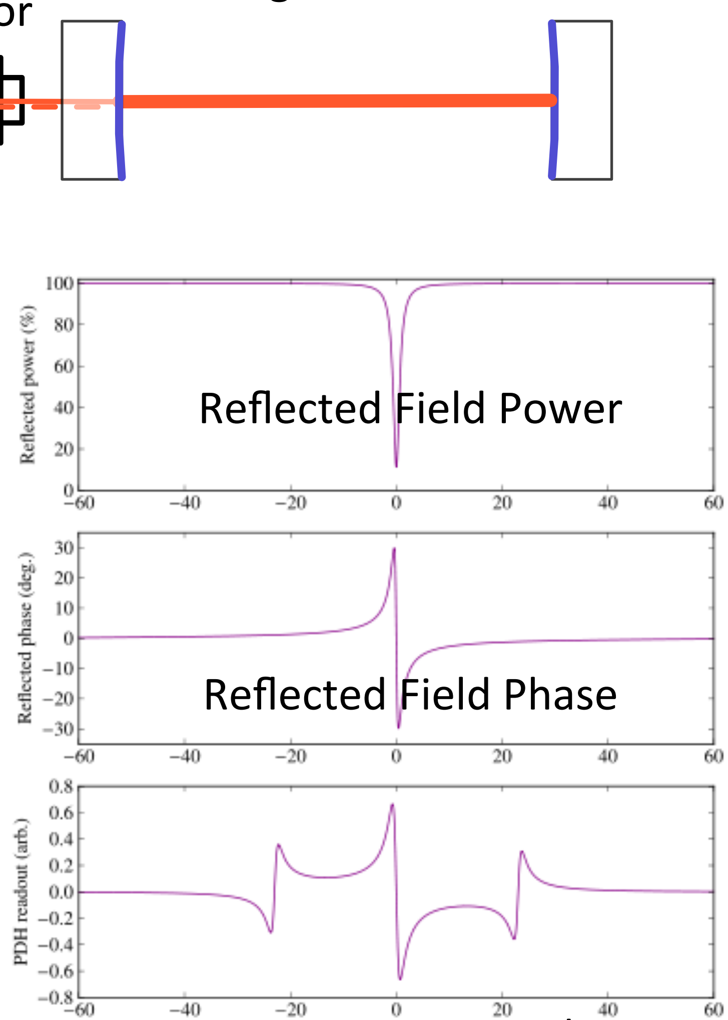
$$\Delta L = \frac{L\lambda}{c}\Delta f$$

Intro to PDH

Robert V. **P**ound
Ron W P **D**rever
John L **H**all

Locks laser frequency to resonant cavity, following the length of the cavity as it changes



