Cosmic Explorer Input Optics Design and Layout

Gravitational Waves Advanced Detector Workshop

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Cocoa Beach, Florida

Motivation

- The Advanced LIGO PSL and Input Optics subsystems deliver one of the most stable high power 1064 nm lasers in the world.
    - In the 10 Hz regime Advanced LIGO has measured frequency noise < 1 μHz/rtHz and intensity noise < 10^{-8} RIN/rtHz.

- Cosmic Explorer requirements on input laser stability are *more stringent*.
    - Made more difficult by the low FSR = 3.8 kHz.

Open Questions related to Input Optics

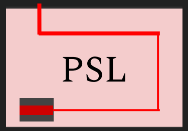
1. How are we going to frequency stabilize without using CARM?
2. Are there clever ways to improve our usual stabilization technology?
3. Biggest problem with noisebudgets here is unknown controls cross-coupling
4. Second biggest problem is unknown interferometer thermal states

IO Layout

Solution:

Three mode cleaners

1) Pre-mode cleaner
   16 m
2) Input mode cleaner 1
   100 m
3) Input mode cleaner 2
   330 m



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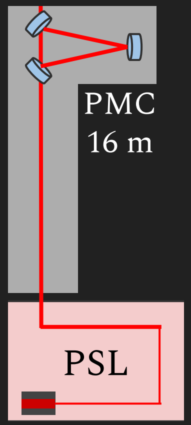

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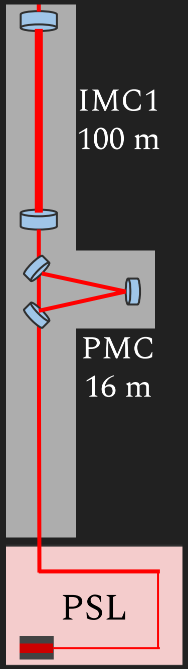

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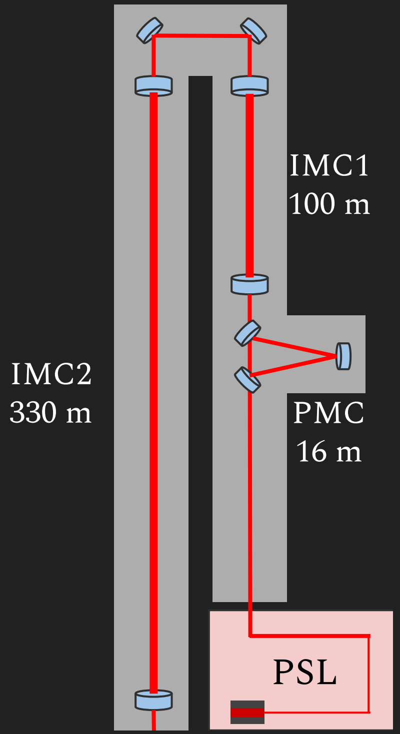

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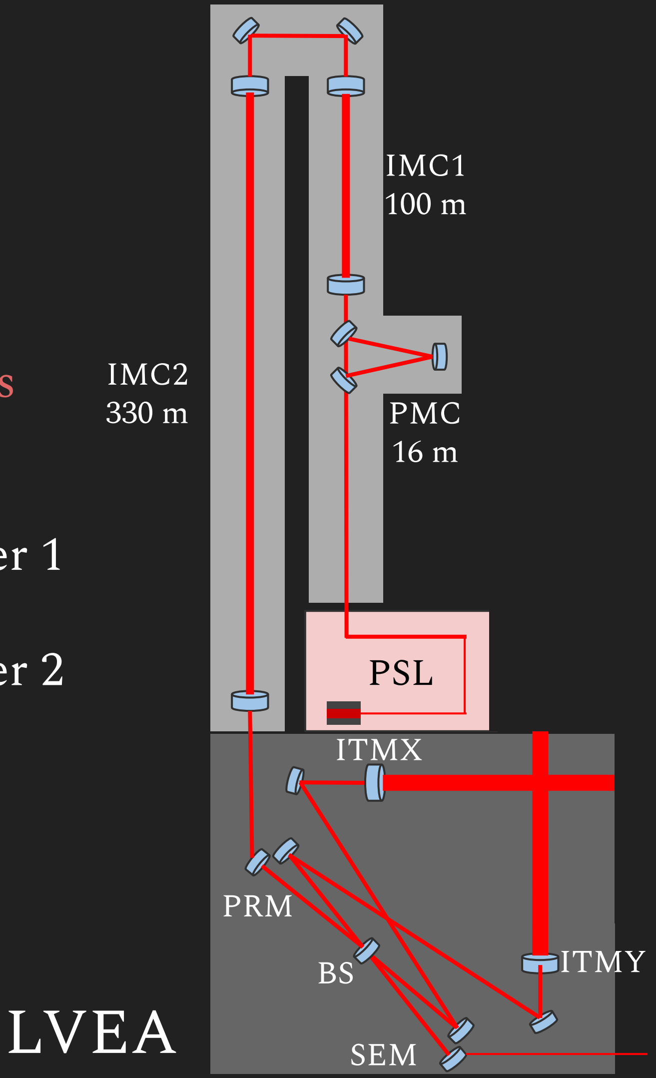

