Impressions of CARM/ALS

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

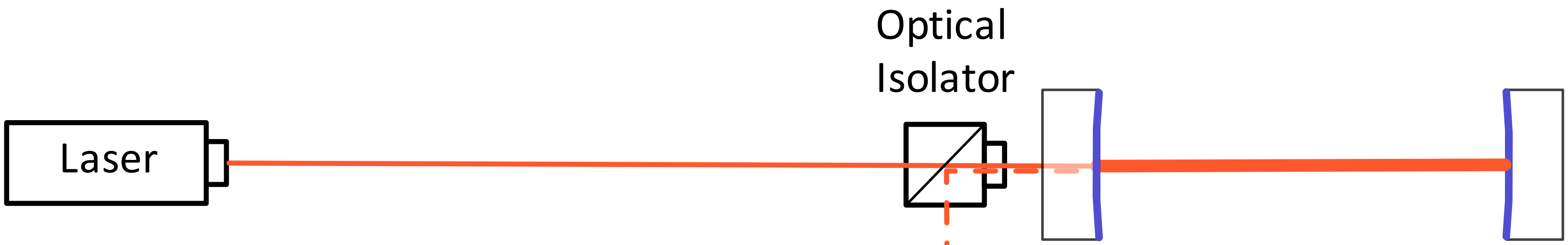
Primer

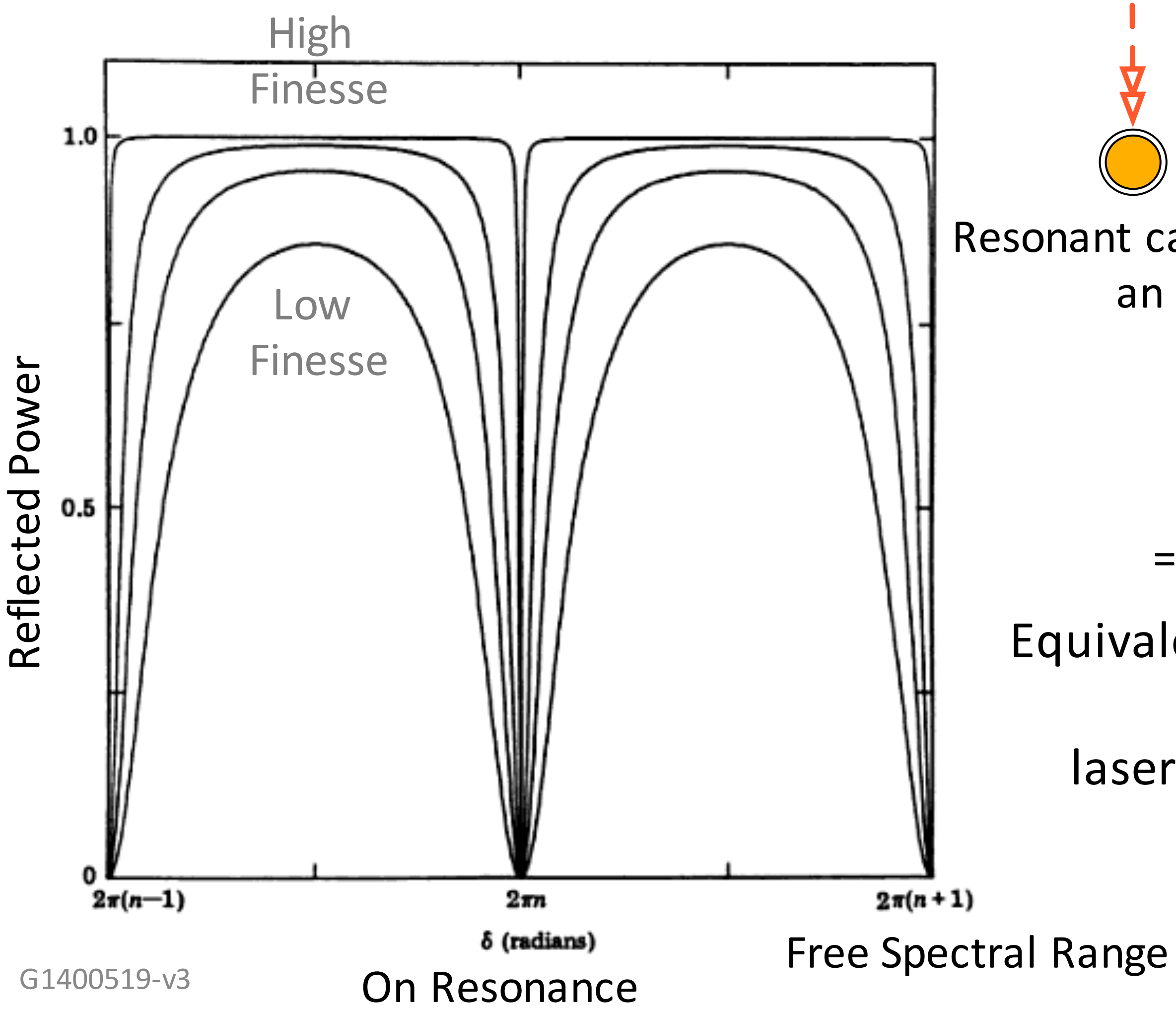
The development of CARM/ALS spans many decades, many people, and many subsystems, so documentation isn't always consistent and it's tough to find the big picture with everything included in one place. This is my attempt.

- I'm *still* getting to know the subsystem
- This presentation will not be perfect
- Go to references (Related Documents on DCC file card) for further reading, they've done a better job at some of the details.
- This is now a "course" meant to be taught over a few days, so forgive its length

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

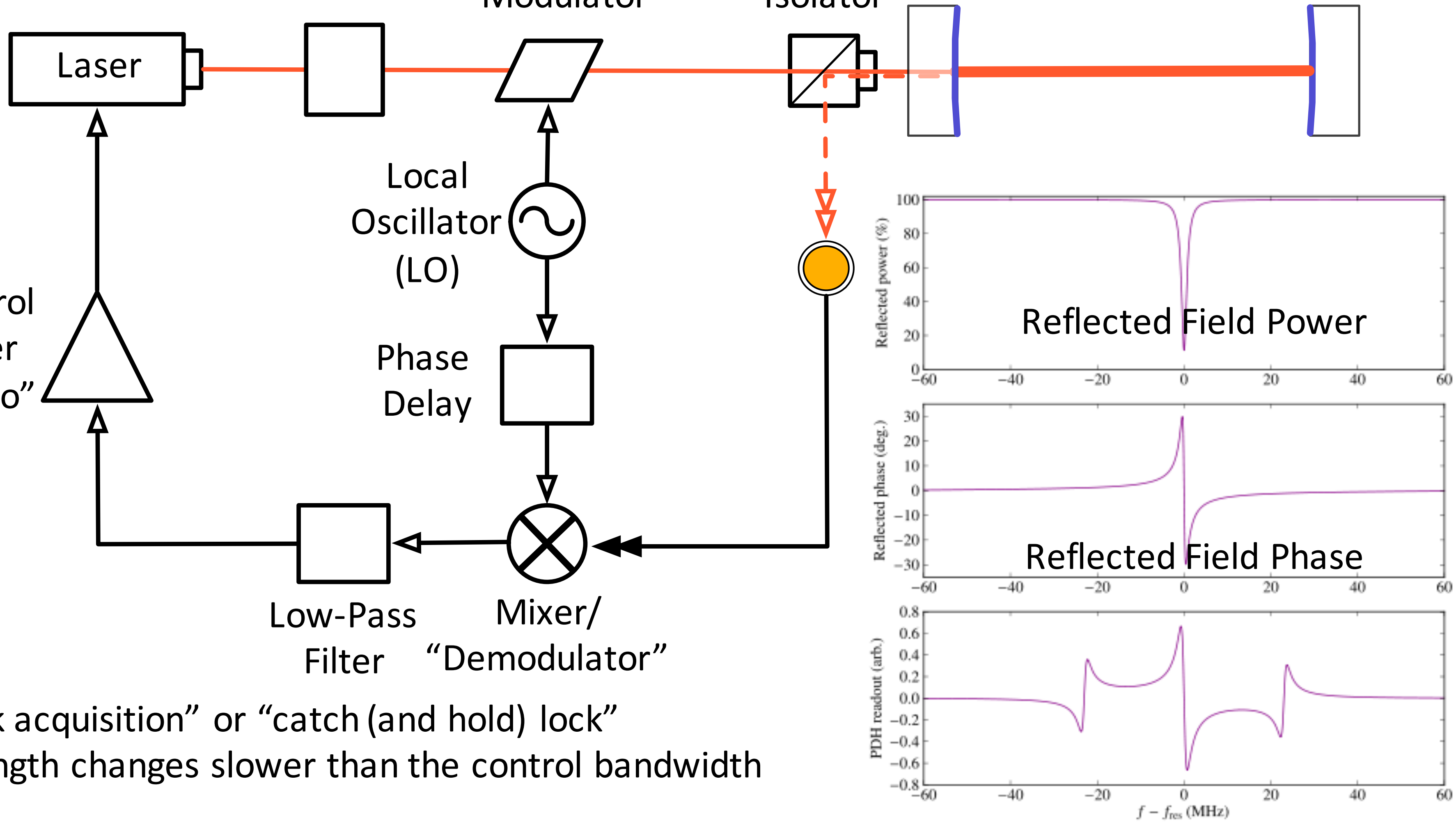
Equivalent noise sources to this system:
cavity length changes or
laser frequency/wavelength changes

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

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



Laser

Faraday Isolator

Phase / Frequency Modulator

Optical Isolator

Local Oscillator (LO)

Phase Delay

Control Filter "Servo"

Low-Pass Filter

Mixer/ "Demodulator"

Reflected Field Power

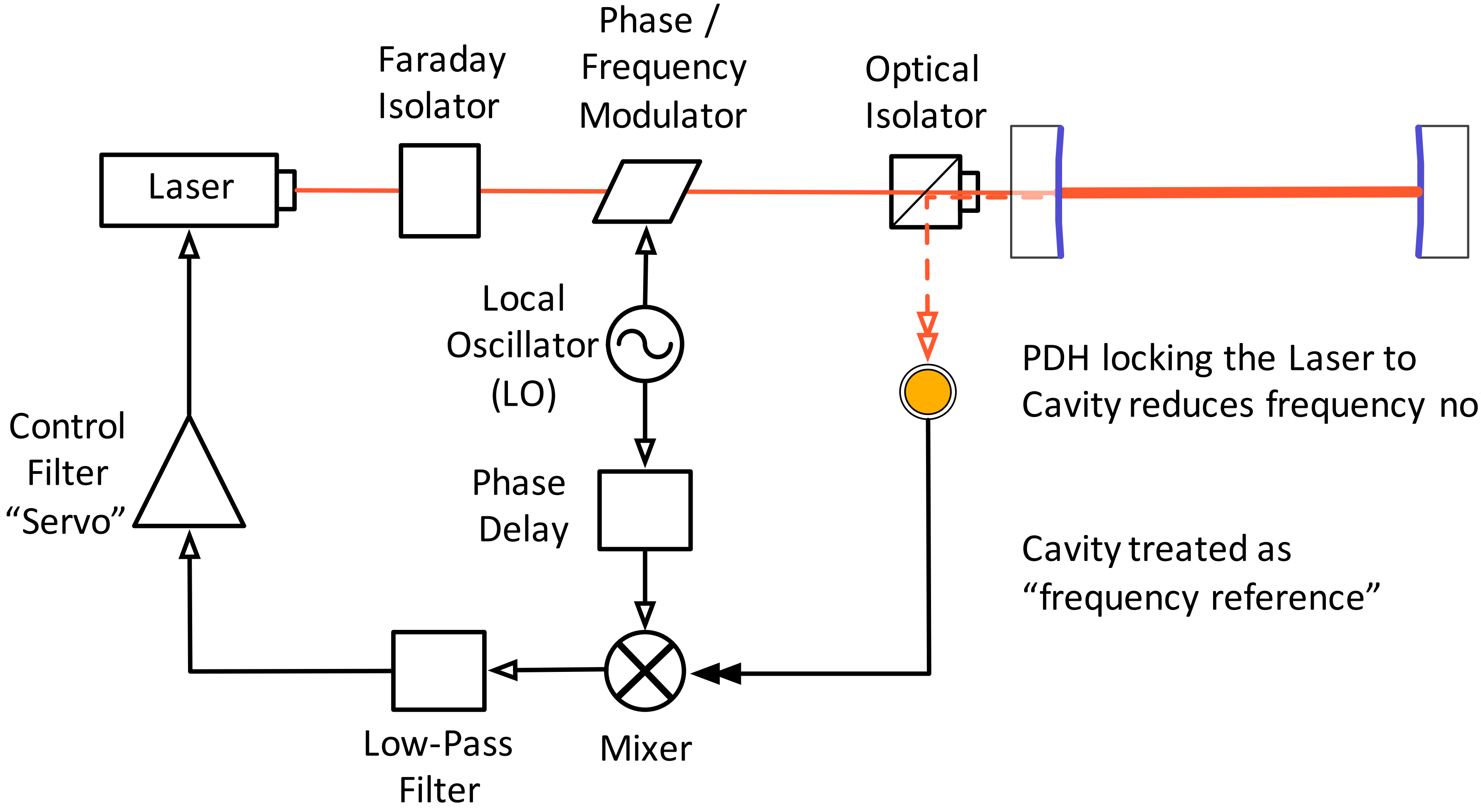
Reflected Field Phase

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”