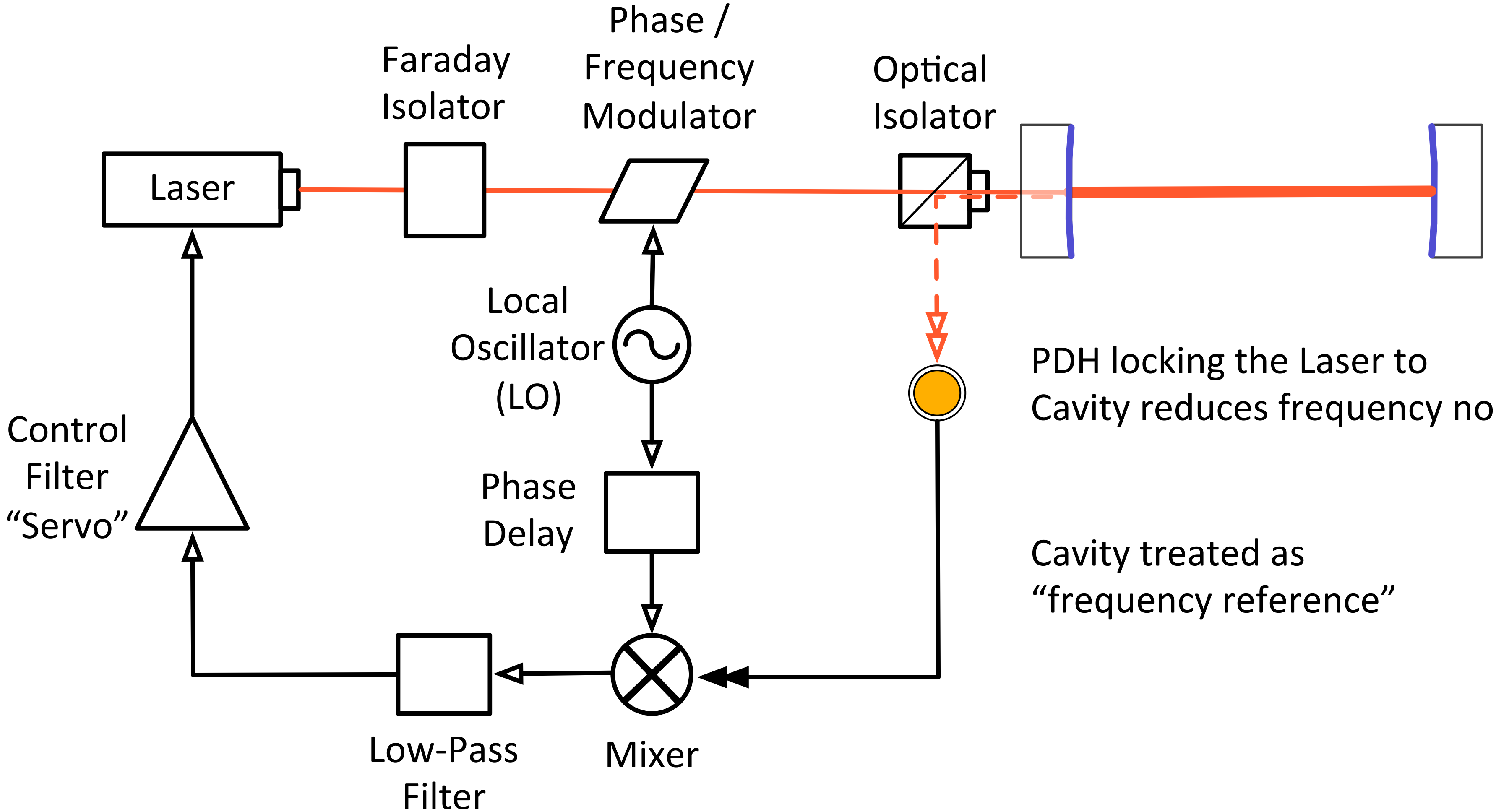


PDH Error Signal
Non-linear in regions outside cavity linewidth

“Lock acquisition” or “catch (and hold) lock”
= Length changes slower than the control bandwidth

Control servo holds the laser frequency within linear operating regime

Intro to PDH



PDH locking the Laser to Cavity reduces frequency noise

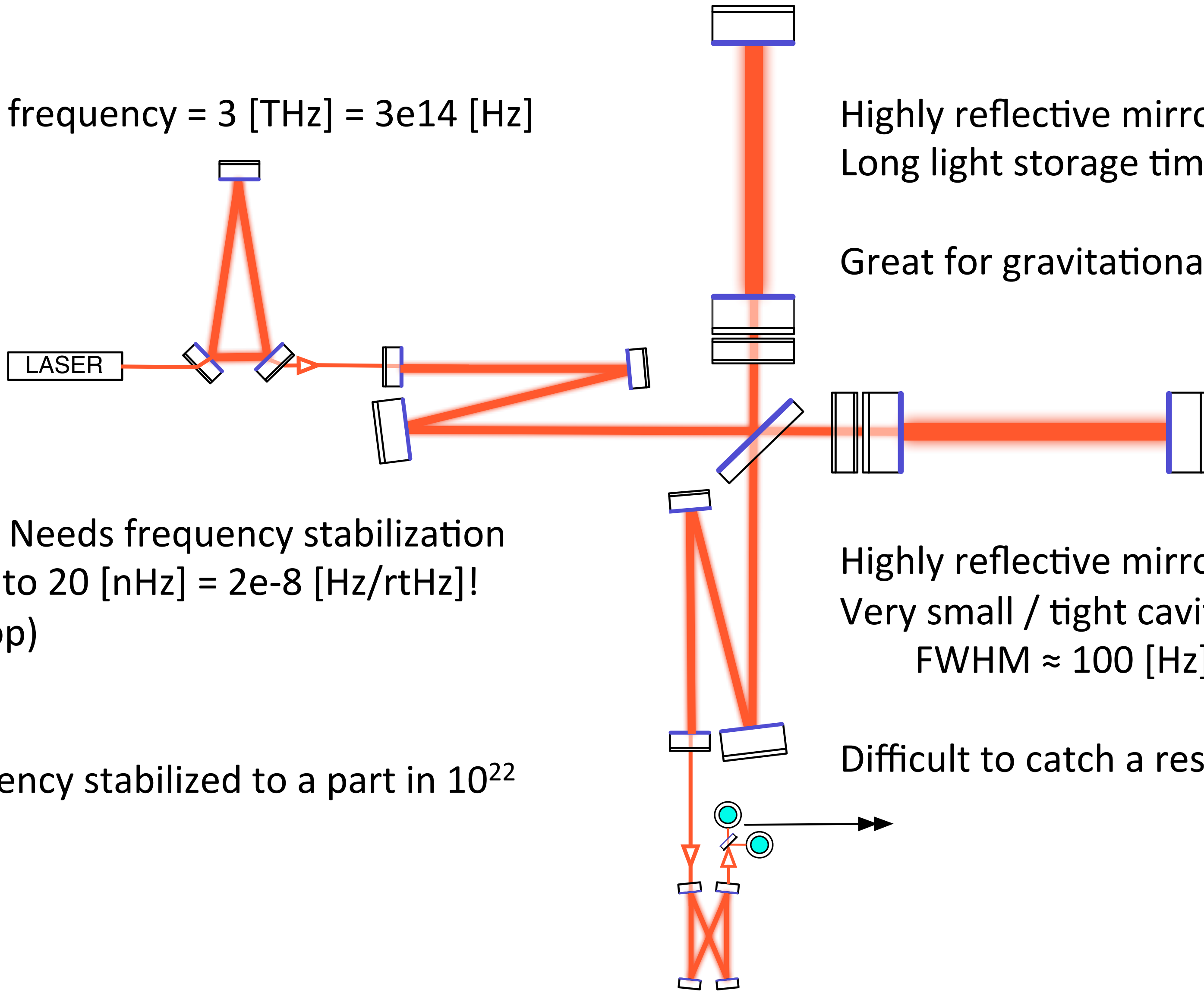
Cavity treated as "frequency reference"