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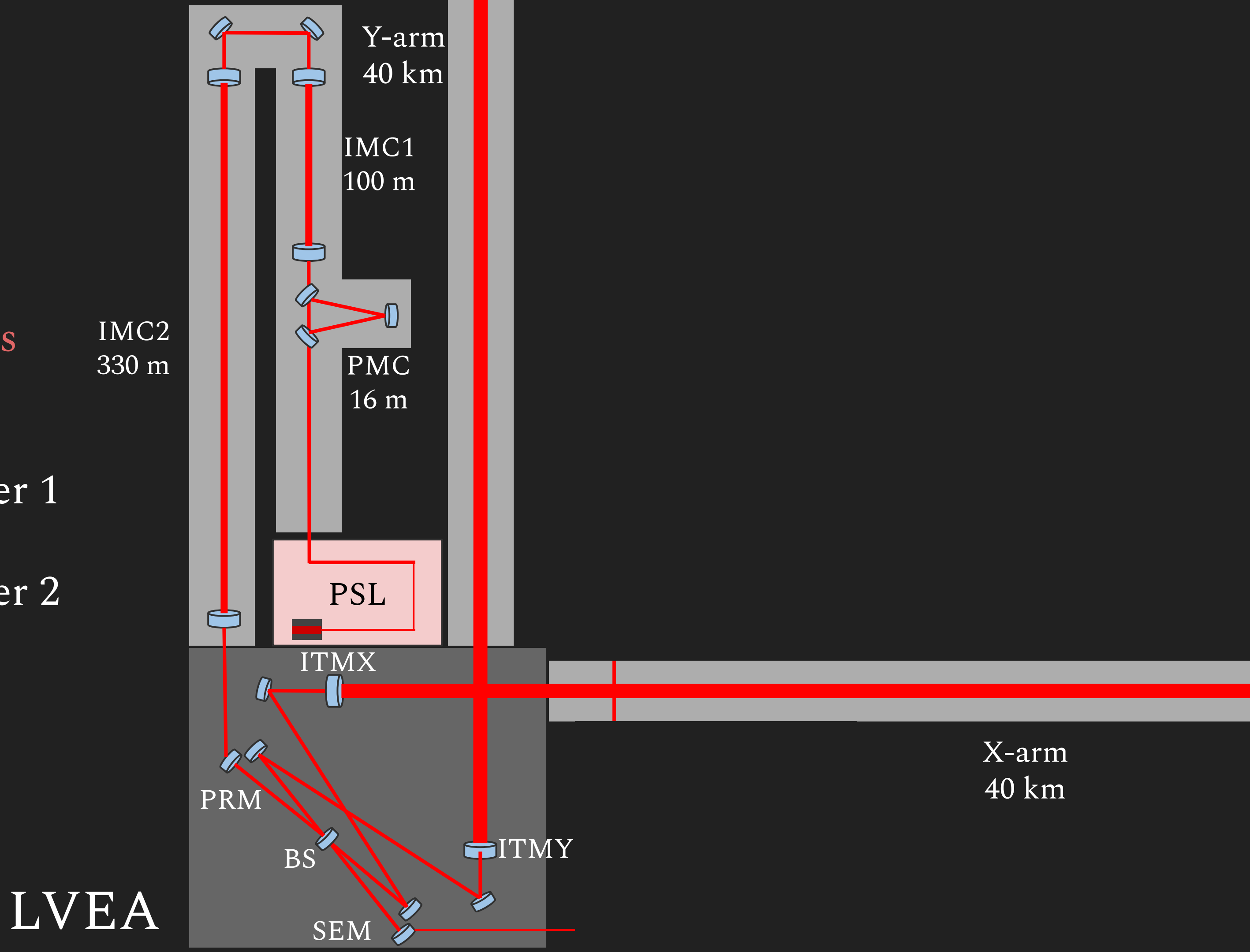

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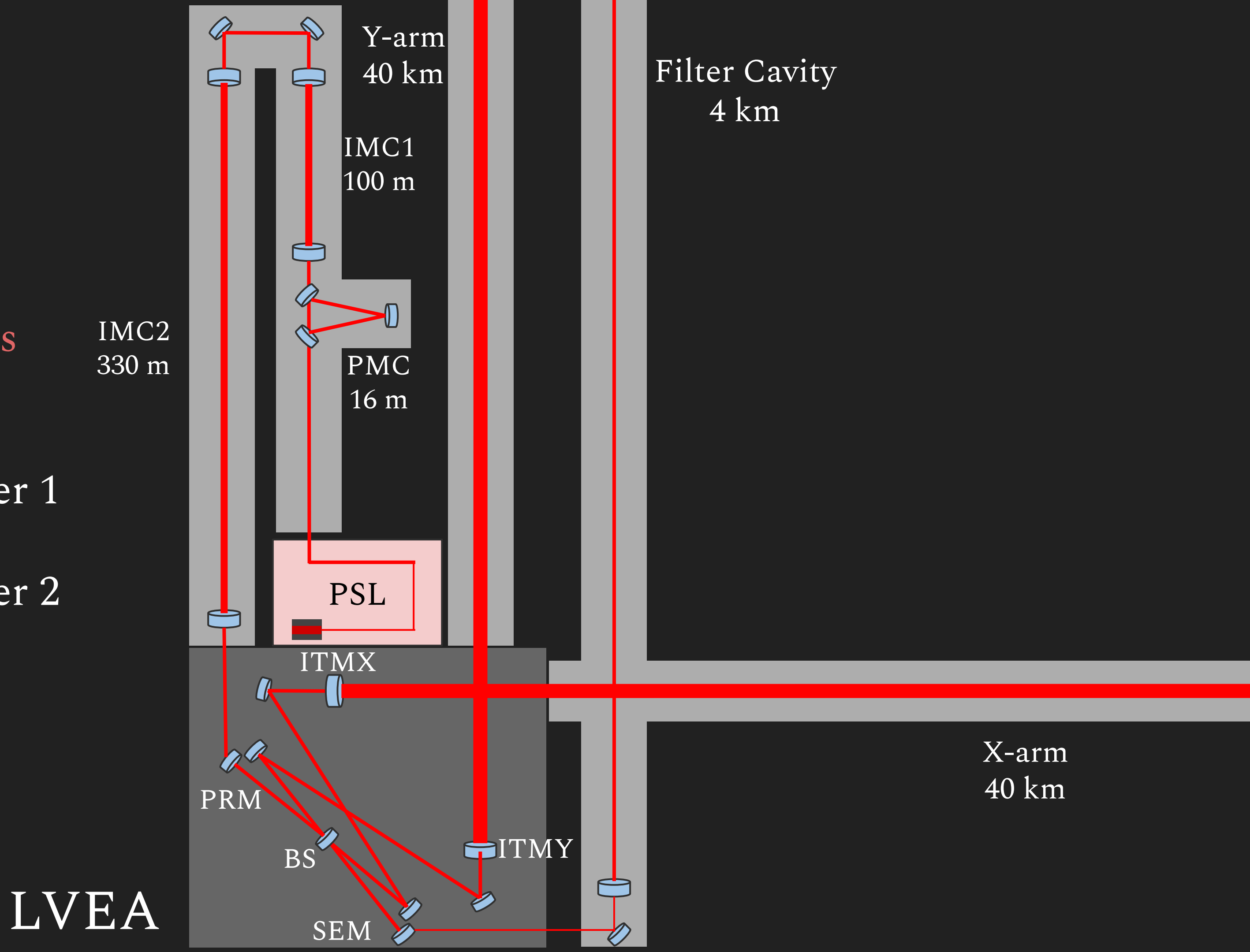