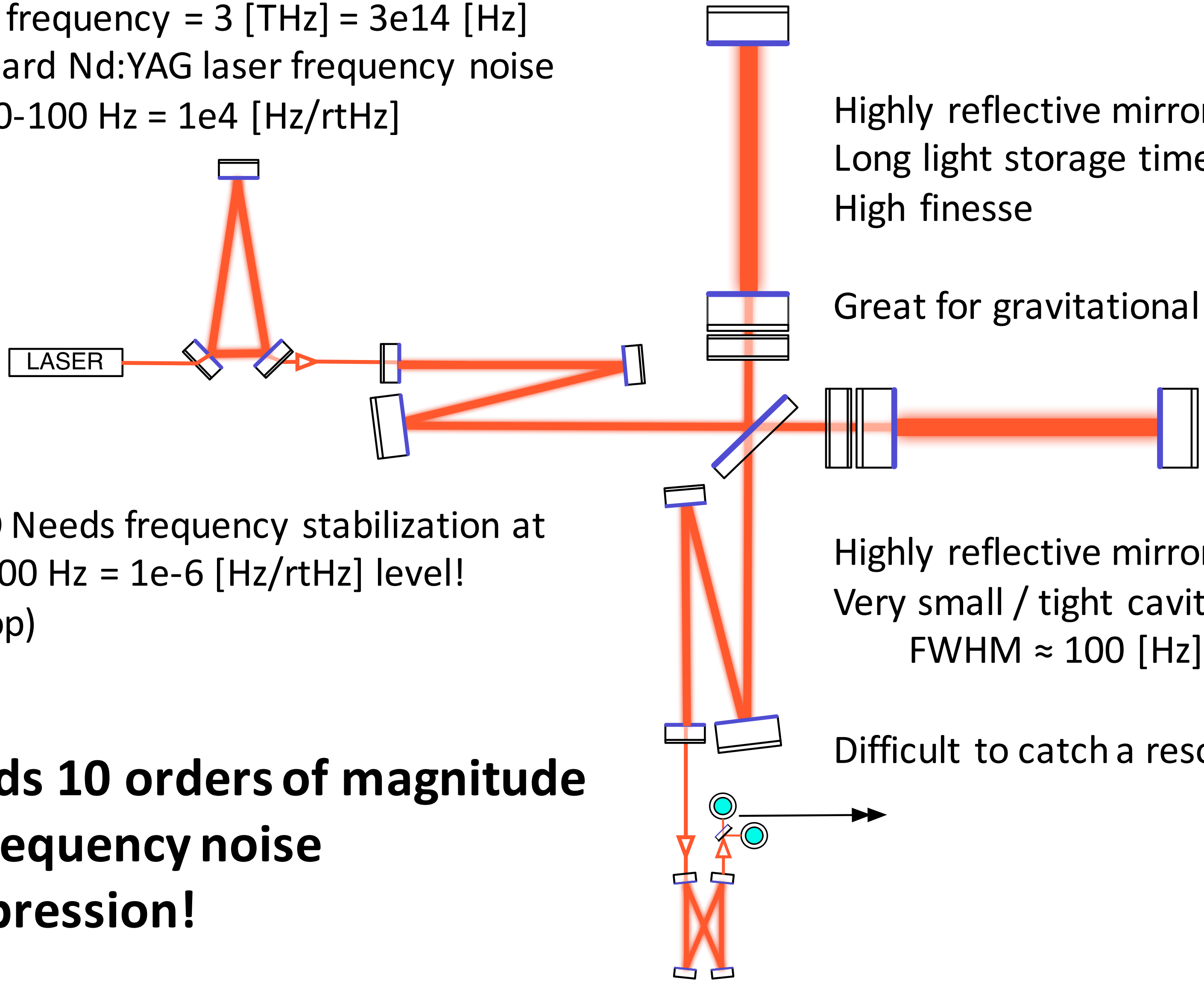
$$\Delta f = \frac{\lambda}{c\,L}\Delta L \qquad \frac{\Delta L}{L} = \frac{\Delta f}{f}$$

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

See Appendix A for more Essential Cavity Eqs.

The LIGO Arm Cavity Problem

Laser frequency = 3 [THz] = 3e14 [Hz]
Standard Nd:YAG laser frequency noise
at ~10-100 Hz = 1e4 [Hz/rtHz]



Highly reflective mirrors
Long light storage time
High finesse

Great for gravitational wave detection

aLIGO Needs frequency stabilization at
~10-100 Hz = 1e-6 [Hz/rtHz] level!
(in loop)

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

Difficult to catch a resonance condition

Needs 10 orders of magnitude of frequency noise suppression!

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

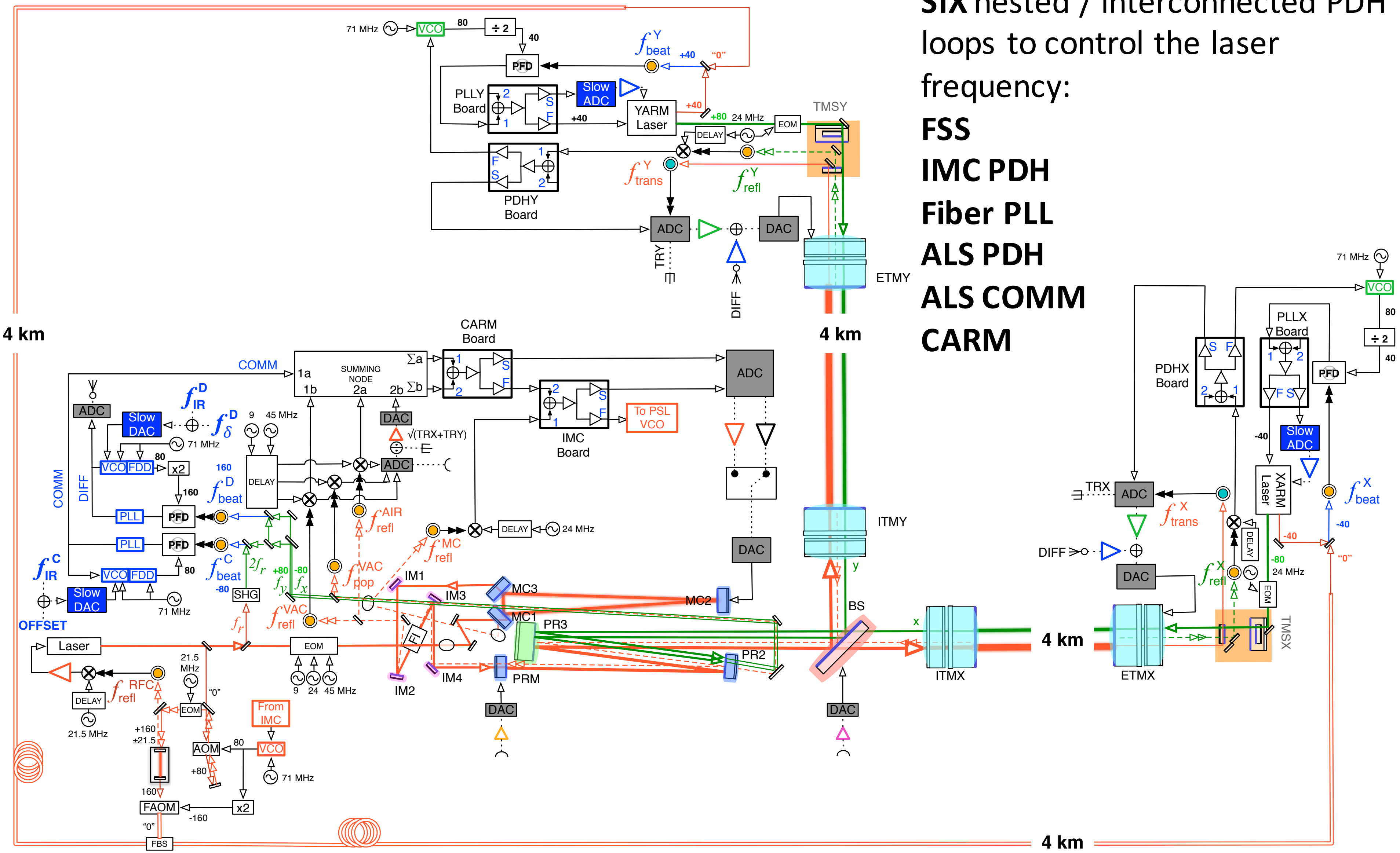
IMC PDH

Fiber PLL

ALS PDH

ALS COMM

CARM



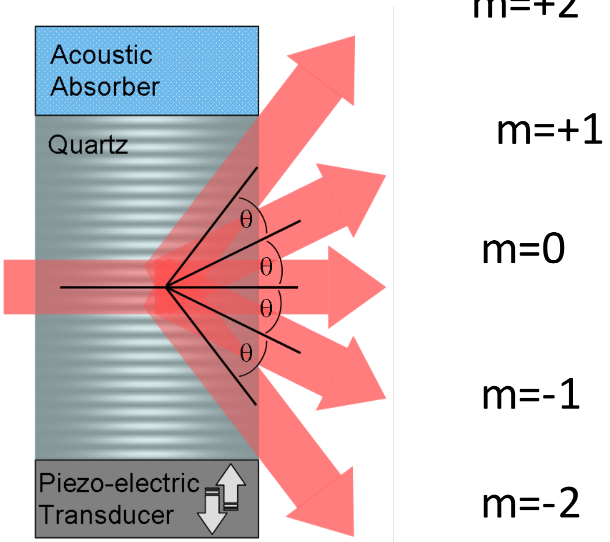
Frequency Actuators on Light
AOMs vs. EOMs

Acousto-Optic Modulator

- Bragg Crystal acoustically excited by PZT
- Diffraction light frequency is Doppler shifted to

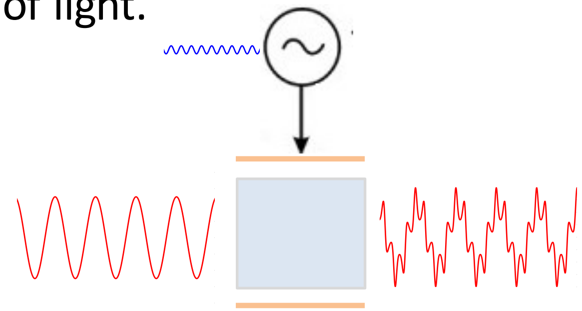
  f -> f + m F

  where m is the diffraction order and F is excitation frequency



Electro-Optic Modulator

- Creates sidebands via phase modulation via Pockels effect
  - Refractive index is a function of the electric field
  - Output phase proportional to how much time in crystal
  - Change electric field, change refractive index, change the phase of light.



$$A\, e^{iwt} \rightarrow A\, e^{iwt+i\Gamma \sin(Wt)}$$

$$\sim A\, e^{iwt} (1 + i\, \Gamma \sin(Wt) + \ldots) \text{ (for small } \Gamma)$$

$$\sin(x) = (1/2i)\ e^{+ix} - e^{-ix}$$

$$= A\, e^{iwt} (1 + \Gamma/2\, e^{+iWt} - \Gamma/2\, e^{-iWt} + \ldots)$$

$$= A\, (e^{iwt} + \Gamma/2\, e^{+i(w+W)t} - \Gamma/2\, e^{+i(w-W)t} + \ldots)$$

Frequency Stabilization Servo

Just a fancy PDH loop!

Light sent into **Reference Cavity** serving as an external frequency reference

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

- **EOM** adds 21.5 MHz sidebands for PDH locking the laser to the reference cavity

- **AOM** shifts the picked-off laser frequency up by +80 upon first pass and then another +80 upon second

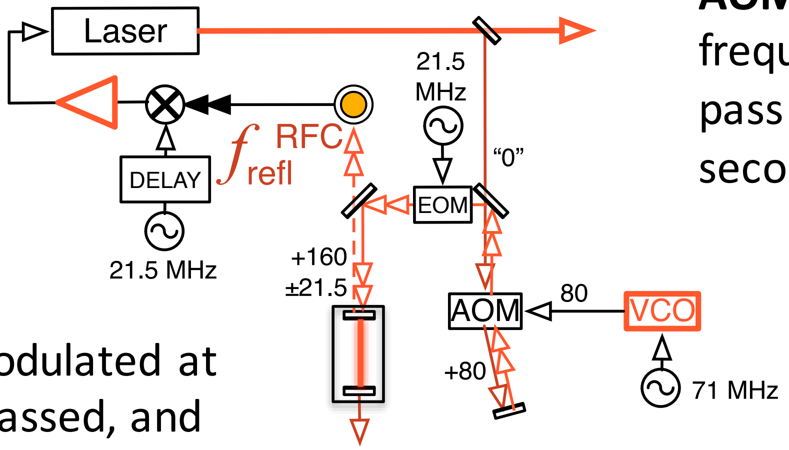


Photo-diode demodulated at 21.5 [MHz], low passed, and control filtered, and sent to laser
Low Frequency = "**Slow**" = laser temperature
High Frequency = **"Fast"** = Laser cavity length

- Voltage-Controlled Oscillator (**VCO**) provides adjustable local oscillator (**LO**) frequency at 80 +/- 1 [MHz], so **we can adjust the main PSL carrier frequency.**

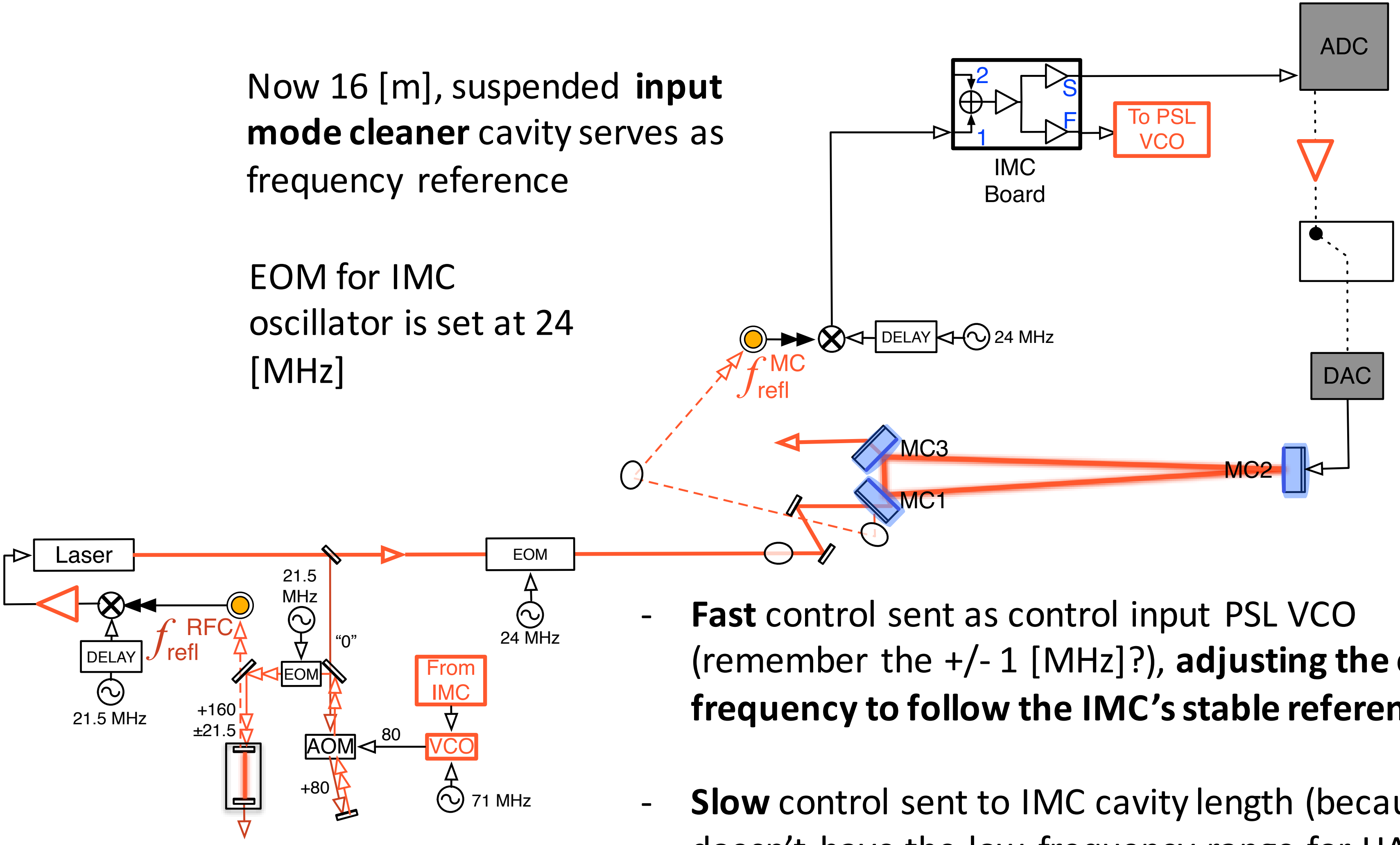
Input Mode Cleaner PDH

Just a fancy PDH loop!