$$\Delta L \frac{c}{L\lambda} = \Delta f$$

The LONGER the cavity, and/or the SMALLER the length changes, the better the frequency reference, the lower the frequency noise

The LIGO Arm Cavity Problem

Laser frequency = 3 [THz] = 3e14 [Hz]



Highly reflective mirrors
Long light storage time

Great for gravitational wave detection

aLIGO Needs frequency stabilization
down to 20 [nHz] = 2e-8 [Hz/rtHz]!
(in loop)

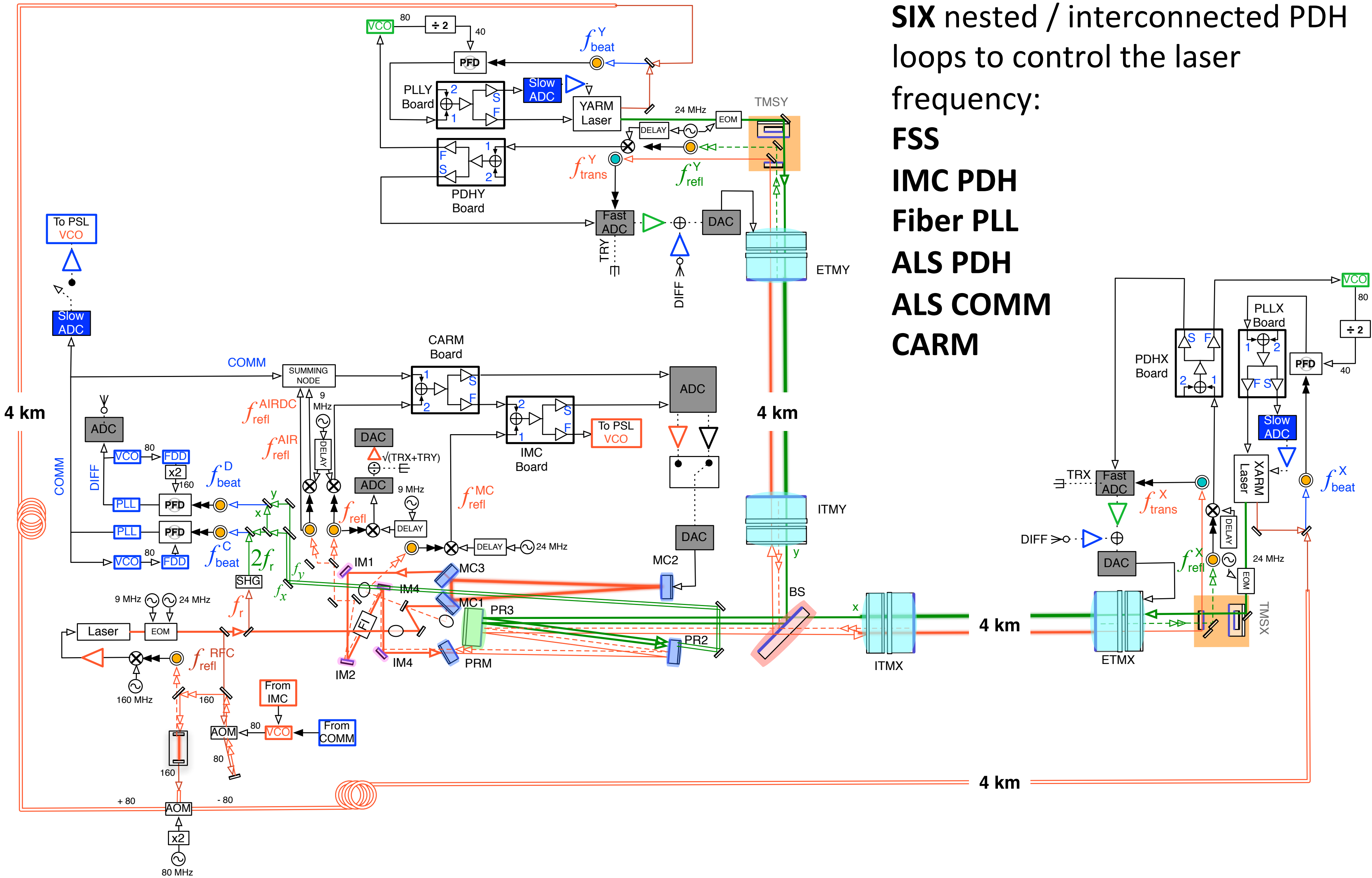
Highly reflective mirrors
Very small / tight cavity line width:
FWHM ≈ 100 [Hz] ≈ 1 [nm]

Frequency stabilized to a part in 10^{22}

Difficult to catch a resonance condition

In order to merge corner station with arms during lock acquisition, while building up frequency stability, we need *LOTS* of loops.