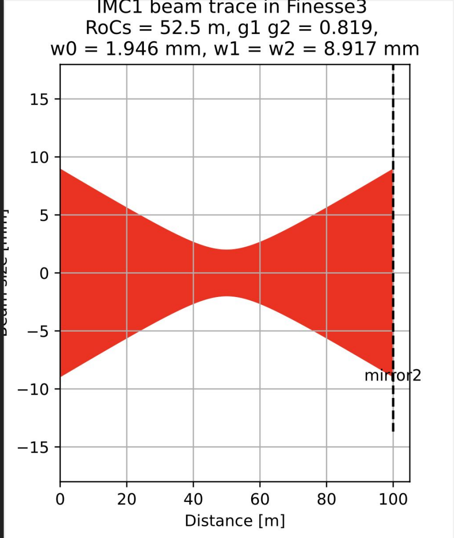
Layout considerations

- Two mirror mode cleaner cavities are planned
  - ✅ Easier to control and align
  - ✅ Fewer mirrors, less loss
  - ✅ Reverse propagating beam is controlled
  - ✅ Bigger beam spots, less thermal deformation
  - ❌ Worse polarization control, may need suspended polarizers
  - ❌ Higher backscatter
  - ❌ Input and output ports far away from each other
- Need to pass RF sidebands through IMCs for length control
  - ❌ RF sidebands injected 330 meters away?
- Gentle beam geometry throughout
  - May need mode sensing and control for input into IMCs and main IFO

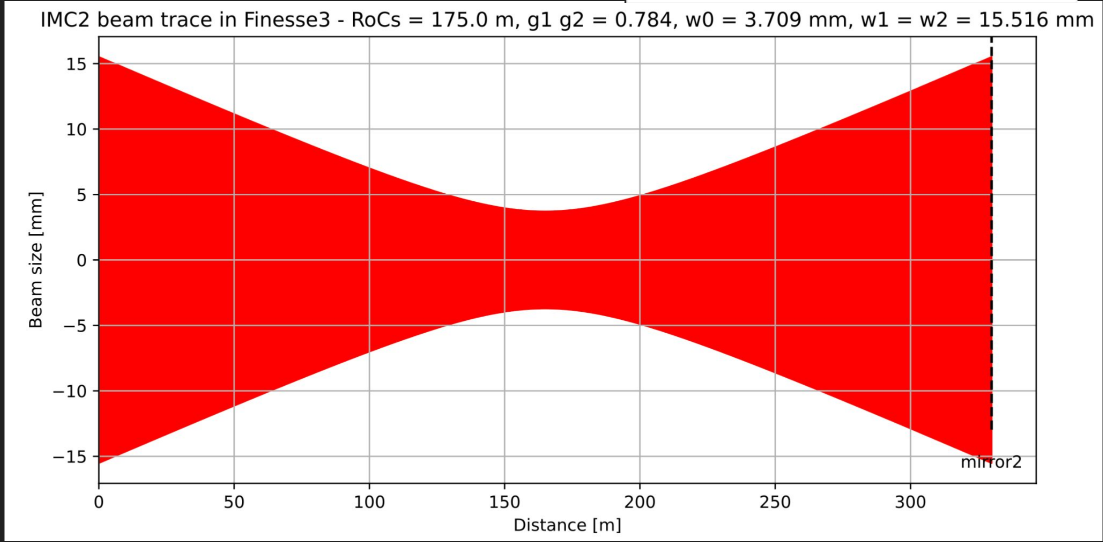
IMC geometry

- Fairly concentric cavities planned (g1 g2 = 0.8)
- Two mirror cavity gives us two BIG beam spots, instead of one BIG and two small.
  - Beam spot diameters = {1.8 cm, 3 cm}
  - Peak intensities at mirrors = {51 kW / cm^2, 14 kW / cm^2}
    - Can help limit thermo-refractive noise
    - Will lower thermal deformation
- Planar three mirror cavities are another option.