(but now nested with FSS)

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

EOM for IMC oscillator is set at 24 [MHz]



- **Fast** control sent as control input PSL VCO (remember the +/- 1 [MHz]?), **adjusting the carrier frequency to follow the IMC's stable reference**

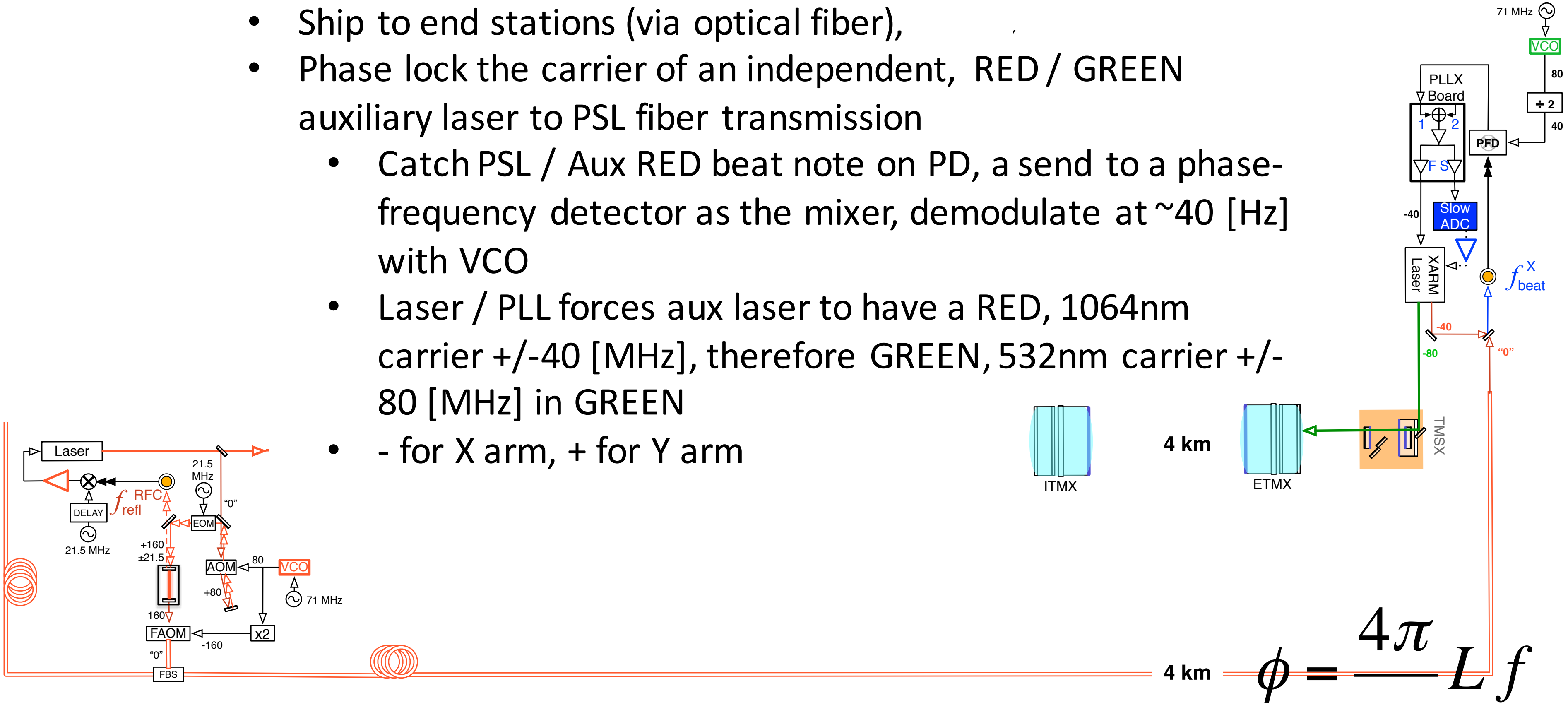
- **Slow** control sent to IMC cavity length (because VCO doesn't have the low-frequency range for HAM2-HAM3 differential motion)

FSS
IMC PDH
Fiber PLL
ALS PDH
ALS COMM
ALS DIFF

PSL / End-Station Laser Phase-Locking Loop

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

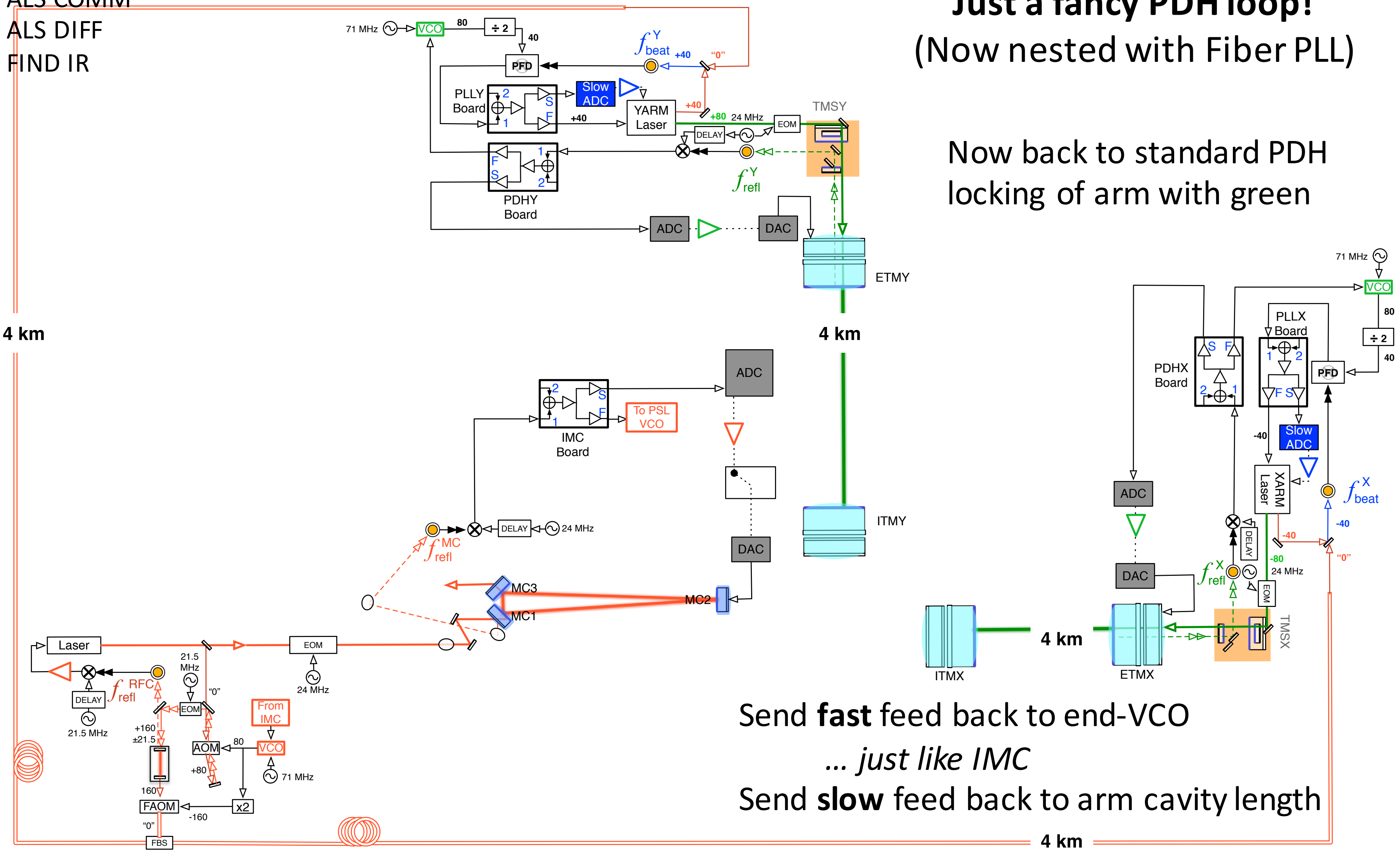
- Take the *transmitted* light from Reference Cavity,
- feed it into a optical fiber (on the PSL),
- down-shift back to 0 [MHz] with fiber AOM (in the PSL racks)
- Ship to end stations (via optical fiber),
- Phase lock the carrier of an independent, RED / GREEN auxiliary laser to PSL fiber transmission
  - Catch PSL / Aux RED beat note on PD, a send to a phase-frequency detector as the mixer, demodulate at ~40 [Hz] with VCO
  - Laser / PLL forces aux laser to have a RED, 1064nm carrier +/-40 [MHz], therefore GREEN, 532nm carrier +/-80 [MHz] in GREEN
  - \- for X arm, + for Y arm



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

Phase-Locking Loop = PLL

Arm Length Stabilization PDH



Just a fancy PDH loop!

(Now nested with Fiber PLL)

Now back to standard PDH locking of arm with green

Send **fast** feed back to end-VCO

... just like IMC

Send **slow** feed back to arm cavity length

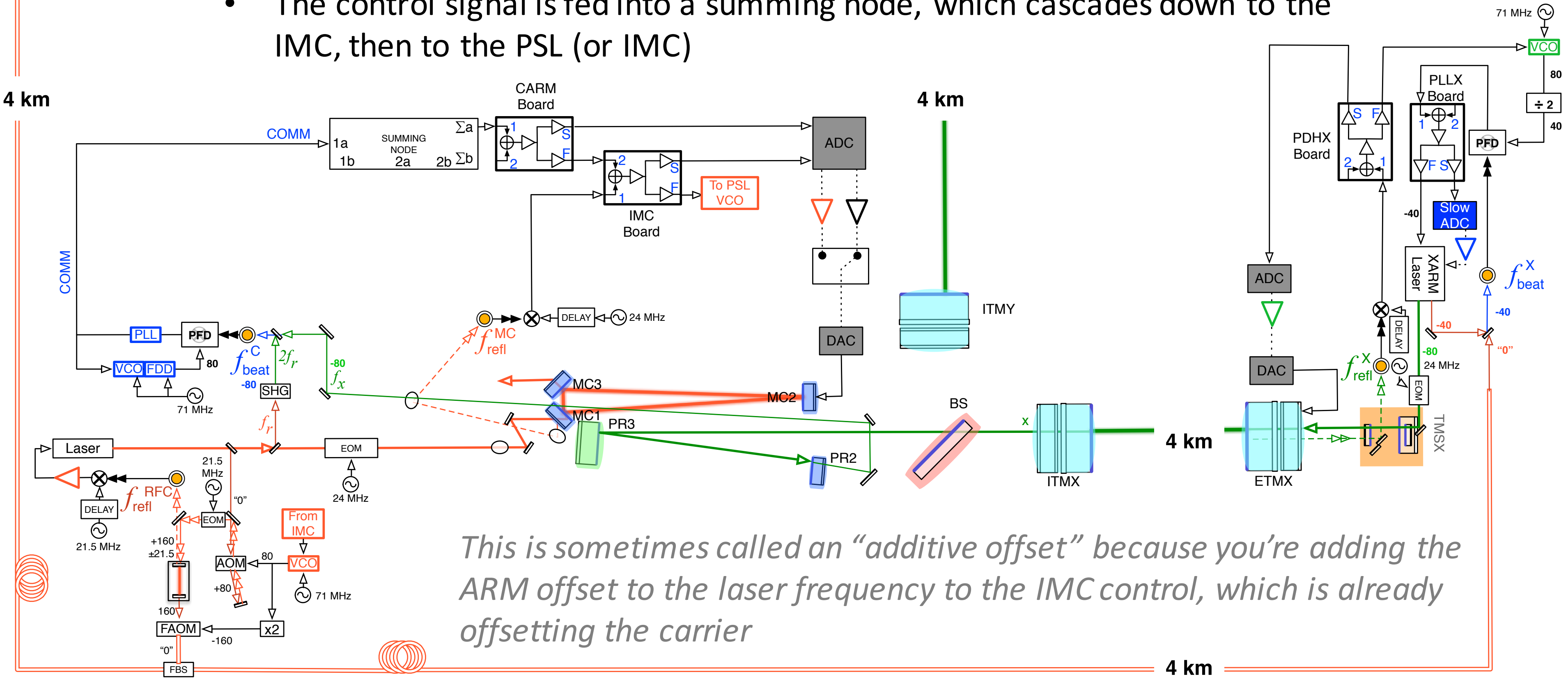
... just like IMC

Fiber PLL
ALS PDH
ALS COMM
ALS DIFF
FIND IR
IR FOUND

PSL / Common Arm Stabilization

Now we nest the green and red frequency, starting to sync the PSL to the arms.