LIGO = PDH to the MAX



SIX nested / interconnected PDH loops to control the laser frequency:

FSS

IMC PDH

Fiber PLL

ALS PDH

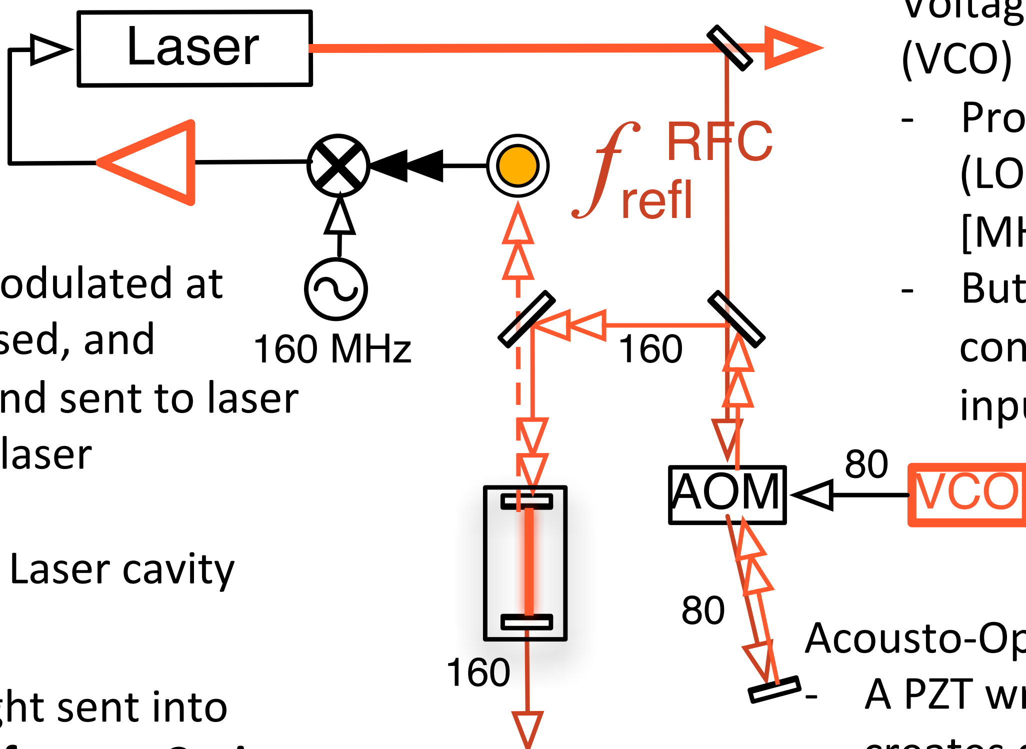
ALS COMM

CARM

FSS
IMC PDH
Fiber PLL
ALS PDH
ALS COMM
CARM

Frequency Stabilization Servo

Just a fancy PDH loop!



Voltage-Controlled Oscillator (VCO)

- Provides local oscillator (LO) frequency at ~80 [MHz]
- But Oscillator Frequency is controllable (via a voltage input) to +/- 1 [MHz]

Photo-diode demodulated at 160 [Hz], low passed, and control filtered, and sent to laser
Low Frequency = laser temperature
High Frequency = Laser cavity length

Light sent into **Reference Cavity**

- L ≈ 0.5 [m]
- In a vacuum can on the PSL

Acousto-Optic Modulator (AOM)