IMC1



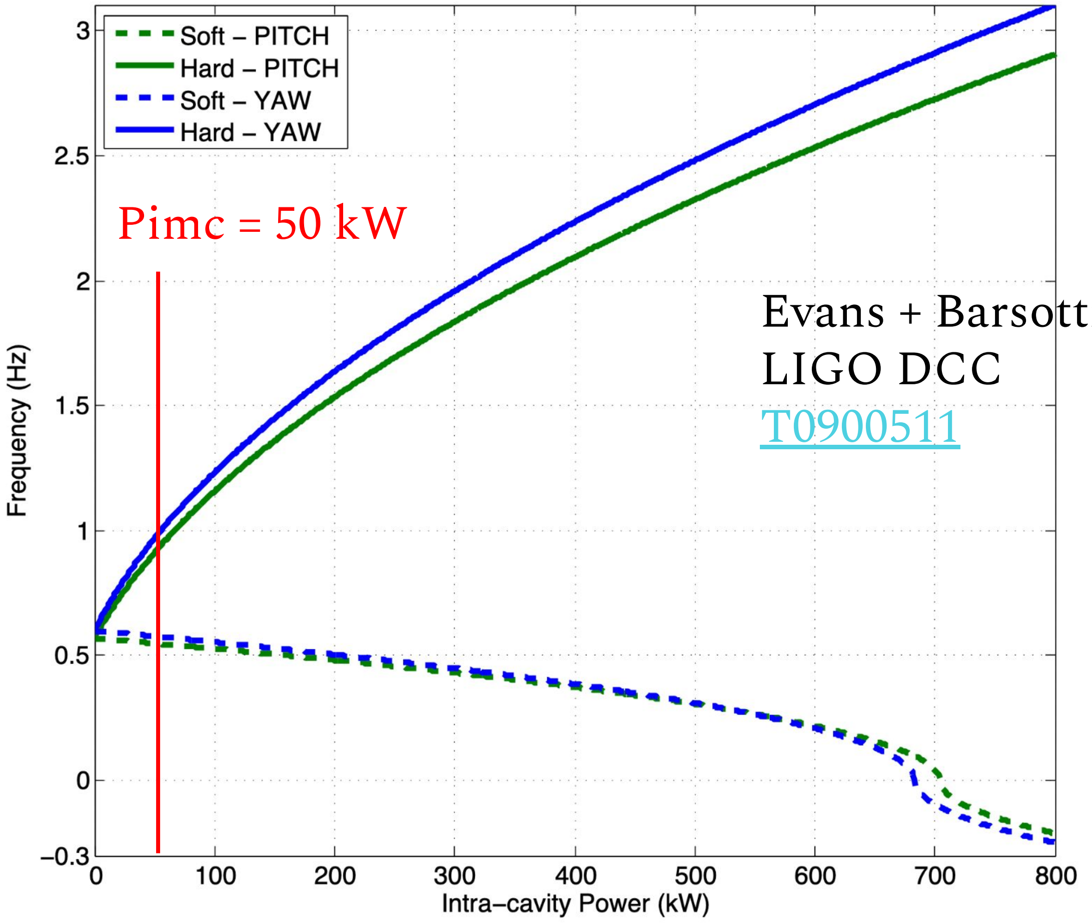
IMC2



IMC2 Sidles-Sigg

Anticipate around Pimc = 50 kW, for a finesse of 700 and Pin = 250 W.

If we assume Advanced LIGO-like quad suspensions, ASC will of SOFT and HARD modes will be stable but not static



Evans + Barsotti
LIGO DCC
T0900511

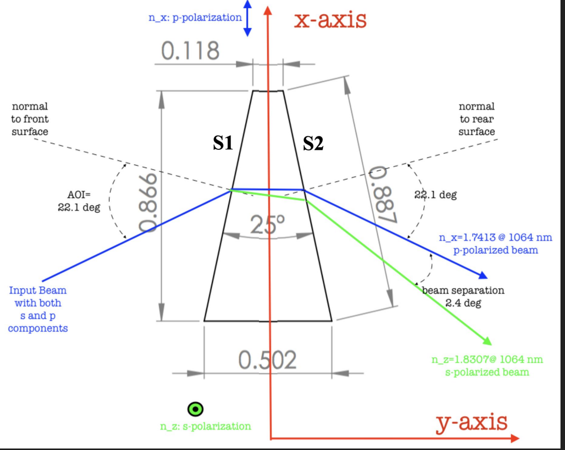
Figure 6: Frequency of the Hard and Soft modes for PITCH and YAW in advanced LIGO, as function of the intra-cavity power.

Polarization control

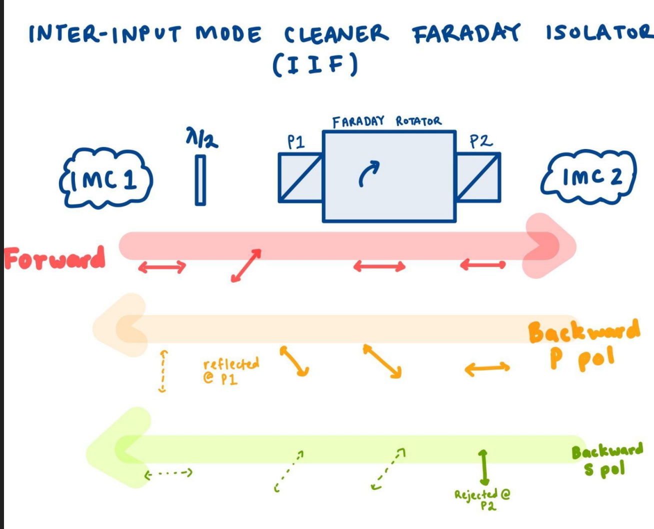
To deal with backscatter, we plan for an additional suspended polarizer before Faraday Isolator.

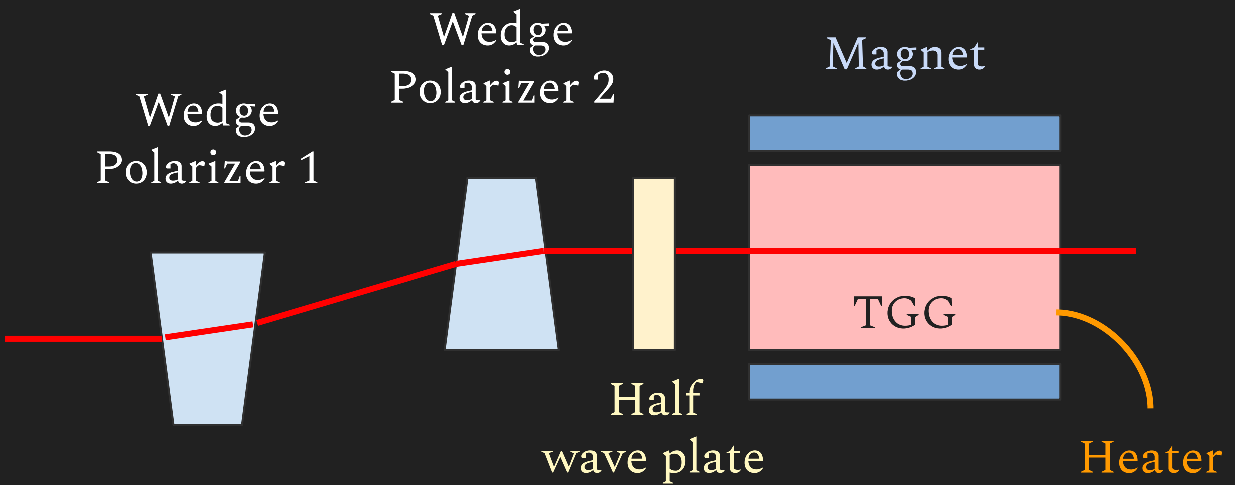
Wedge polarizers can have 10 ppm throughput loss and an isolation ratio of 50 dB.

Need no S-pol in reflection:
We can tune the temperature of the FIs to adjust the Verdet constant in situ.