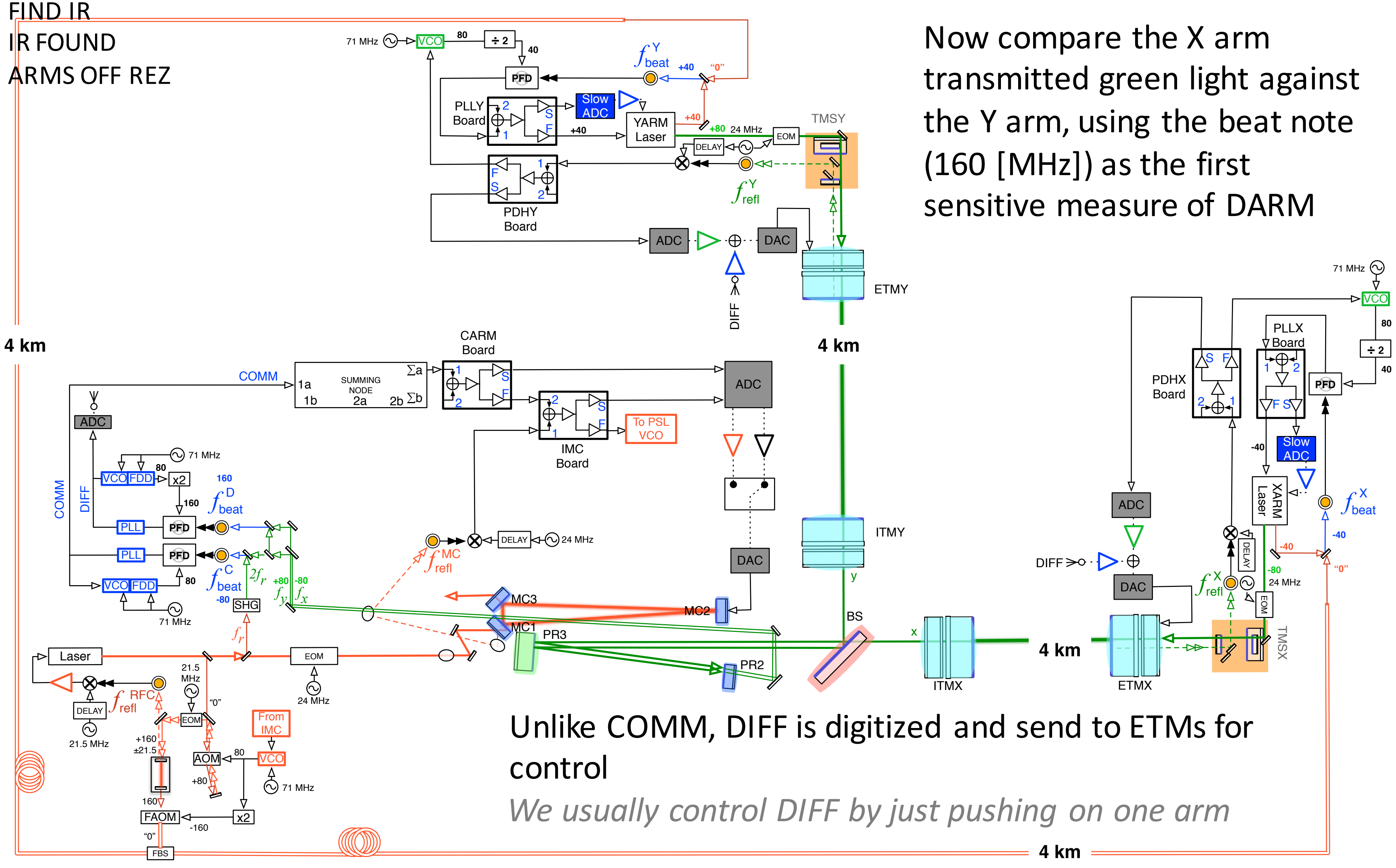
- Transmitted green from X arm is steered to combine with a pick-off of the PSL, frequency-doubled (turning RED to GREEN) via second harmonic generator (SHG).
- That beat note (-80 [MHz]), is fed into another PLL / VCO combination
- The control signal is fed into a summing node, which cascades down to the IMC, then to the PSL (or IMC)



This is sometimes called an "additive offset" because you're adding the ARM offset to the laser frequency to the IMC control, which is already offsetting the carrier

ALS PDH
ALS COMM
ALS DIFF
FIND IR
IR FOUND
ARMS OFF REZ

Differential Arm Length Stabilization



Now compare the X arm transmitted green light against the Y arm, using the beat note (160 [MHz]) as the first sensitive measure of DARM

Unlike COMM, DIFF is digitized and send to ETMs for control

We usually control DIFF by just pushing on one arm

ALS PDH
ALS COMM
ALS DIFF
FIND IR
IR FOUND
ARMS OFF REZ

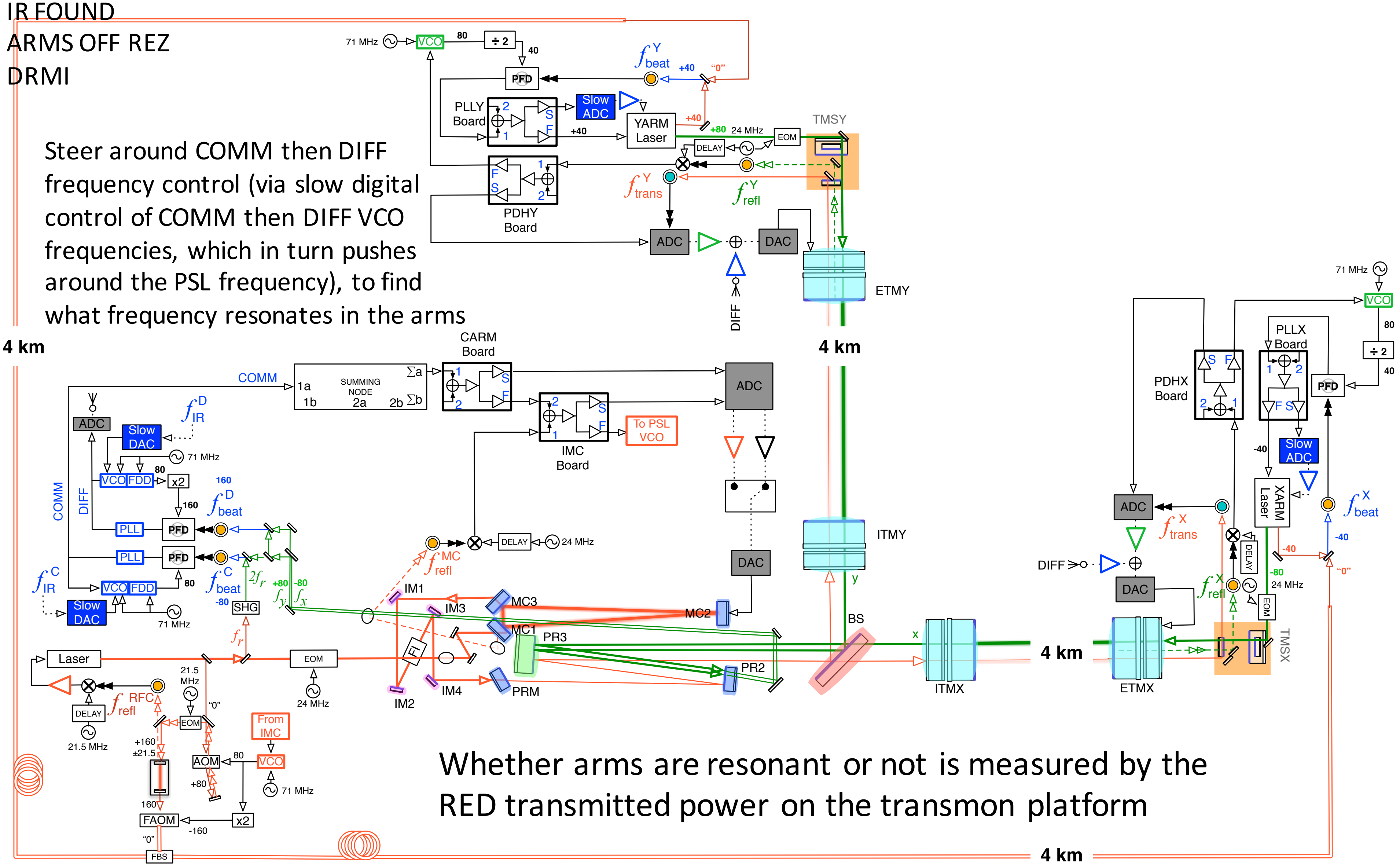
The Rest of the Lock Acquisition Sequence

- From here, we have the arms controlled, but at this point the frequency control is no where near good enough, and we don’t have DRMI locked.
- The next MANY steps are all in place such that we can lock DRMI independently, then slowly bring the arms into resonance *with* DRMI.
- It’s a convoluted process that involves slowly/carefully switching between equivalent sensors and actuators, but going from high noise / high range to low noise / low range.

Let’s go!

ALS COMM
ALS DIFF
FIND IR
IR FOUND
ARMS OFF REZ
DRMI

FIND IR



Steer around COMM then DIFF frequency control (via slow digital control of COMM then DIFF VCO frequencies, which in turn pushes around the PSL frequency), to find what frequency resonates in the arms

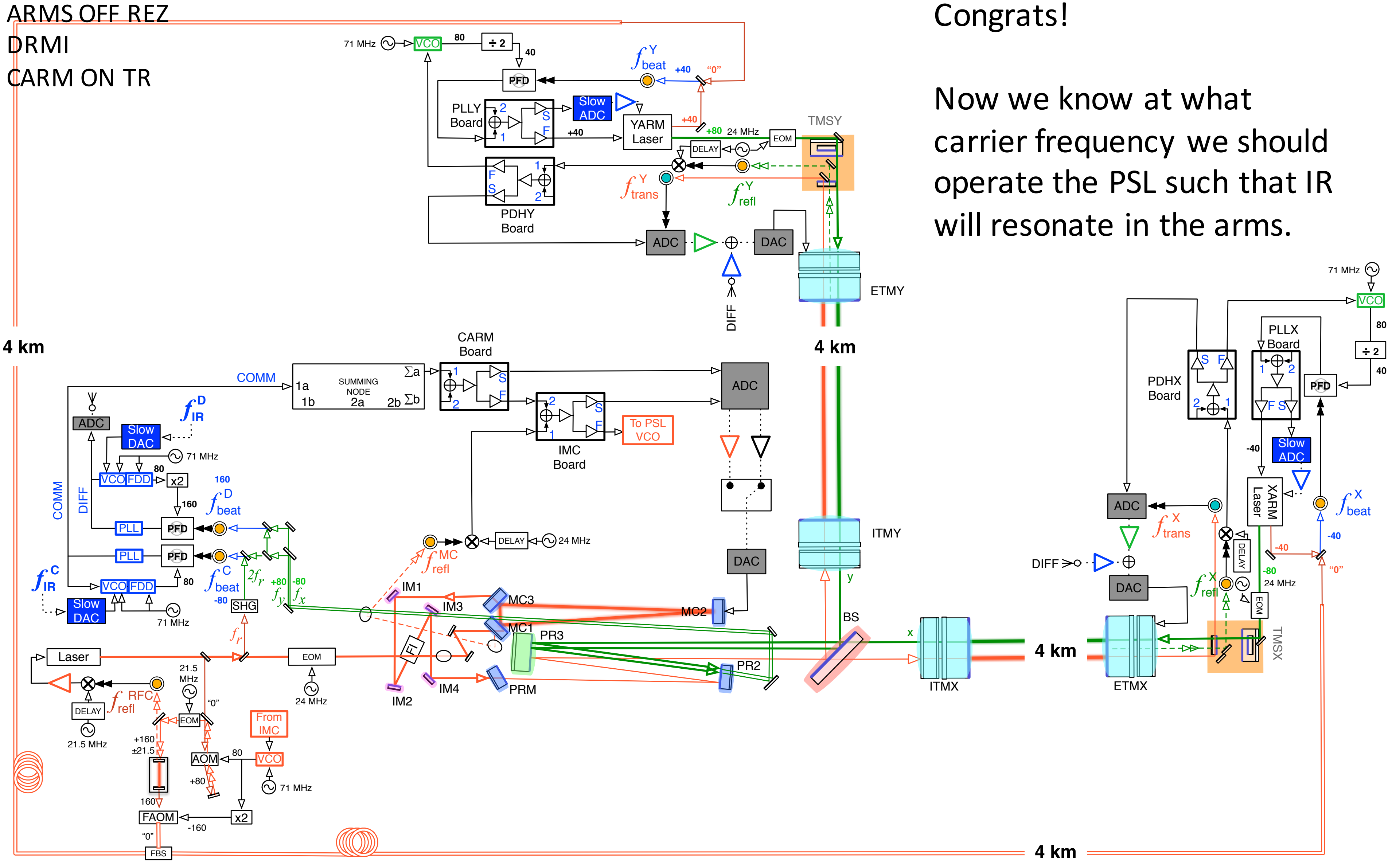
Whether arms are resonant or not is measured by the RED transmitted power on the transmon platform

ALS DIFF
FIND IR
IR FOUND
ARMS OFF REZ
DRMI
CARM ON TR

IR FOUND

Congrats!

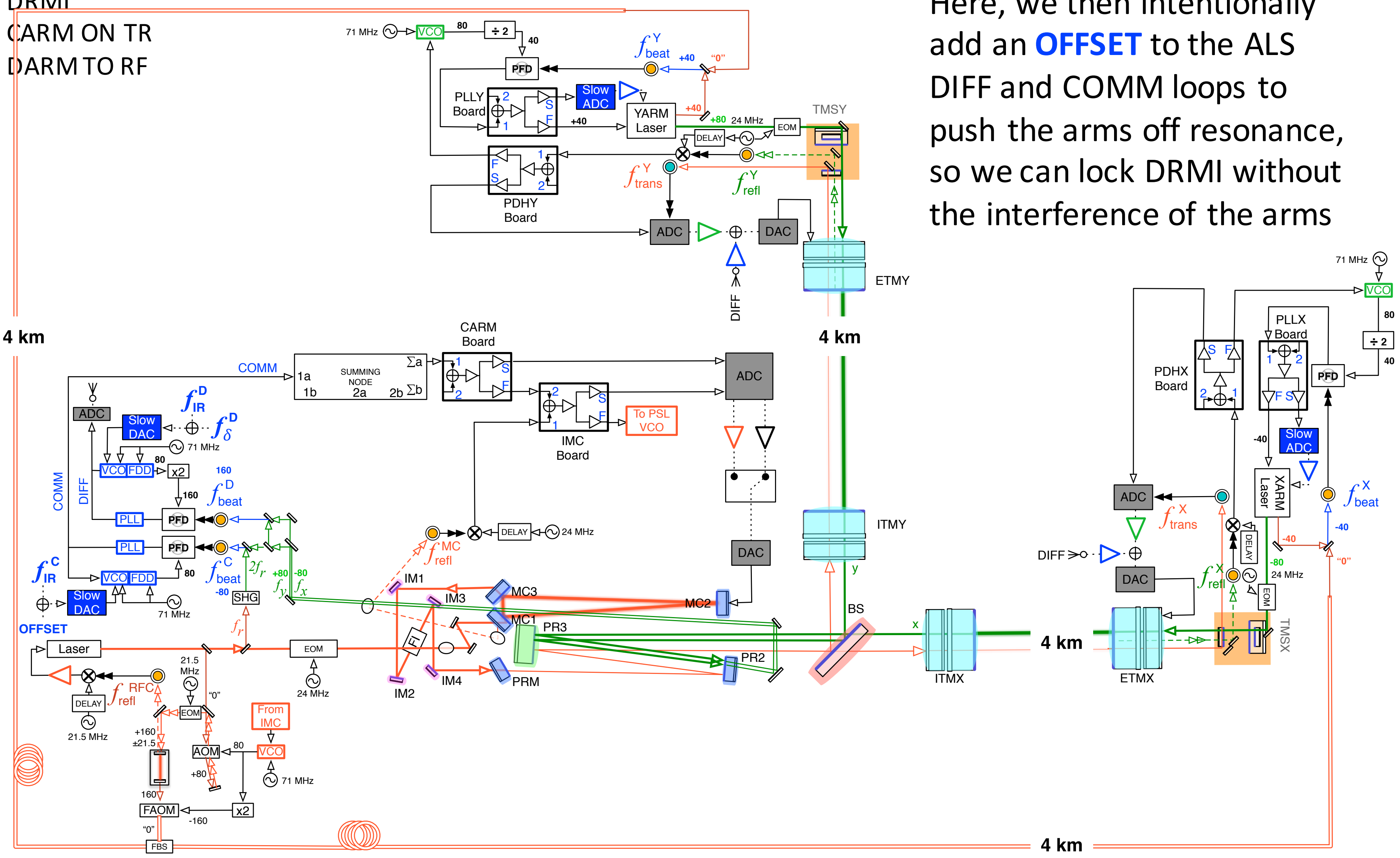
Now we know at what carrier frequency we should operate the PSL such that IR will resonate in the arms.