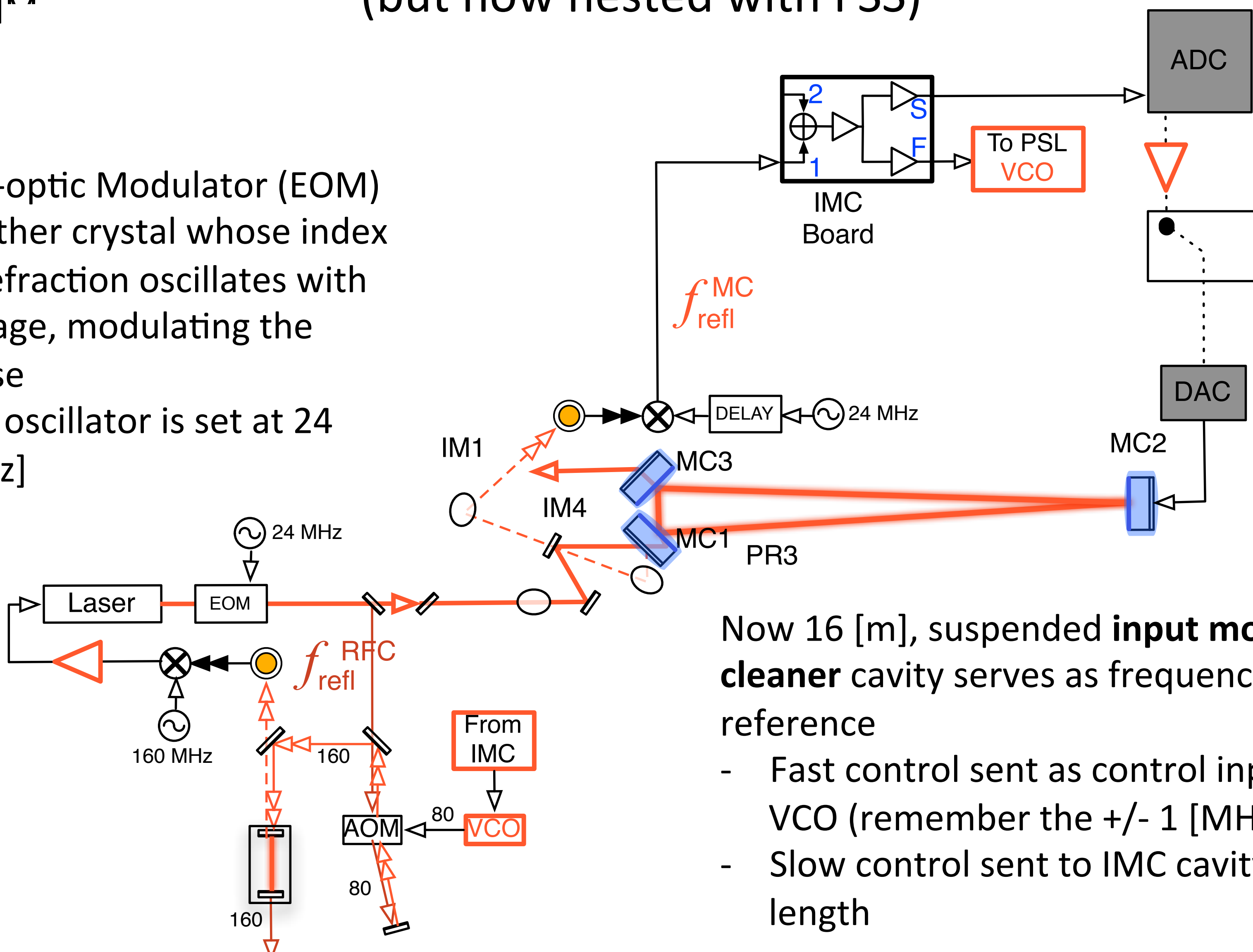
- A PZT wrapped around a crystal, creates diffraction pattern, with each fringe shifted by oscillator frequency
- We catch the first, and send it through twice, so modulation frequency is ~160 [MHz]

FSS
IMC PDH
Fiber PLL
ALS PDH
ALS COM
CARM

Input Mode Cleaner PDH

Just a fancy PDH loop!

(but now nested with FSS)



Electro-optic Modulator (EOM)

- Another crystal whose index of refraction oscillates with voltage, modulating the phase
- IMC oscillator is set at 24 [MHz]

Now 16 [m], suspended **input mode cleaner** cavity serves as frequency reference

- Fast control sent as control input PSL VCO (remember the +/- 1 [MHz]?)
- Slow control sent to IMC cavity length

FSS
IMC PDH
Fiber PLL
ALS PDH
ALS COMM
CARM

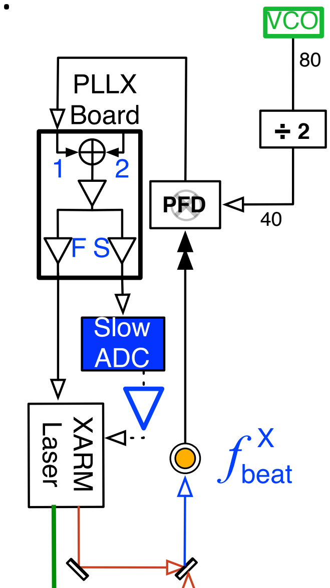
PSL / End-Station Laser Phase-Locking Loop