DCC E1900284



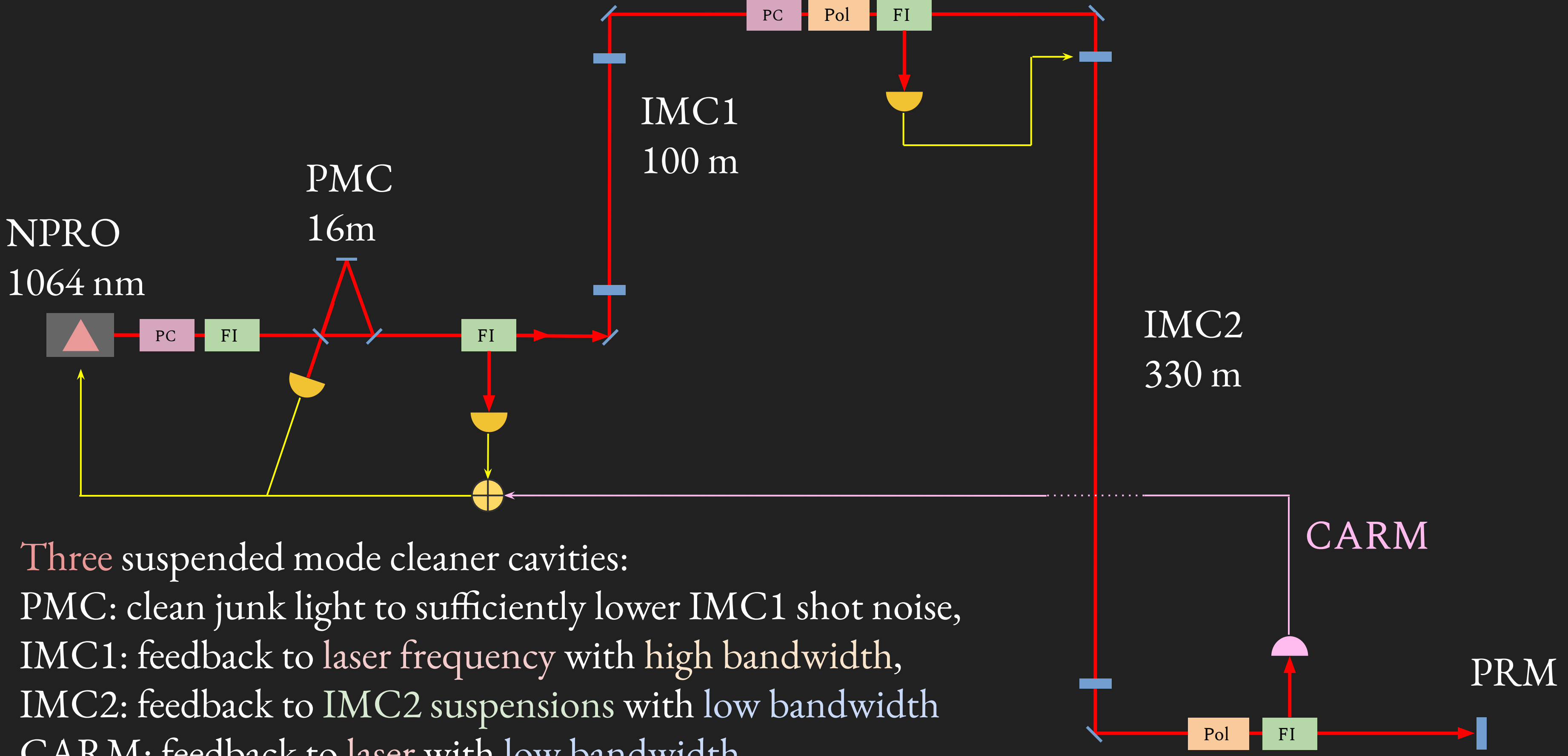


IMC noise considerations

- Nontrivial cross-couplings of control loops
  - Intensity to frequency noise coupling expected to be limiting
  - aLIGO IMC ASC impacts intensity noise limit at low frequency
  - May end up imprinting interferometer LSC + ASC controls on laser noise
    - Feedforward a must

- Need exceptional mode-matching into IMC1 to achieve shot noise limit
  - Primary motivation for inclusion of the suspended triangular PMC

Frequency Control

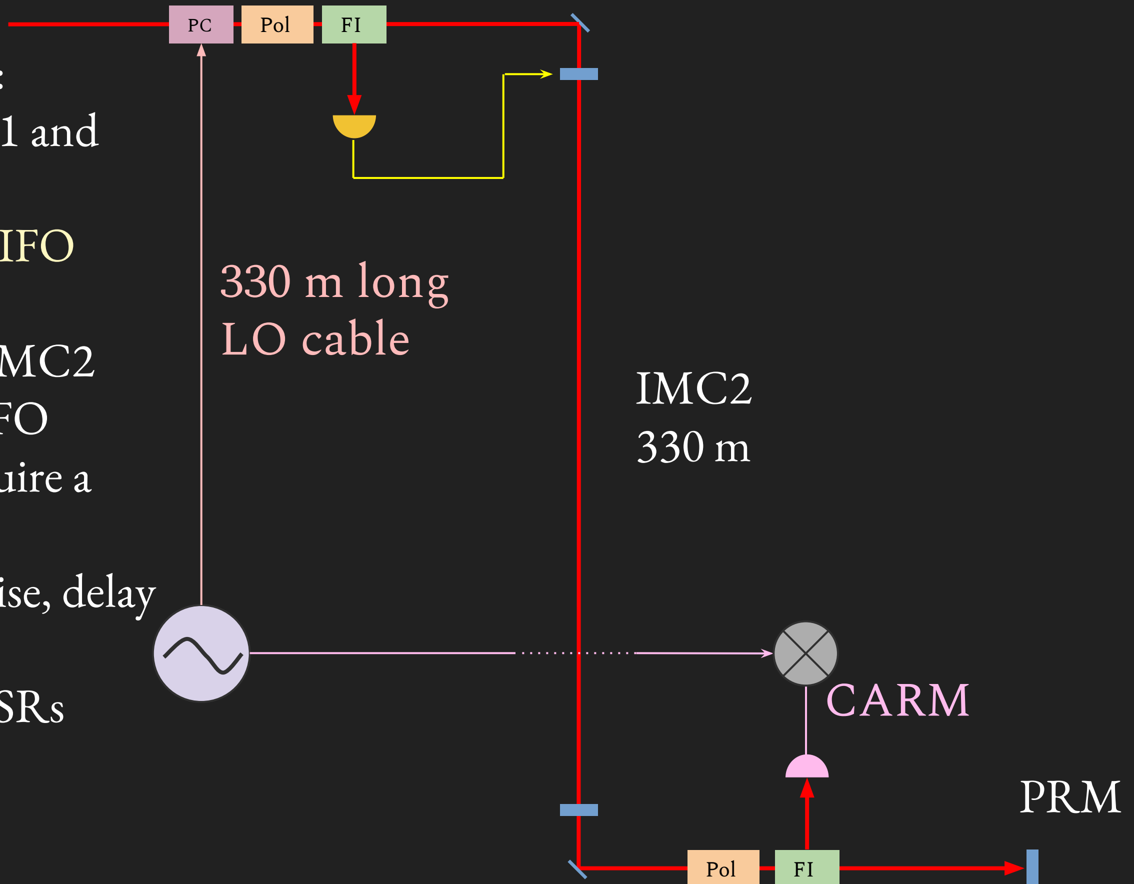


Three suspended mode cleaner cavities:
PMC: clean junk light to sufficiently lower IMC1 shot noise,
IMC1: feedback to laser frequency with high bandwidth,
IMC2: feedback to IMC2 suspensions with low bandwidth
CARM: feedback to laser with low bandwidth