FIND IR
IR FOUND
ARMS OFF REZ
DRMI
CARM ON TR
DARM TO RF

ARMS OFF RESONANCE

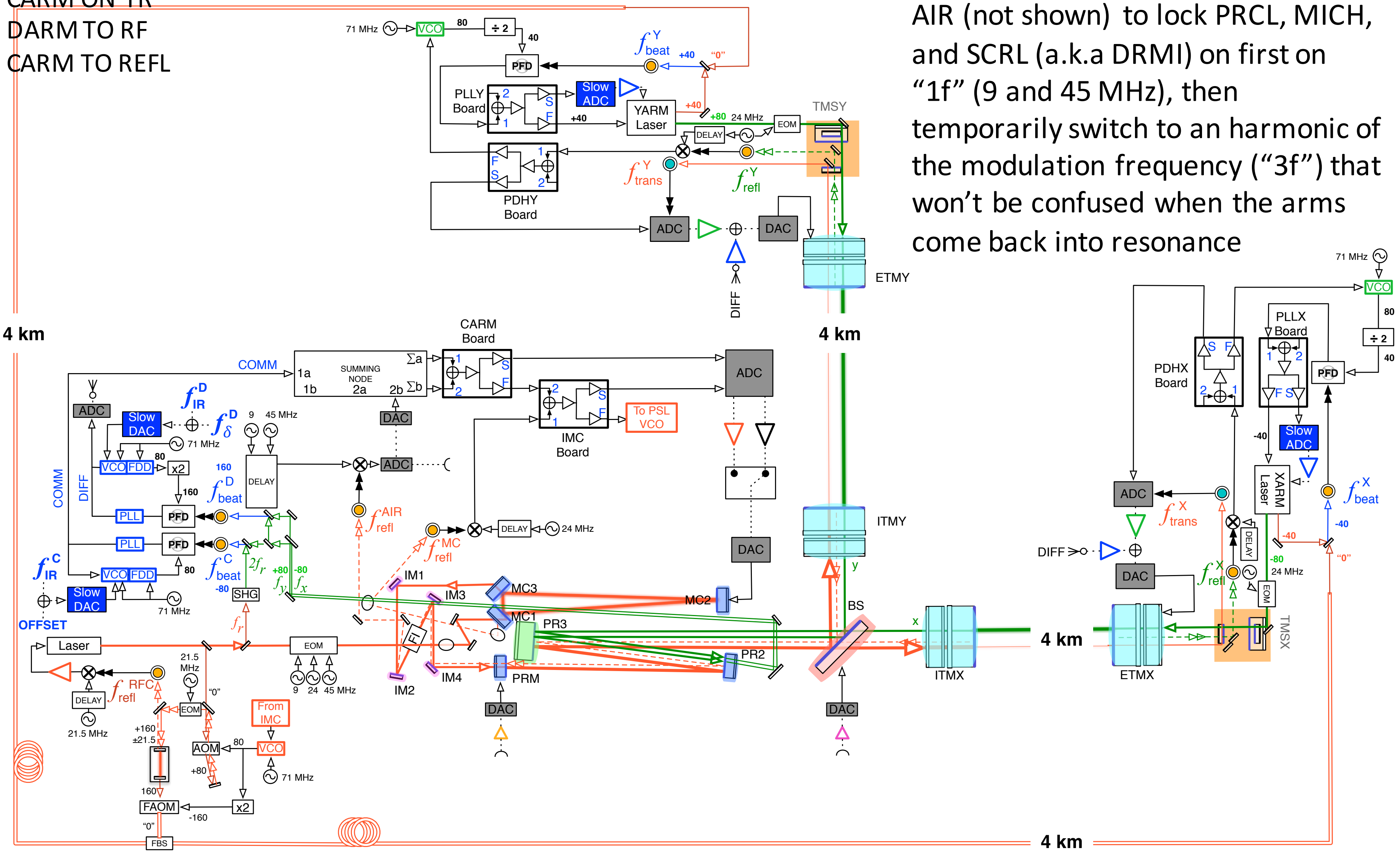
Here, we then intentionally add an **OFFSET** to the ALS DIFF and COMM loops to push the arms off resonance, so we can lock DRMI without the interference of the arms



IR FOUND
ARMS OFF REZ
DRMI
CARM ON TR
DARM TO RF
CARM TO REFL

DRMI (1F, 3F)

In this step, we use the temporary sensors, REFL AIR (shown) and AS AIR (not shown) to lock PRCL, MICH, and SCRL (a.k.a DRMI) on first on “1f” (9 and 45 MHz), then temporarily switch to an harmonic of the modulation frequency (“3f”) that won’t be confused when the arms come back into resonance



IR FOUND
ARMS OFF REZ
DRMI
CARM ON TR
DARM TO RF
CARM TO REFL

An aside: Why 1f vs 3f DRMI?

I lied to you a bit on slide 8 when I said

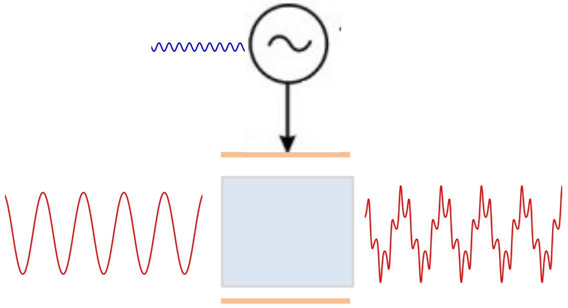
$A e^{iwt} \rightarrow A e^{iwt+i\Gamma \sin(Wt)}$

$\sim A e^{iwt} (1 + i\,\Gamma \sin(Wt) + \ldots)$ (for small Γ)

$\sin(x) = (1/2i)\ e^{+ix} - e^{-ix}$

$= A e^{iwt} (1 + \Gamma/2\ e^{+iWt} - \Gamma/2\ e^{-iWt})$

$= A (e^{iwt} + \Gamma/2\ e^{+i(w+W)t} - \Gamma/2\ e^{+i(w-W)t})$



To be more complete…

$A e^{iwt} \rightarrow A e^{iwt+i\Gamma \sin(Wt)}$

$= A e^{iwt}\ \Sigma_k [\ J_k(\Gamma)\ e^{ikWt}\ ]$

$J_k(\Gamma) \sim 1/k!\ (\Gamma/2)^k$ (for small Γ)

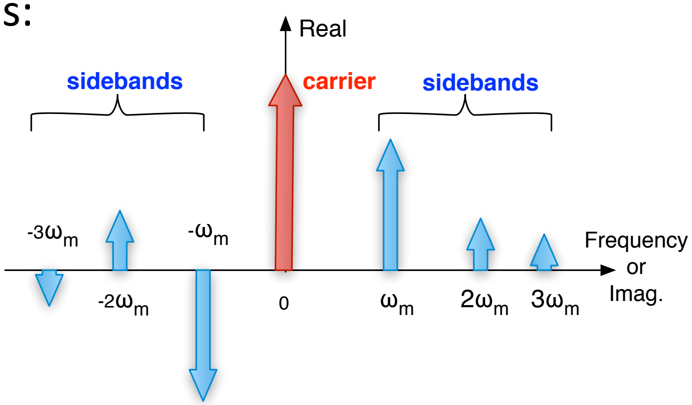
$J_{-k}(\Gamma) = -\ J_k(\Gamma)$

$= A e^{iwt} (\ldots - \Gamma/6\ e^{-i3Wt} - \Gamma/4\ e^{-i2Wt} - \Gamma/2\ e^{-iWt}$

$+ 1$

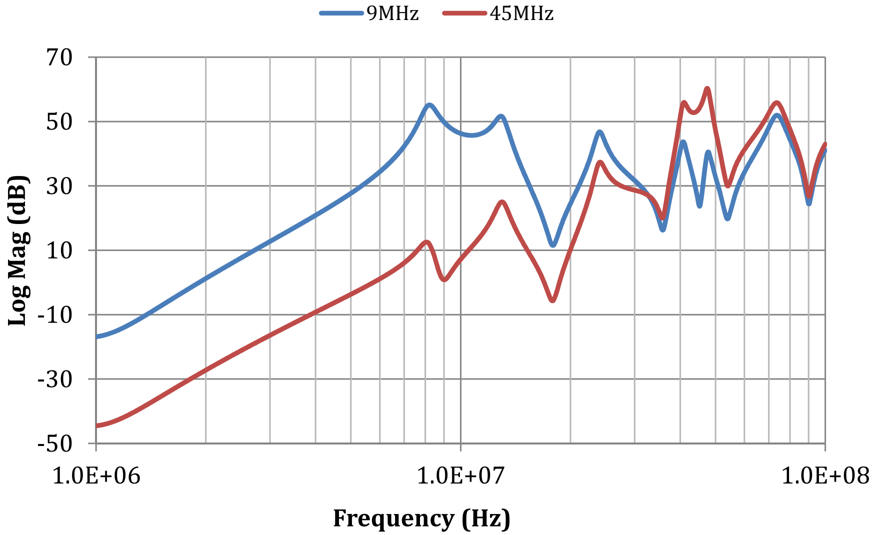
$+ \Gamma/2\ e^{+iWt} + \Gamma/4\ e^{-i2Wt} + \Gamma/6\ e^{-i3Wt} + \ldots)$

… one modulation frequency yields lots of harmonics:



And that's the electric *field*.
Photodetectors measure *power* (=|field|^2), so there will be cross-terms as well…

9, (2*9)=18, (2*9-45) = 27, (9-45)=36, 45, etc.



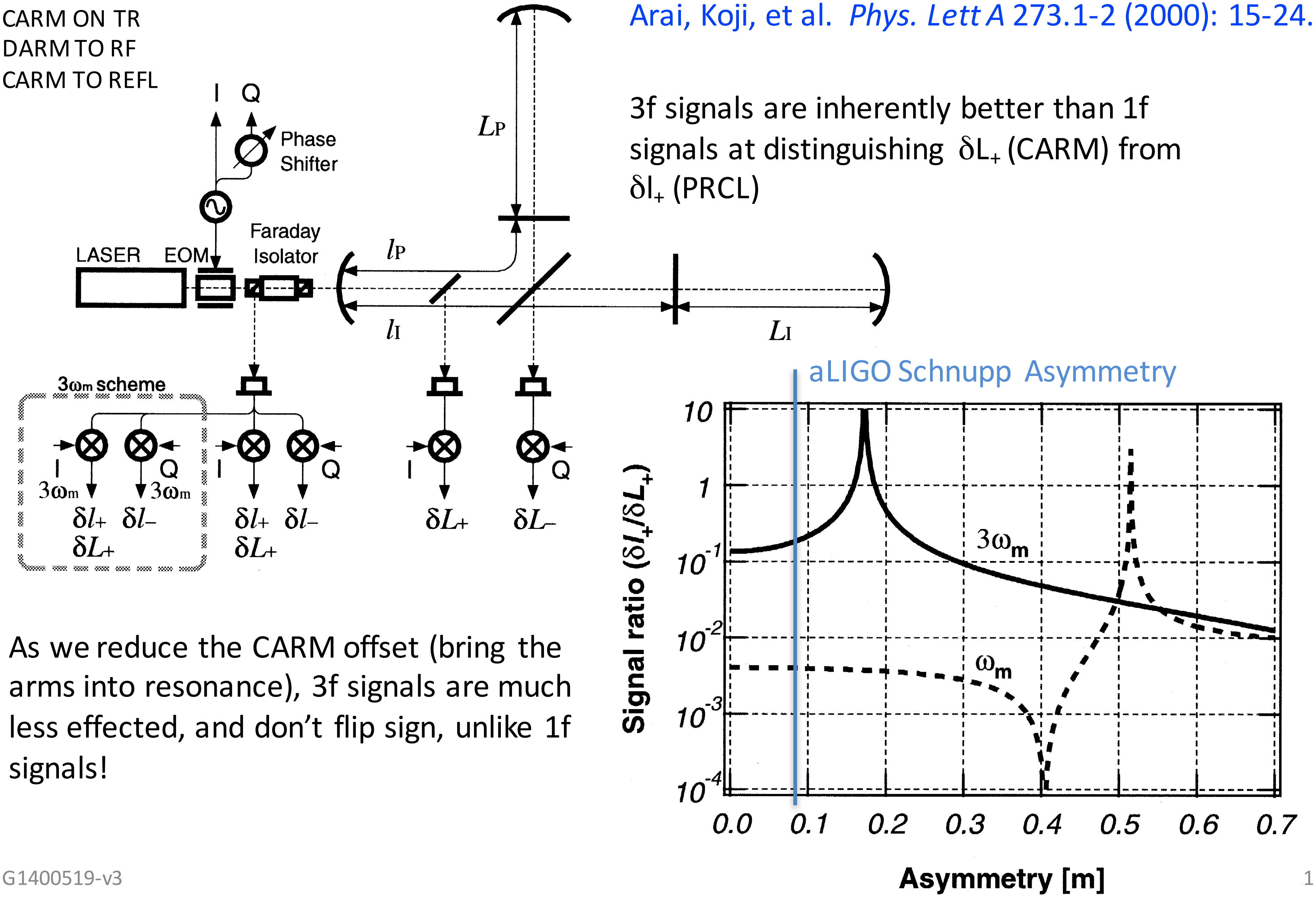
The RF response of our LSC photodetectors

IR FOUND
ARMS OFF REZ
DRMI
CARM ON TR
DARM TO RF
CARM TO REFL

An aside: Why 1f vs 3f DRMI?

Arai, Koji, et al. *Phys. Lett A* 273.1-2 (2000): 15-24.