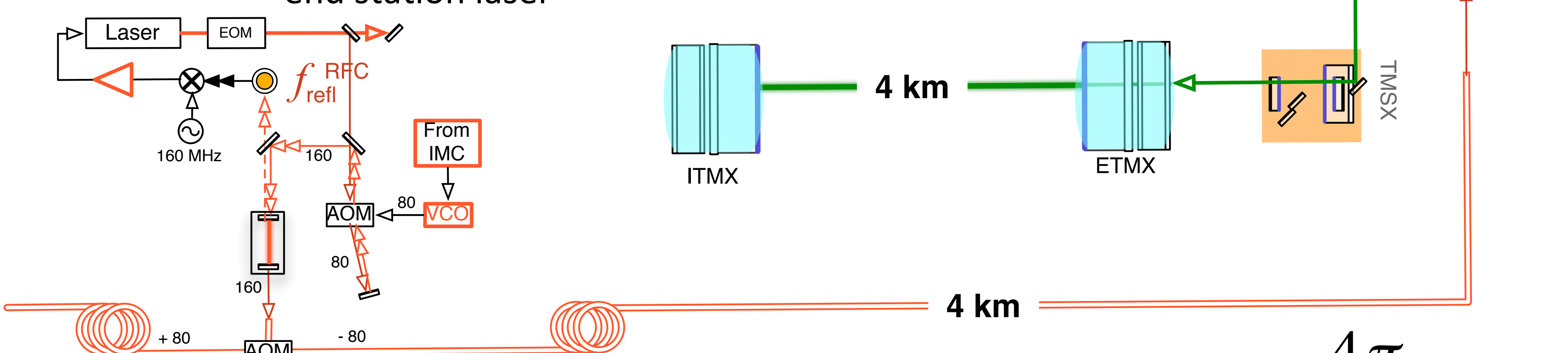
MEANWHILE!!! Begin to prep the arms for merging with the red…

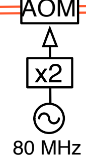
Take the *transmitted* light from Reference Cavity, use another oscillator to down-shift back to 80 [MHz]

Ship to end stations via optical fiber, and phase lock a RED / GREEN auxiliary laser tuned to have ~ 40 [MHz] beat note with PSL

Catch beat note on PD, a send to a phase-frequency detector as the mixer, demodulate at ~40 [Hz] with VCO and control end station laser







$$\phi = \frac{4\pi}{c} L f$$

Phase-Locking Loop = PLL

FSS
IMC PDH
Fiber PLL
ALS PDH
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CARM

Arm Length Stabilization PDH

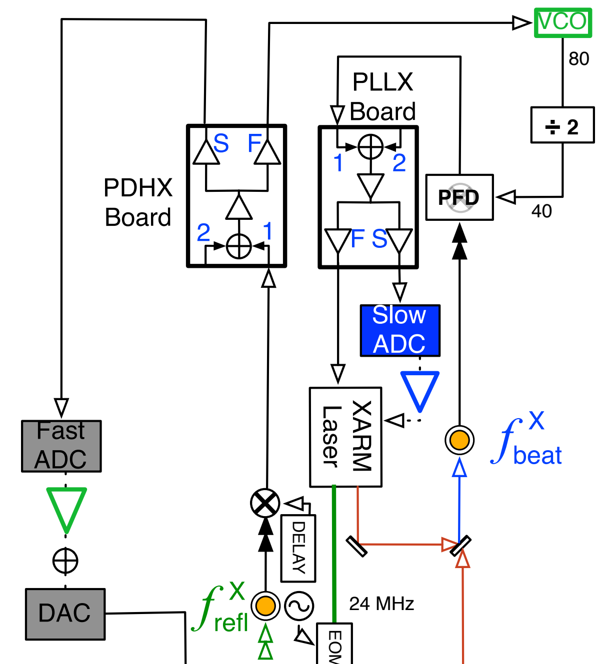
Just a fancy PDH loop!

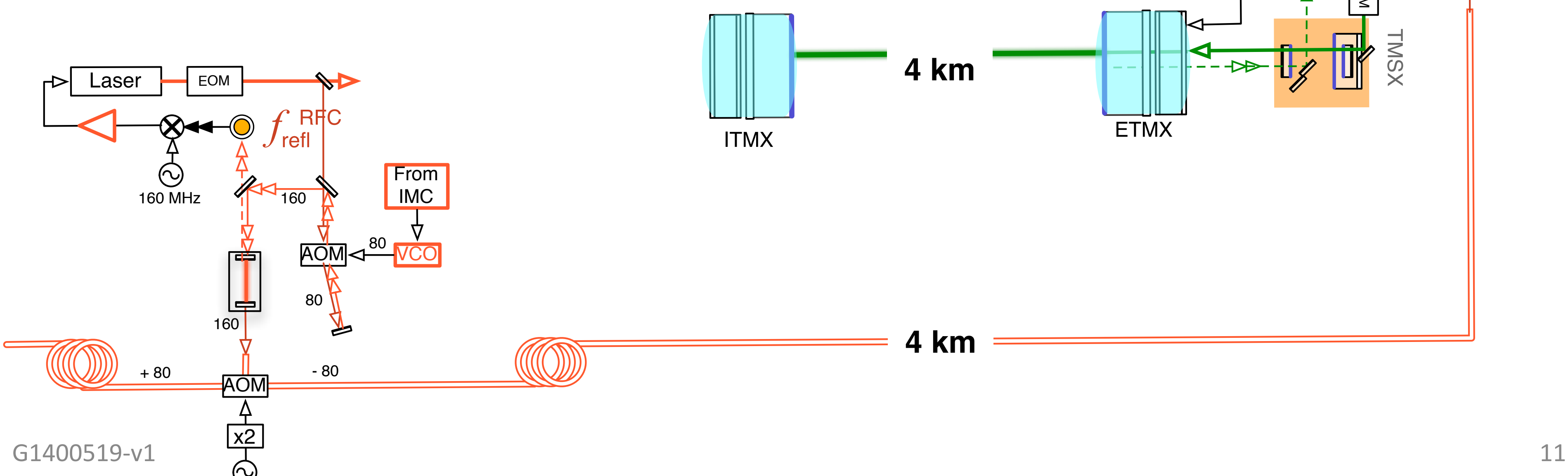
(Now nested with Fiber PLL)