Frequency Control: RF sideband injection

Potential problem with current setup:

- We want RF filtering from IMC1 and IMC2.
- Need to inject RF sidebands for IFO somewhere in IO chain
    - Currently injected before IMC2
- Injecting the RF sidebands for IFO control before IMC2 would require a 330 meter long LO cable
    - Could be susceptible to noise, delay
- Other options:
    - Match IMC1 and IMC2 FSRs
    - Use a triangular cavity



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Option 1

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Option 2

Input the RF sidebands before IMC1, and match the IMC1 and IMC2 FSRs to pass the RF sidebands through.

How should we inject the interferometer RF sidebands?

Option 1	Option 2	Option 3
Input the RF sidebands before IMC2, and make a 330 m RF cable connecting the LVEA/PSL and the IMC2 input Pockels Cell.	Input the RF sidebands before IMC1, and match the IMC1 and IMC2 FSRs to pass the RF sidebands through.	Input the RF sidebands before IMC2, and use a triangular cavity for IMC2.

How should we inject the interferometer RF sidebands?

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Input the RF sidebands before IMC2, and make a 330 m RF cable connecting the LVEA/PSL and the IMC2 input Pockels Cell.

Option 2

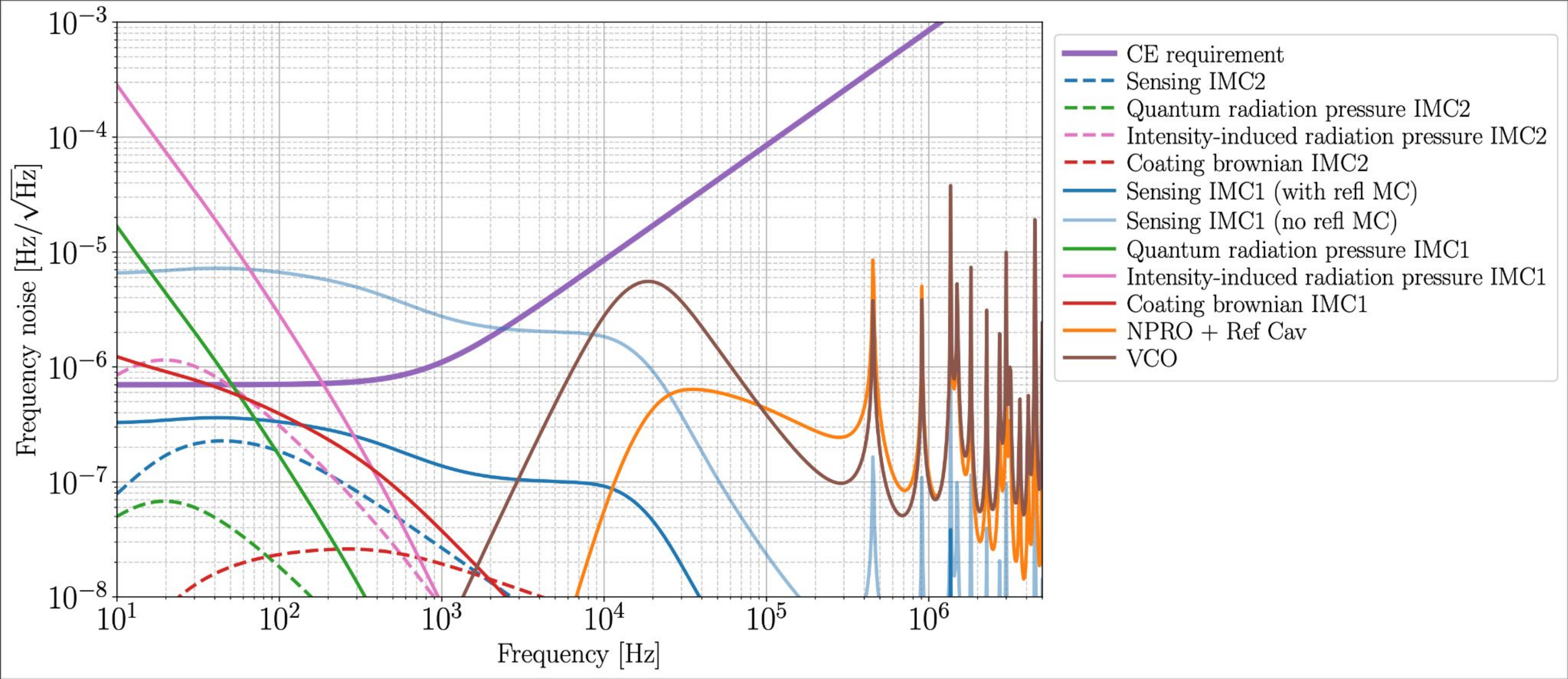
Input the RF sidebands before IMC1, and match the IMC1 and IMC2 FSRs to pass the RF sidebands through.