3f signals are inherently better than 1f signals at distinguishing δL_+ (CARM) from δl_+ (PRCL)

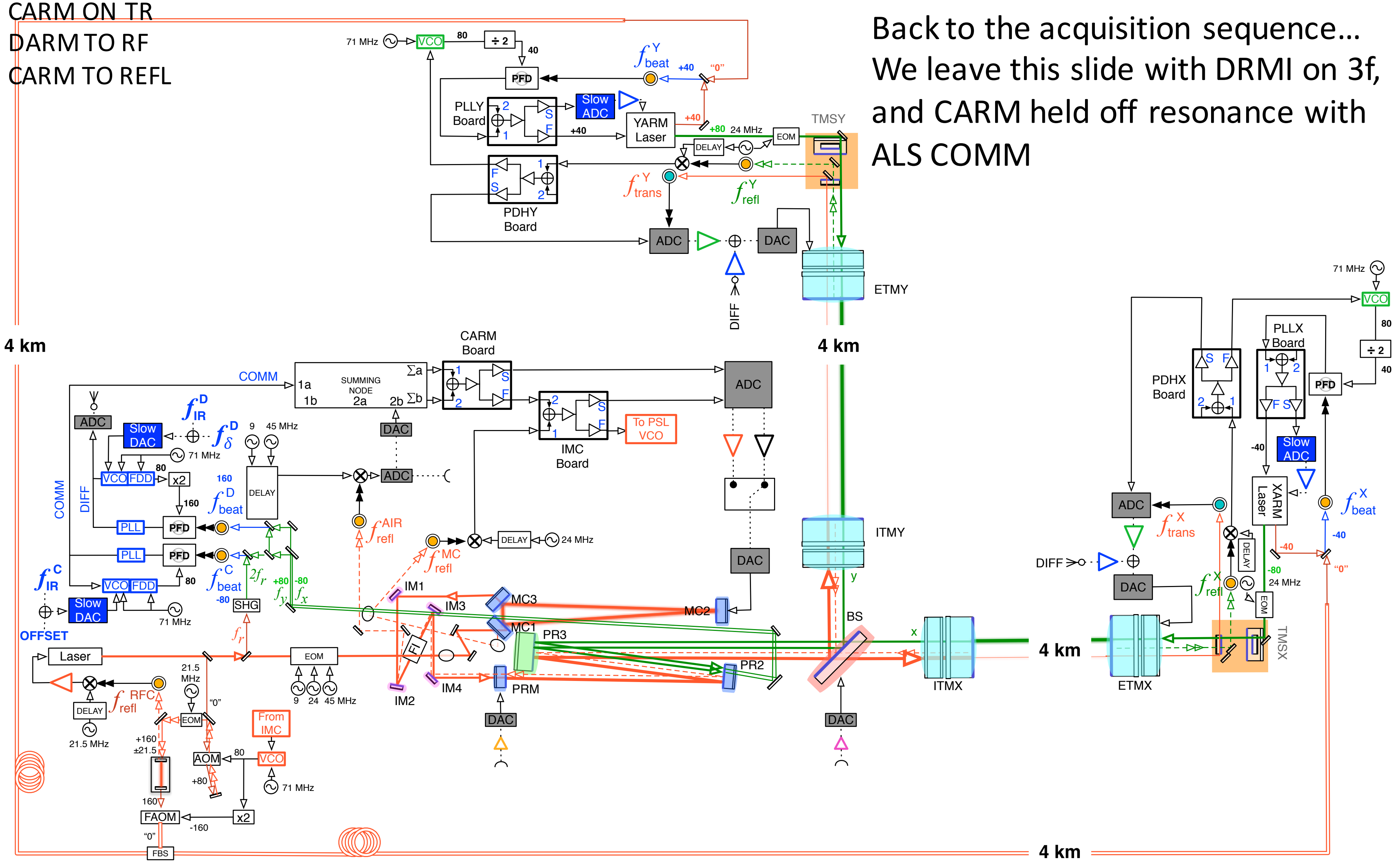


As we reduce the CARM offset (bring the arms into resonance), 3f signals are much less effected, and don't flip sign, unlike 1f signals!

IR FOUND
ARMS OFF REZ
DRMI
CARM ON TR
DARM TO RF
CARM TO REFL

DRMI (1F, 3F)

Back to the acquisition sequence… We leave this slide with DRMI on 3f, and CARM held off resonance with ALS COMM

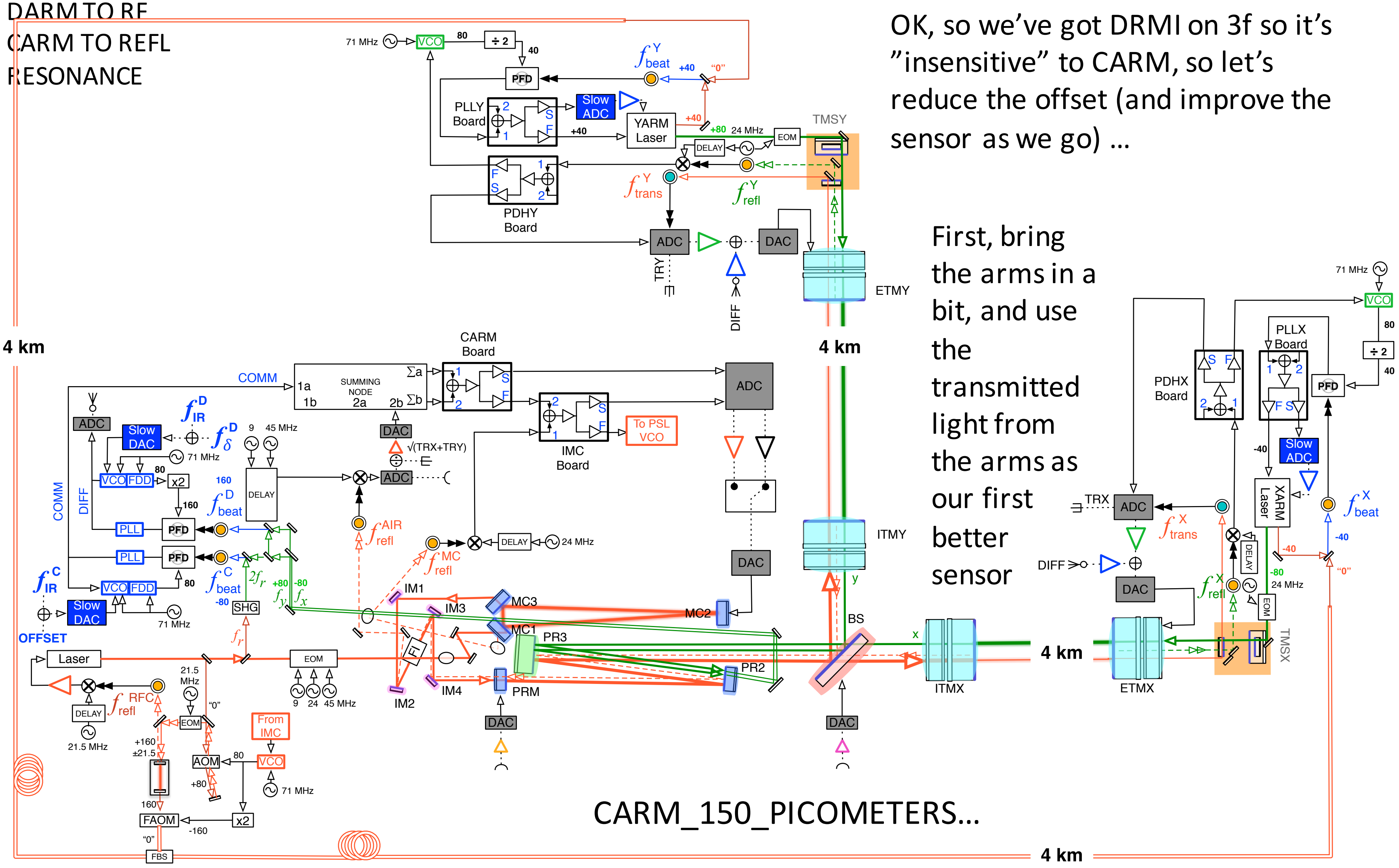


ARMS OFF REZ
DRMI
CARM ON TR
DARM TO RF
CARM TO REFL
RESONANCE

CARM ON TRANSMISSION

OK, so we've got DRMI on 3f so it's "insensitive" to CARM, so let's reduce the offset (and improve the sensor as we go) …

First, bring the arms in a bit, and use the transmitted light from the arms as our first better sensor

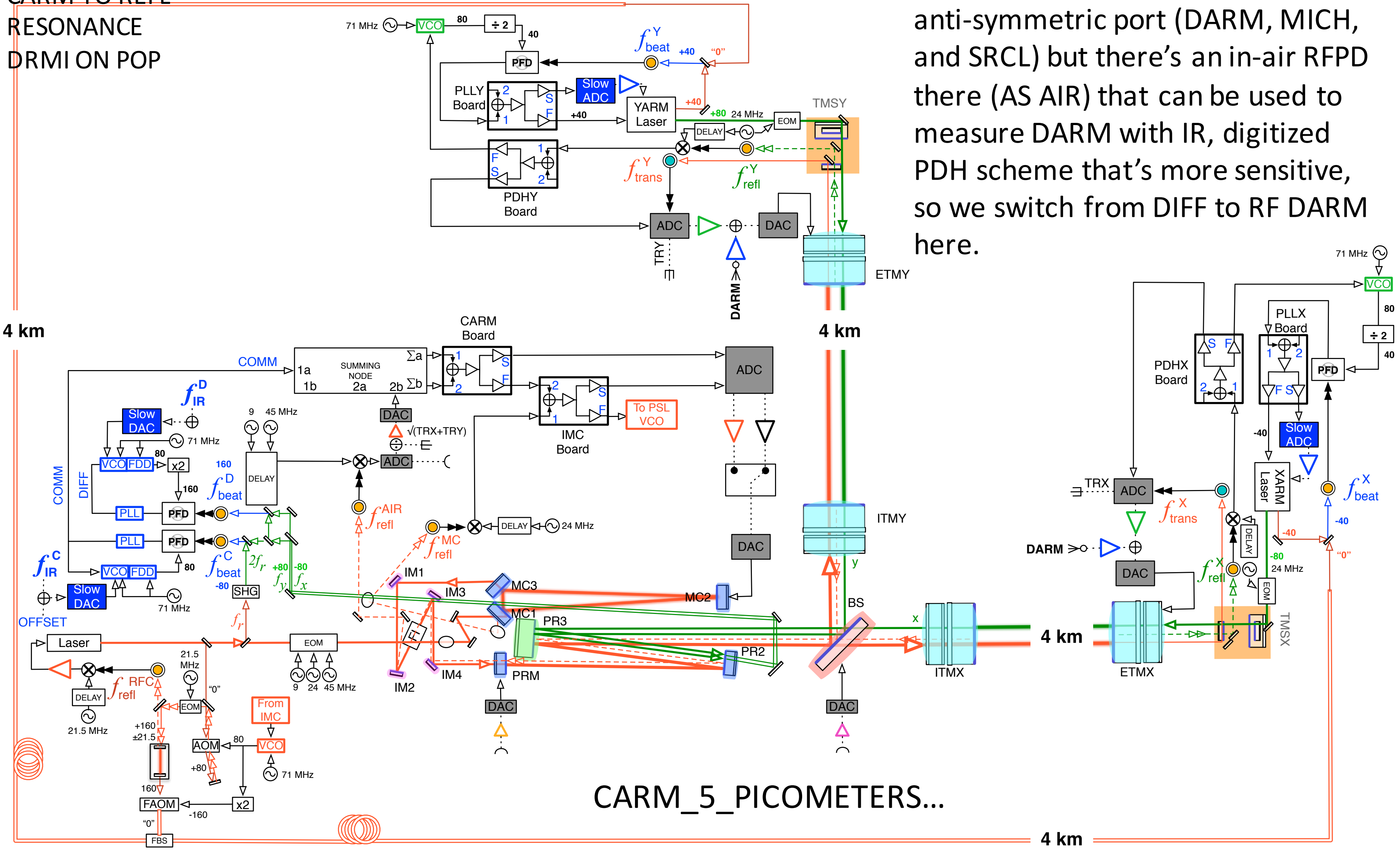


CARM_150_PICOMETERS…

DRMI
CARM ON TR
DARM TO RF
CARM TO REFL
RESONANCE
DRMI ON POP

DARM to RF

OK, this talk admittedly ignores the anti-symmetric port (DARM, MICH, and SRCL) but there's an in-air RFPD there (AS AIR) that can be used to measure DARM with IR, digitized PDH scheme that's more sensitive, so we switch from DIFF to RF DARM here.

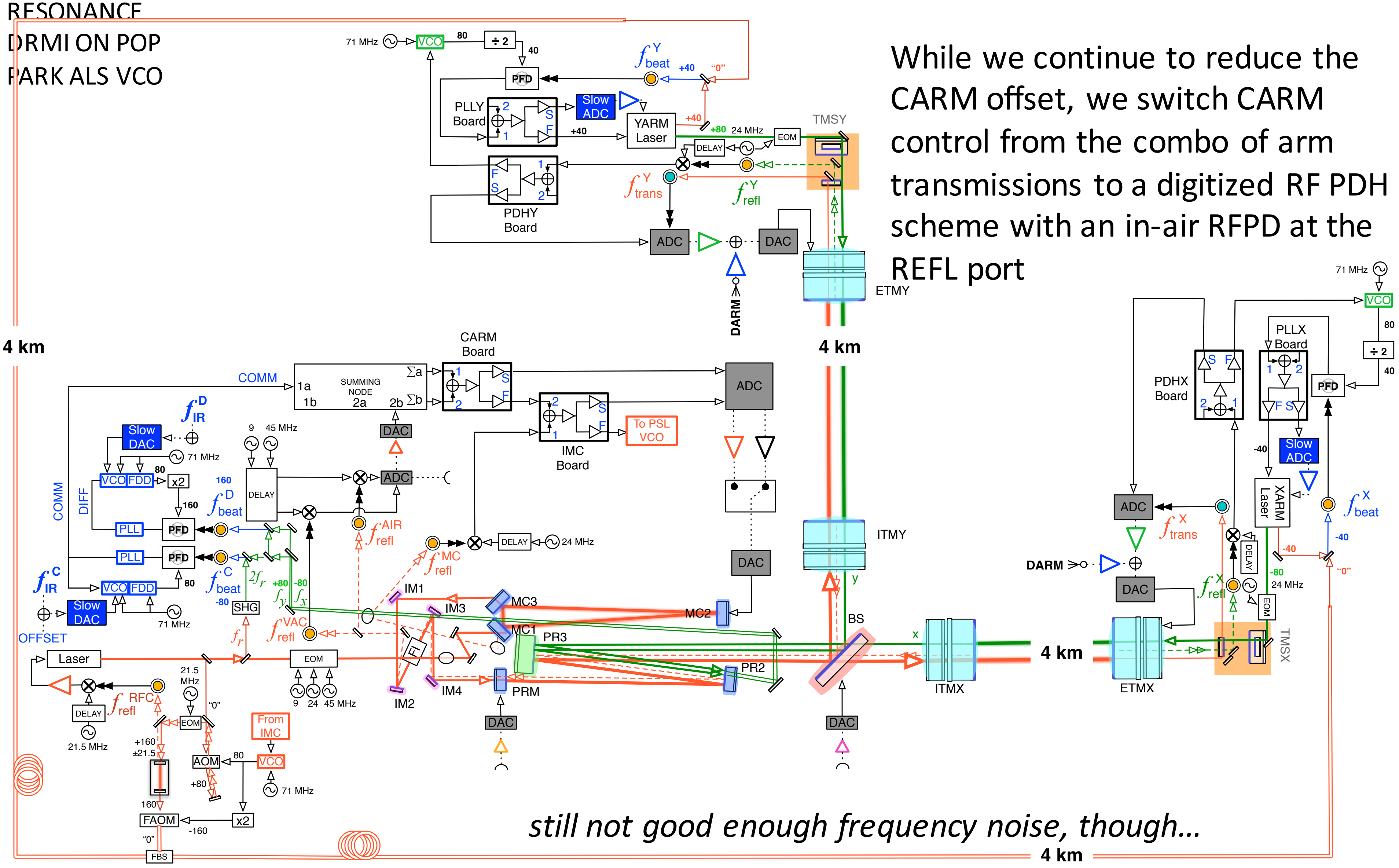


CARM_5_PICOMETERS...