Now back to standard PDH locking of arm with green
(Linewidth in green is lower than for Red)

Send fast feed back to end-VCO (just like the IMC PDH to the FSS VCO)

Send slow feed back to arm cavity length (just like IMC PDH and MCL)





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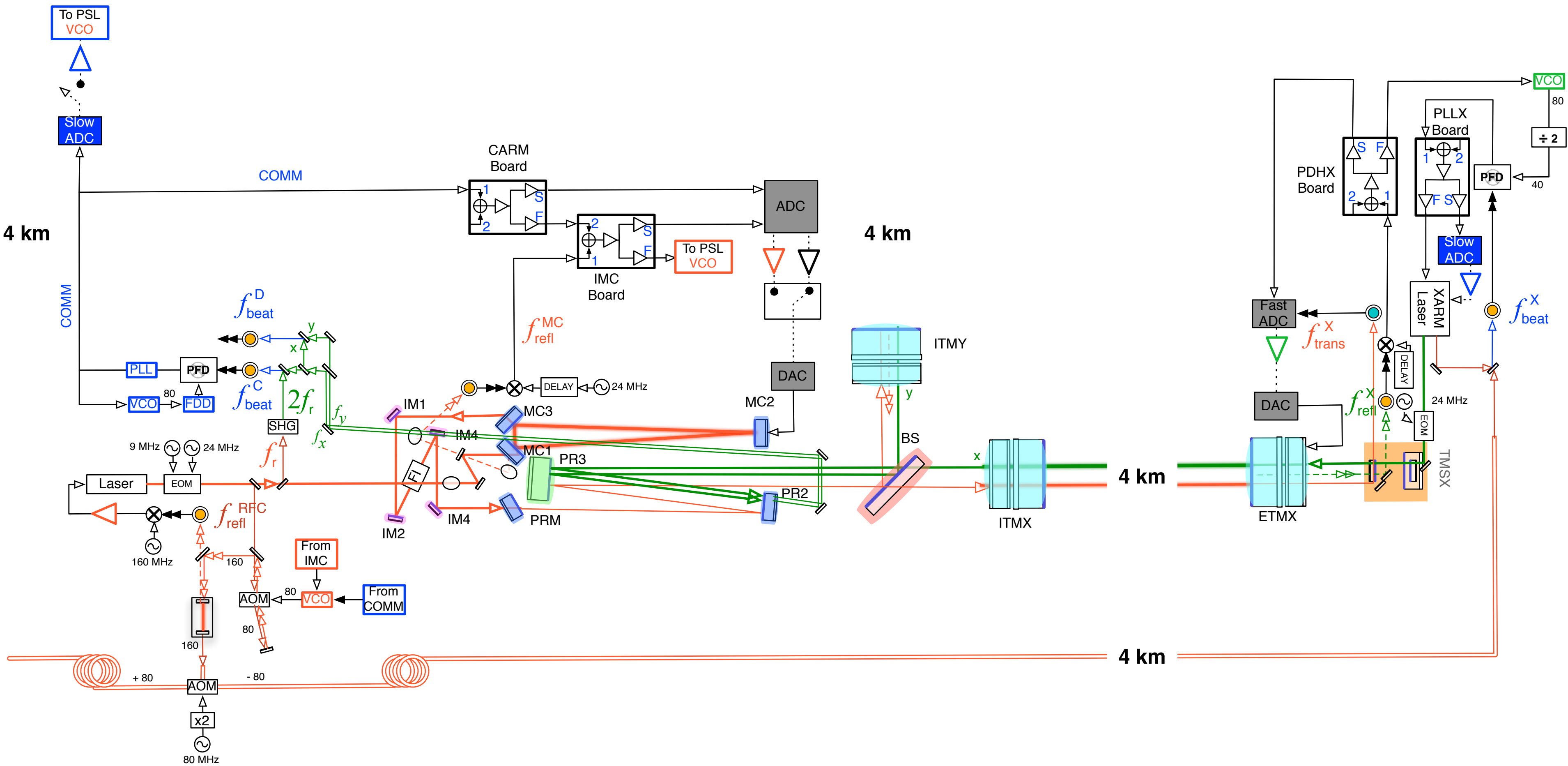
PSL / Common Arm Stabilization