Option 3

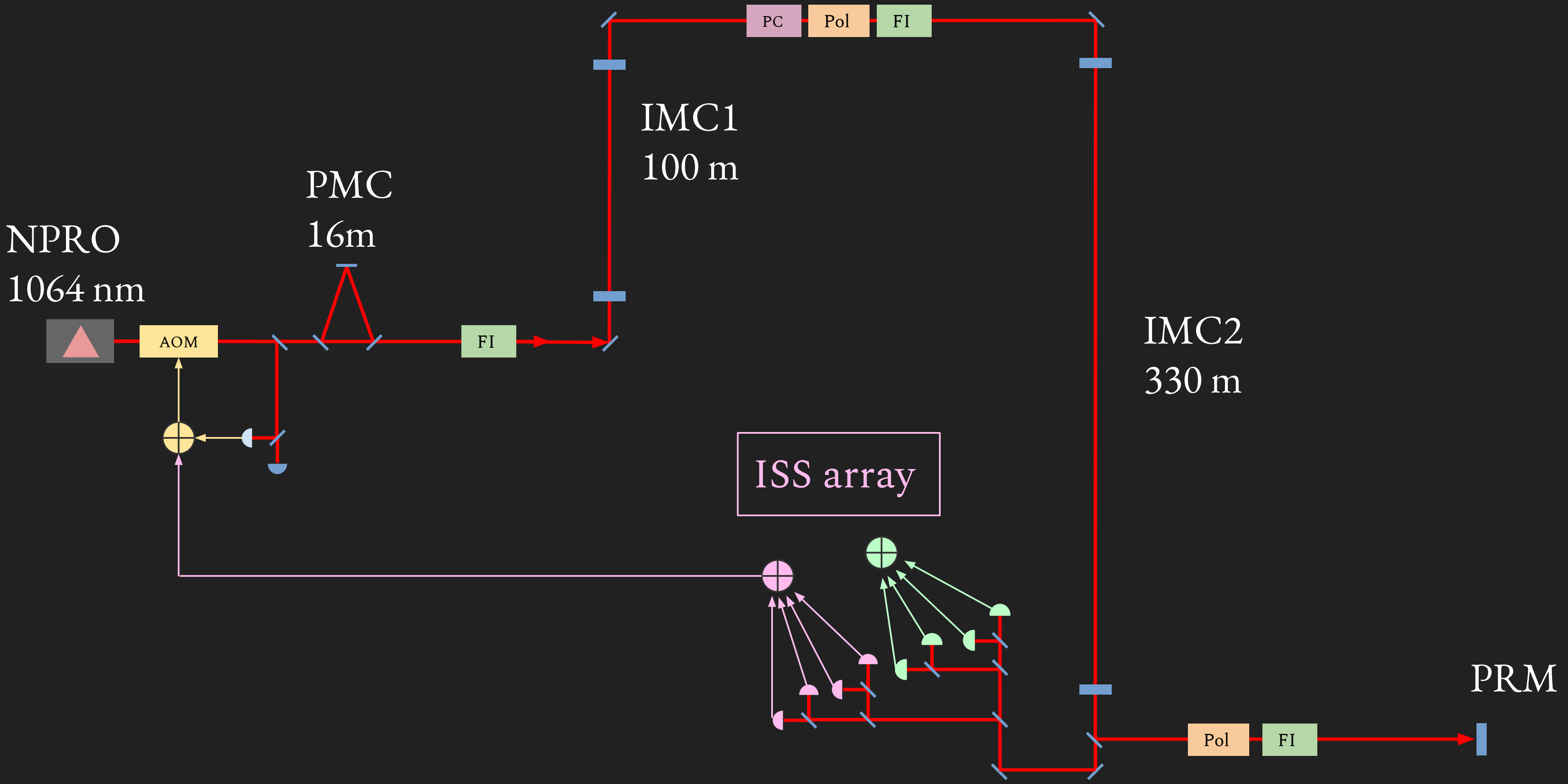
Input the RF sidebands before IMC2, and use a triangular cavity for IMC2.

Option 4: Something even more clever

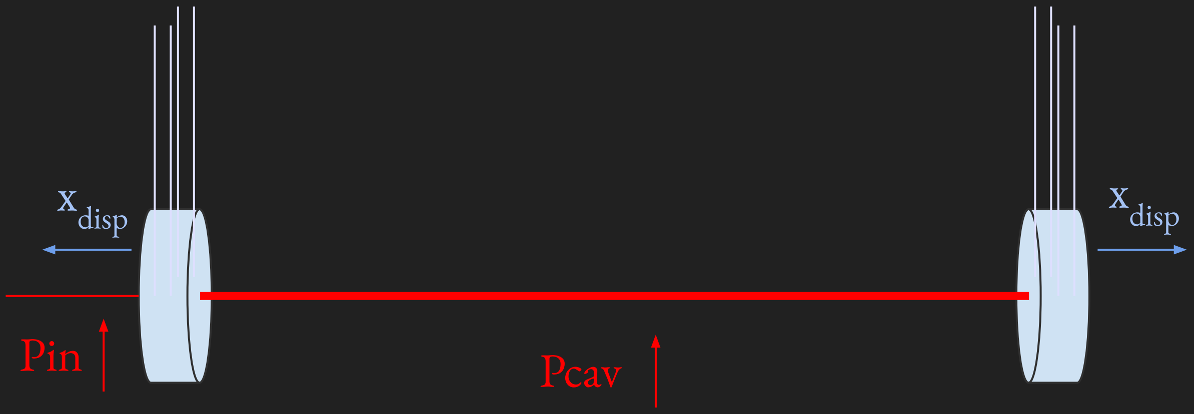
Double IMC frequency noisebudget



Intensity Control



Intensity noise to Frequency Noise



$$\sqrt{S_{\mathrm{shot}}} = 2h\nu_0 P_{\mathrm{pd}} \;[\mathrm{W}/\sqrt{\mathrm{Hz}}]$$

$$\sqrt{S_{\mathrm{RIN}}} = \frac{\sqrt{S_{\mathrm{shot}}}}{P_{\mathrm{pd}}} \;[\frac{\mathrm{W/W}}{\sqrt{\mathrm{Hz}}}]$$

$$\sqrt{S_{\mathrm{disp}}} = -\frac{1}{m\omega^2}\frac{2P_{\mathrm{cav}}}{c}\sqrt{S_{\mathrm{RIN}}}$$