CARM ON TR
DARM TO RF
CARM TO REFL
RESONANCE
DRMI ON POP
PARK ALS VCO

CARM to REFL

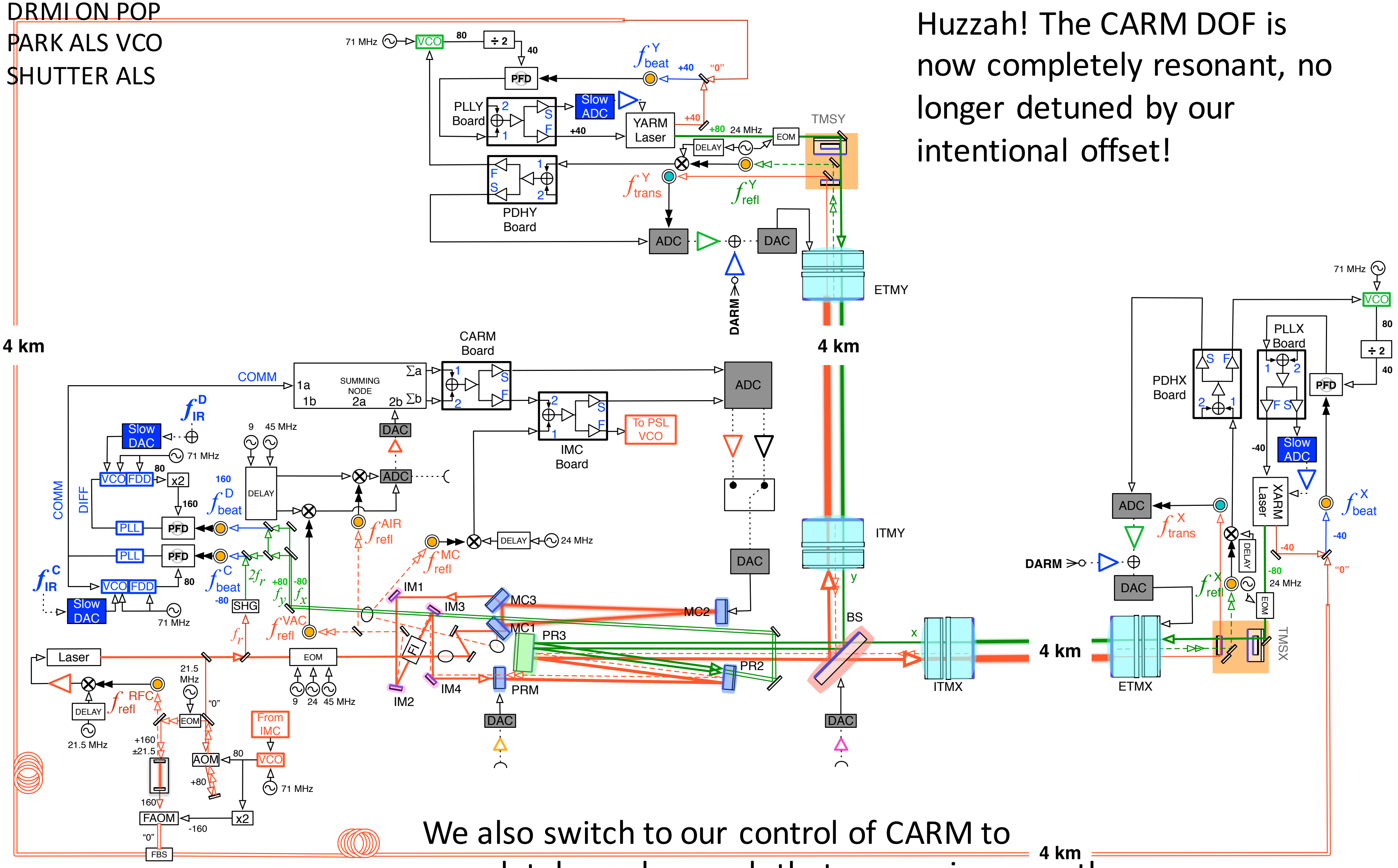
While we continue to reduce the CARM offset, we switch CARM control from the combo of arm transmissions to a digitized RF PDH scheme with an in-air RFPD at the REFL port



still not good enough frequency noise, though…

DARM TO RF
CARM TO REFL
RESONANCE
DRMI ON POP
PARK ALS VCO
SHUTTER ALS

RESONANCE



Huzzah! The CARM DOF is now completely resonant, no longer detuned by our intentional offset!

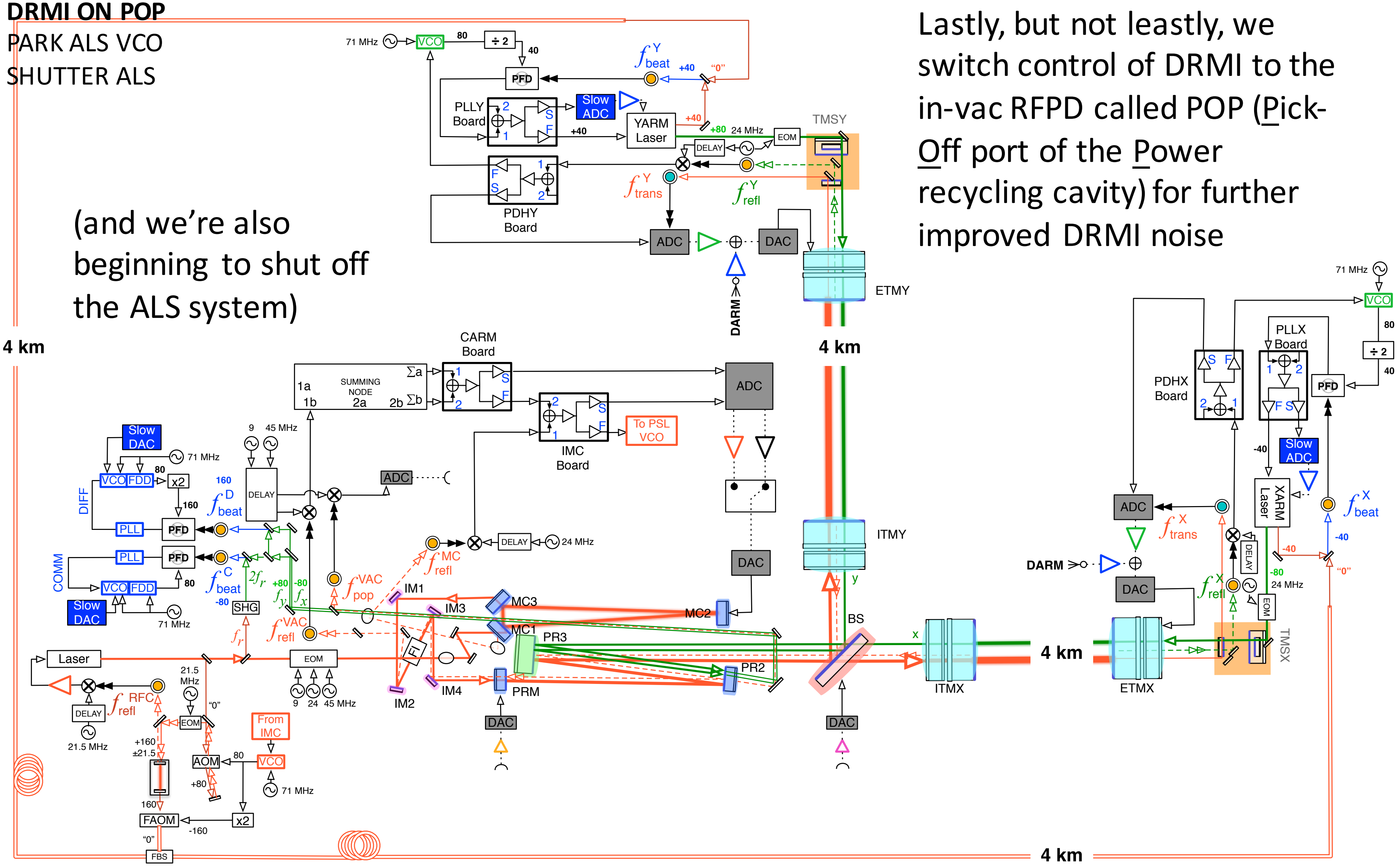
We also switch to our control of CARM to completely analog, such that we can increase the bandwidth of our loop to ~20 kHz

DARM TO RF
CARM TO REFL
RESONANCE
DRMI ON POP
PARK ALS VCO
SHUTTER ALS

DRMI ON POP

Lastly, but not leastly, we switch control of DRMI to the in-vac RFPD called POP (Pick-Off port of the Power recycling cavity) for further improved DRMI noise

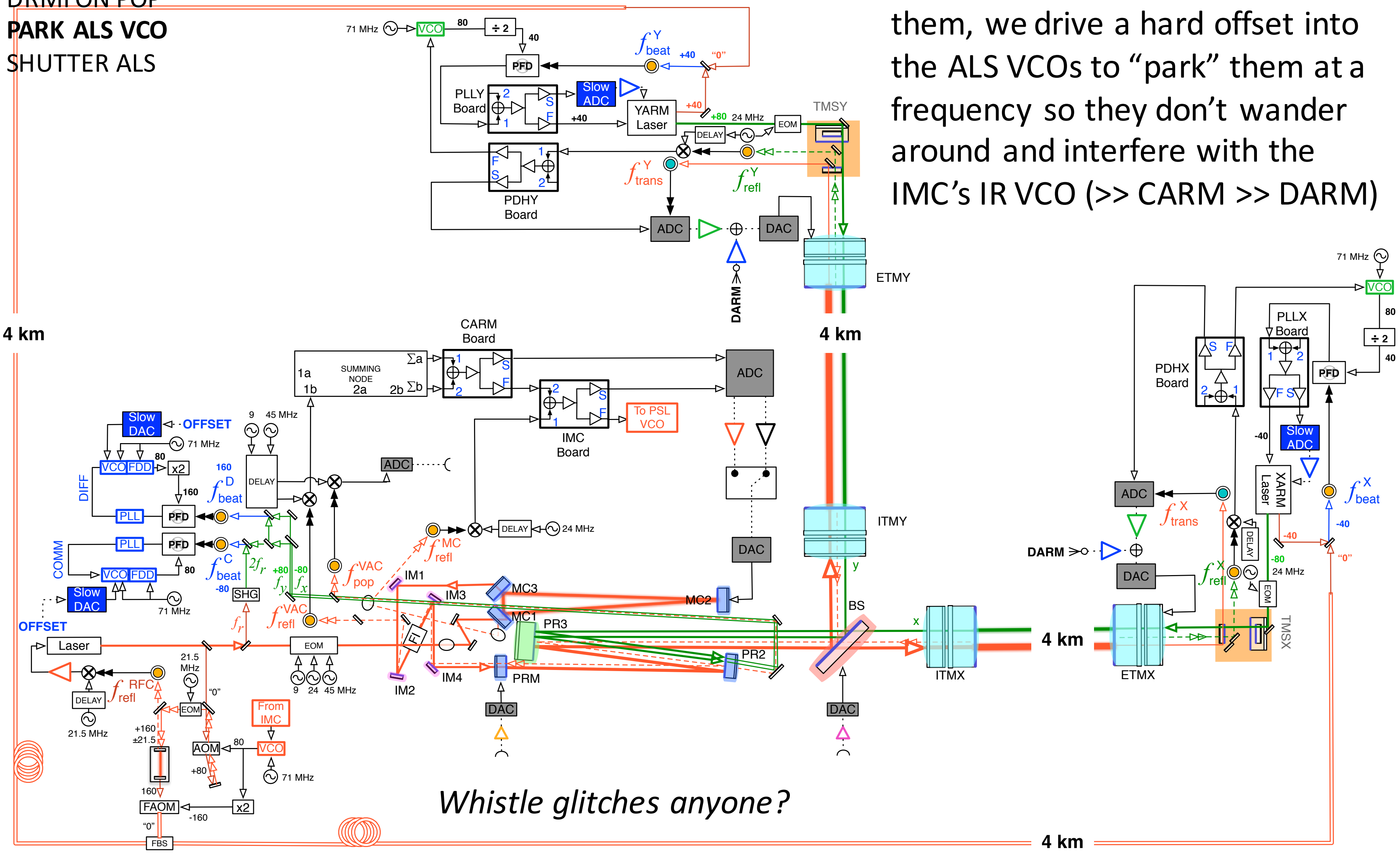
(and we're also beginning to shut off the ALS system)



DARM TO RF
CARM TO REFL
RESONANCE
DRMI ON POP
PARK ALS VCO
SHUTTER ALS

PARK ALS VCO

Now, since we're no longer using them, we drive a hard offset into the ALS VCOs to "park" them at a frequency so they don't wander around and interfere with the IMC's IR VCO (>> CARM >> DARM)



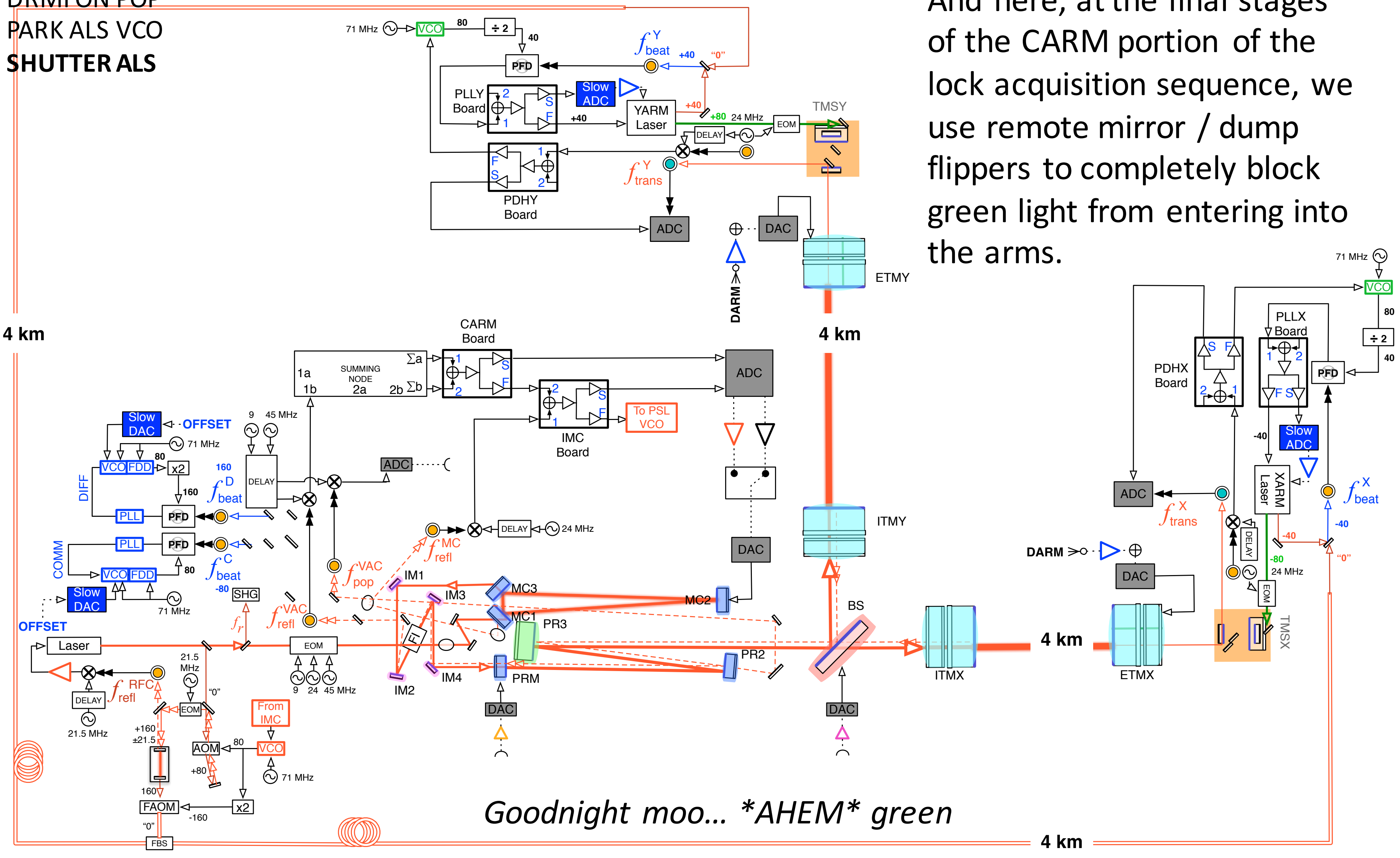
Whistle glitches anyone?