FSS
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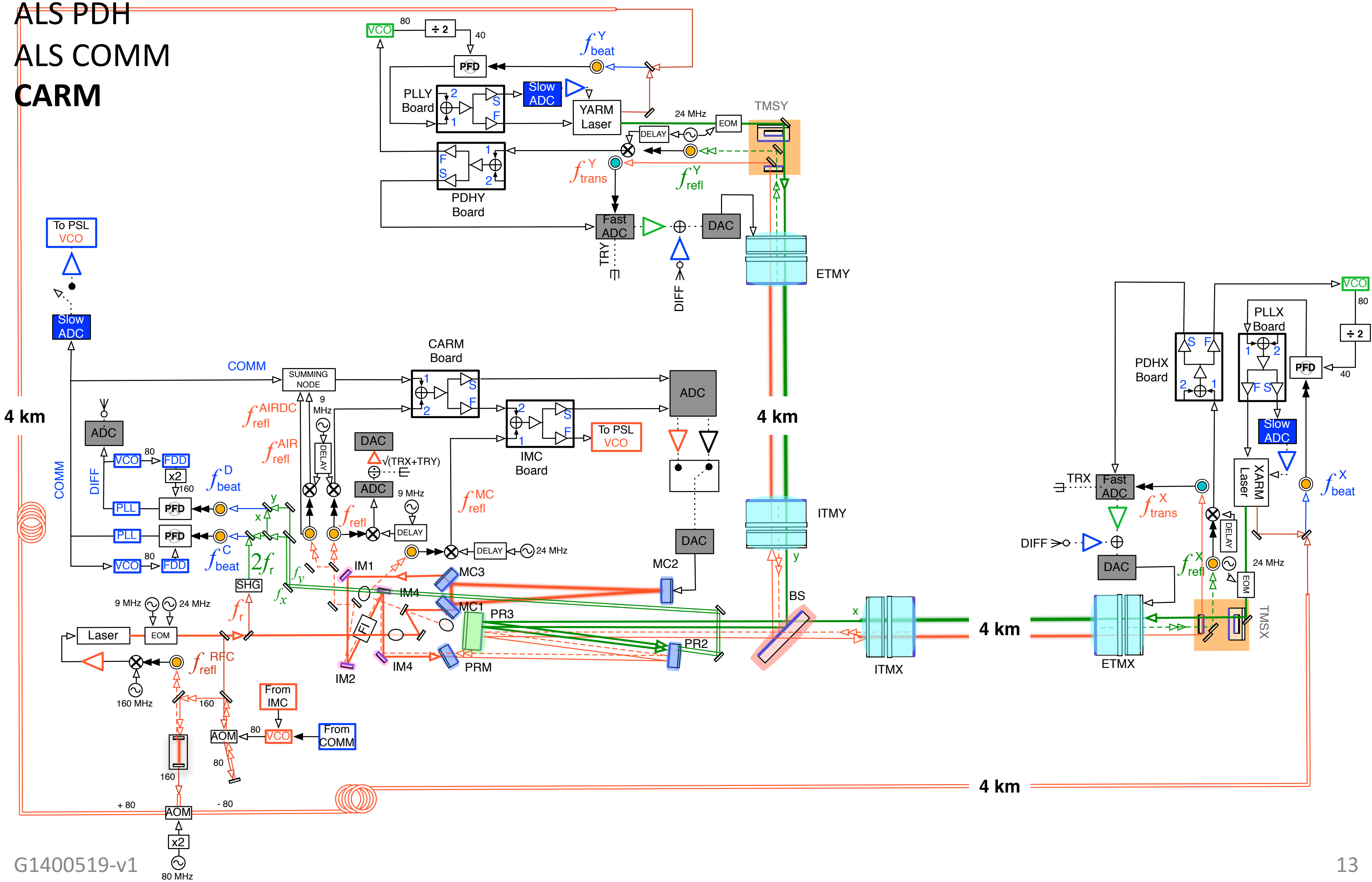
Common Arm Servo



Appendix to PDH (Essential Cavity Equations)

Cavity Resonance Condition
Integer Number of Wavelengths fit inside length of the cavity

$$k\ L = N\pi$$

Phase <-> Length <-> Frequency

$$\phi = \frac{4\pi}{c} L\, f$$

Free Spectral Range

$$2kL = \omega \frac{2L}{c} = 2\pi f \frac{2L}{c} = \frac{2\pi f}{FSR}$$

$$\frac{\Delta L}{L} = \frac{\Delta f}{f}$$

Cavity Linewidth = Full-width Half Maximum = 2* Cavity Pole

$$FWHM = 2 f_p = \frac{2FSR}{\pi} \arcsin\left(\frac{1 - r_1 r_2}{2\sqrt{r_1 r_2}}\right)$$

$$\Delta L = \frac{L\lambda}{c} \Delta f$$

Mirror reflectivities go up, cavity Finesse goes up, Linewidth gets smaller

$$F = \frac{FSR}{FWHM} = \frac{\pi}{2\arcsin\left(\frac{1 - r_1 r_2}{2\sqrt{r_1 r_2}}\right)} \approx \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2} \approx \frac{\pi}{1 - r_1 r_2}$$