No thank you!

DARM TO RF
CARM TO REFL
RESONANCE
DRMI ON POP
PARK ALS VCO
SHUTTER ALS

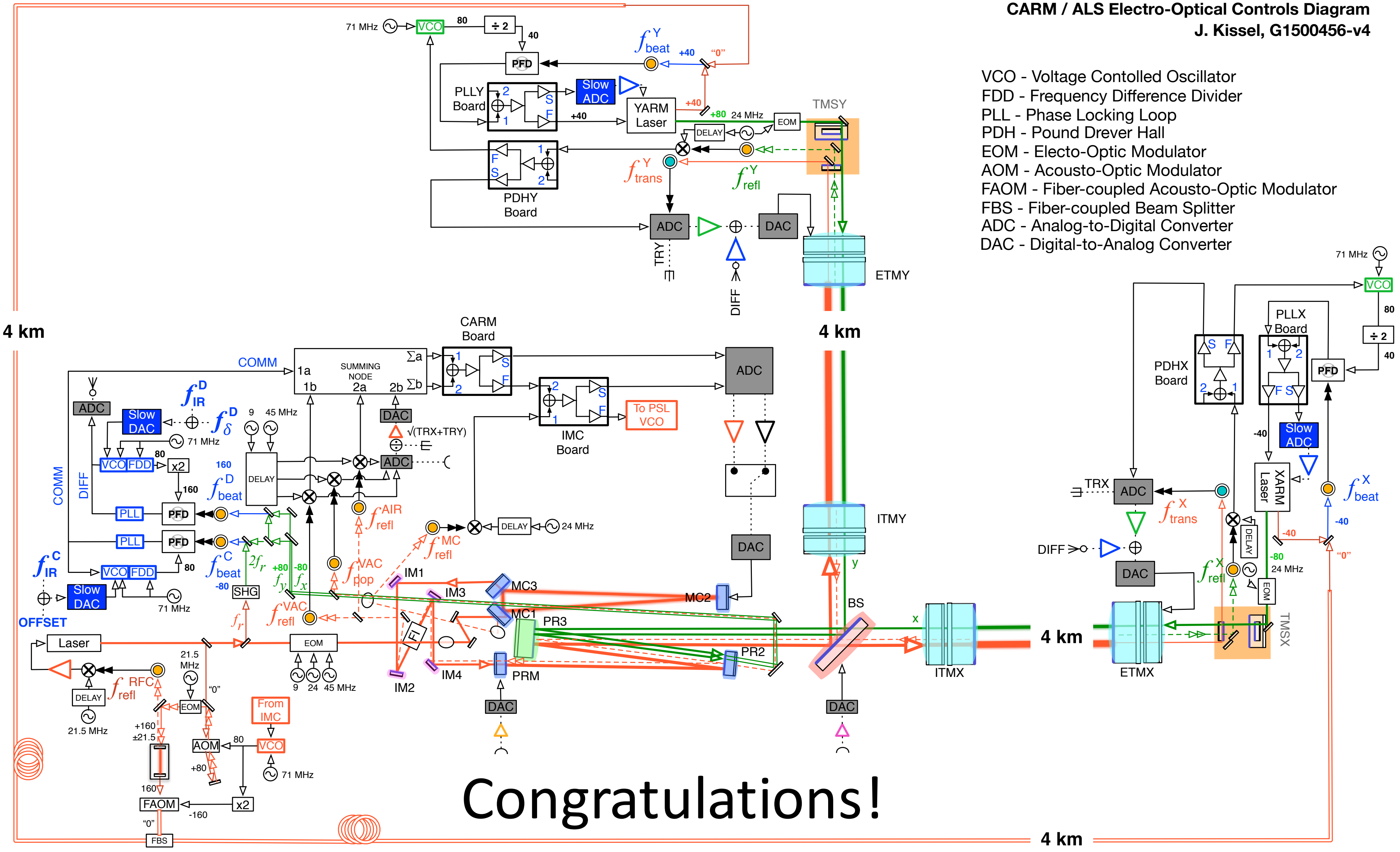
SHUTTER ALS

And here, at the final stages of the CARM portion of the lock acquisition sequence, we use remote mirror / dump flippers to completely block green light from entering into the arms.



*Goodnight moo… *AHEM* green*

Now You Understand this Diagram



CARM / ALS Electro-Optical Controls Diagram
J. Kissel, G1500456-v4

VCO - Voltage Contolled Oscillator
FDD - Frequency Difference Divider
PLL - Phase Locking Loop
PDH - Pound Drever Hall
EOM - Electo-Optic Modulator
AOM - Acousto-Optic Modulator
FAOM - Fiber-coupled Acousto-Optic Modulator
FBS - Fiber-coupled Beam Splitter
ADC - Analog-to-Digital Converter
DAC - Digital-to-Analog Converter

Congratulations!

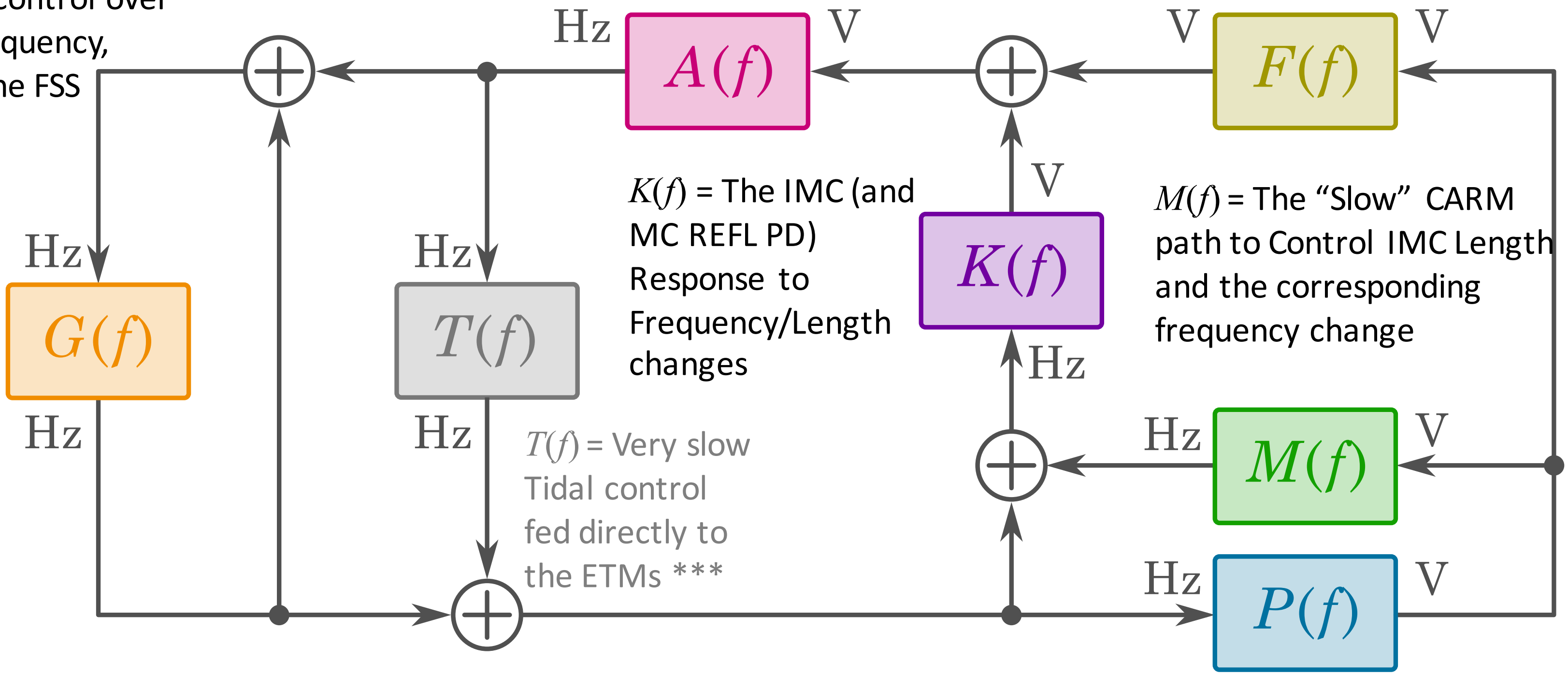
The Nested Loop Topology for Frequency Stabilization

From Evan Hall’s Thesis P1600295

A(*f*) = The IMC PDH control filter and requested voltage control to the AOM frequency before the reference cavity

F(*f*) = The “Fast” CARM path to PDH control a.k.a. “Additive offset” path

G(*f*) = Reference cavity control over PSL frequency, a.k.a the FSS



K(*f*) = The IMC (and MC REFL PD) Response to Frequency/Length changes

M(*f*) = The “Slow” CARM path to Control IMC Length and the corresponding frequency change

T(*f*) = Very slow Tidal control fed directly to the ETMs ***

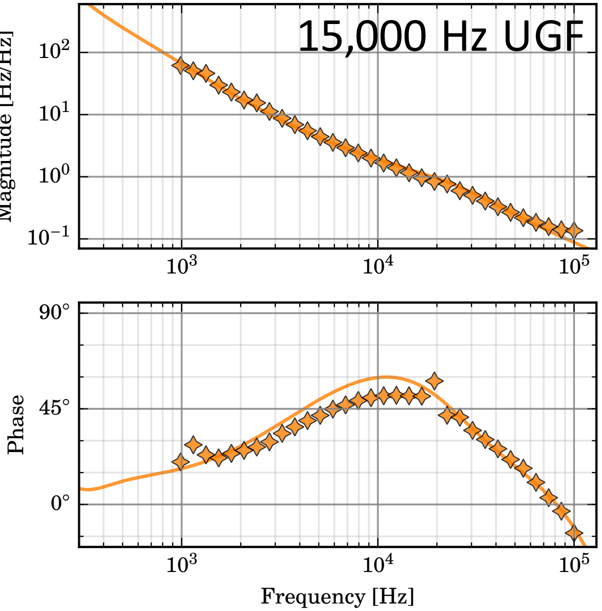
P(*f*) = The interferometer’s CARM degree of freedom (and the REFL PD that measures it) Response to Frequency/ Length changes

*** We didn’t talk about this. See T1400733.

The Nested Loop Open Loop Gain TFs

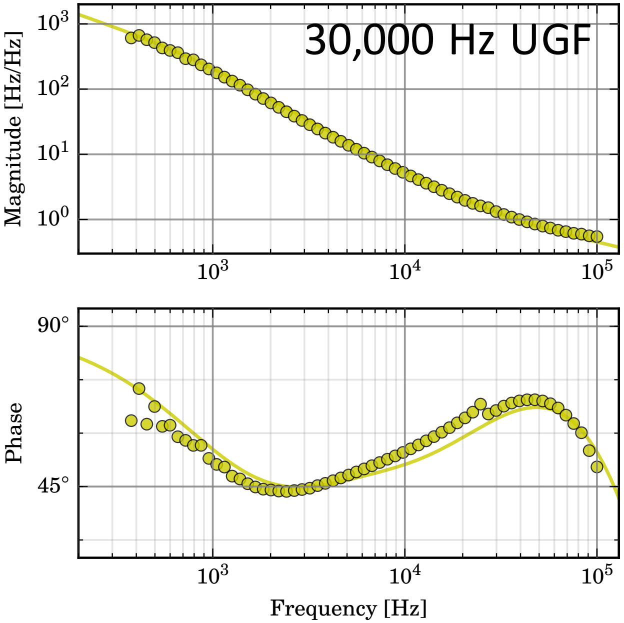
From Evan Hall's Thesis [P1600295]

CARM OLG TF



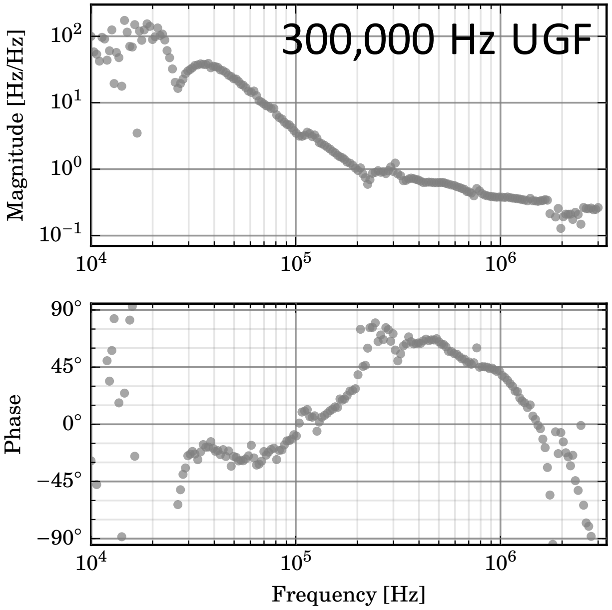
x1e3 at 100 Hz

IMC OLG TF



x1e4 at 100 Hz

FSS OLG TF



x1e3 at 100 Hz

= 10 orders of magnitude 100 Hz

✓

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 (distance / frequency spacing between resonances)

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

$$FSR = \Delta f = \frac{c}{2L} \text{ (in } [Hz])$$

$$FSR = \Delta \lambda = \frac{\lambda^2}{2L} \text{ (in } [m])$$

$$\frac{\Delta L}{L} = \frac{\Delta f}{f} \quad {}^{**}$$

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

Cavity Linewidth = “Full-width Half Maximum” = 2* Cavity Pole Frequency

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

** Check out P010013 for why this is an approximation

Cavity Finesse

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

As mirror reflectivities go up, cavity Finesse, $\mathcal{F}$, goes up, Linewidth gets smaller