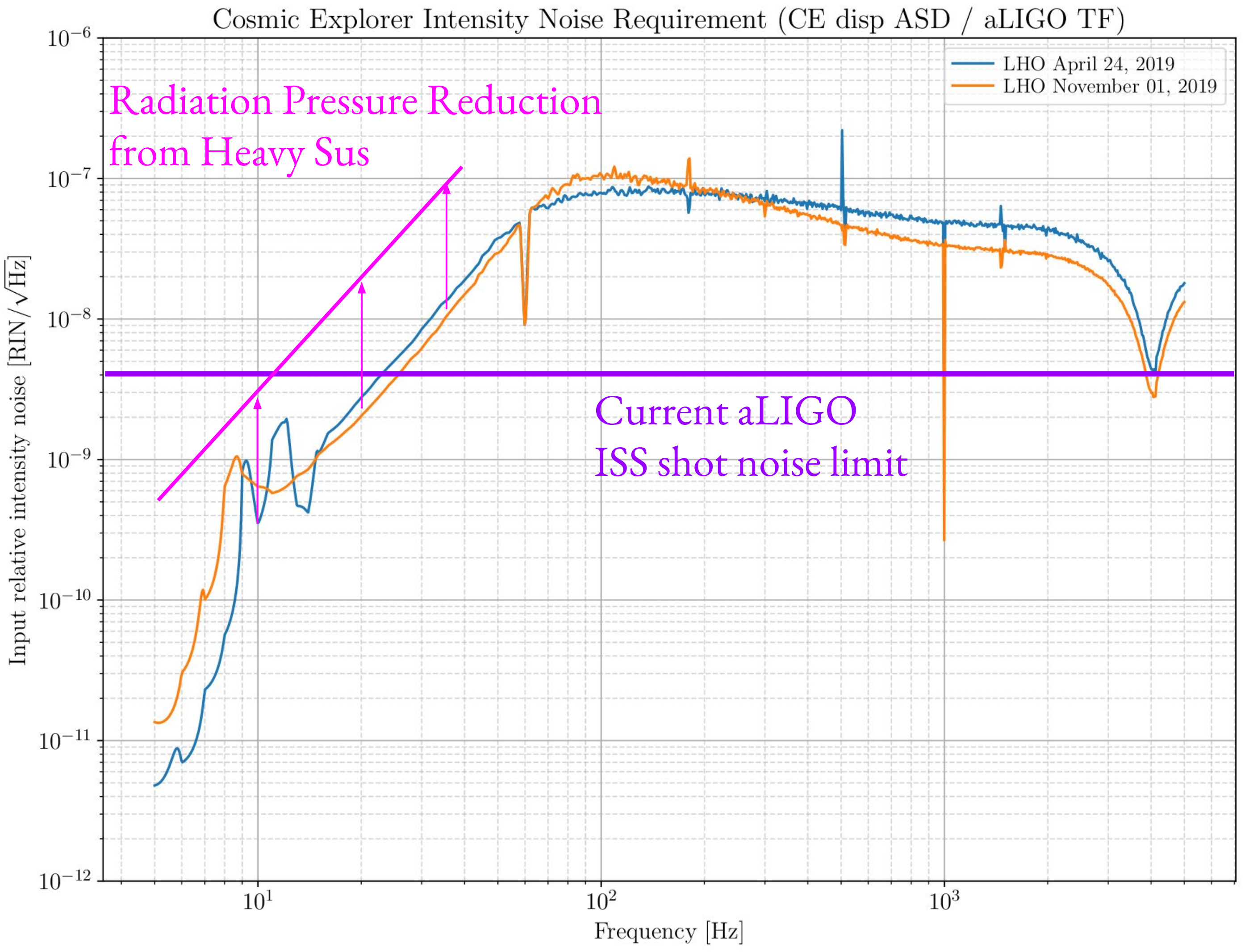
$$\sqrt{S_{\mathrm{rin2freq}}} = -\frac{\nu_0}{L}\,\frac{2}{m\omega^2}\,\frac{2P_{\mathrm{cav}}}{c}\sqrt{\frac{2h\nu_0}{P_{\mathrm{pd}}}}\left[\frac{\mathrm{Hz}}{\sqrt{\mathrm{Hz}}}\right]$$

$$\sqrt{S_{\mathrm{rin2freq}}} = \left(3\times10^{-6}\left[\frac{\mathrm{Hz}}{\sqrt{\mathrm{Hz}}}\right]\right)\left(\frac{3\ \mathrm{kg}}{m}\right)\left(\frac{100\ \mathrm{Hz}}{f}\right)^2\left(\frac{P_{\mathrm{cav}}}{100\ \mathrm{kW}}\right)\left(\sqrt{\frac{30\ \mathrm{mW}}{P_{\mathrm{pd}}}}\right)$$

CE intensity noise requirement

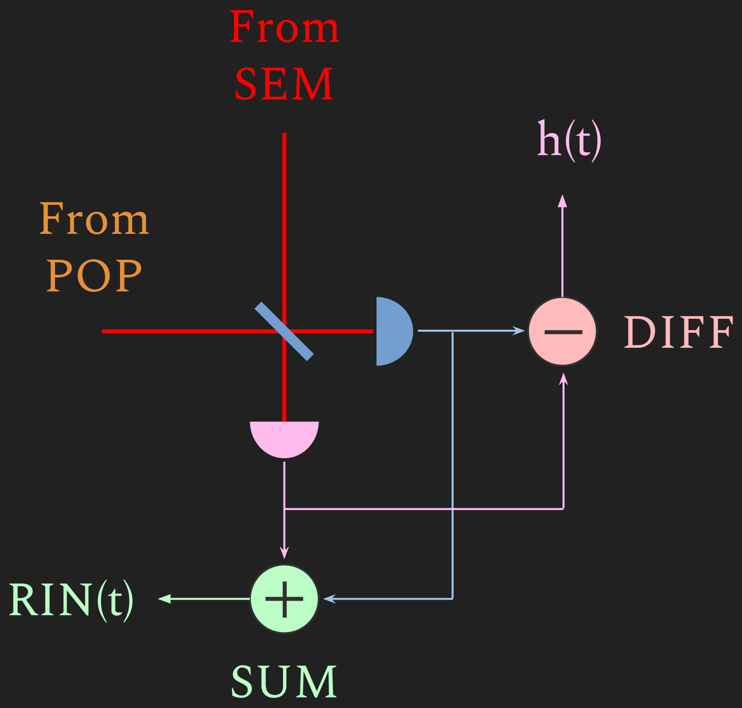
If we take the 40 km CE displacement noise,
and divide it by the aLIGO O3 input RIN to DARM couplings,
we get the following intensity requirement estimates.

No factor of ten was incorporated here.



Balanced Homodyne

- Cosmic Explorer will run in the balanced homodyne (BHD) configuration, which does not require a DARM offset
  - The DIFF channel will detect gravitational waves
  - The SUM channel will detect intensity noise in the Local Oscillator (LO)
- One major reason to switch to BHD is the reduced noise couplings to DARM
  - Both arms will be locked exactly at resonance.
  - This will reduce a number of major noise couplings to DARM, including
    - SECL,
    - frequency, and
    - intensity noise.



Conclusions

1. With current technology in Advanced LIGO,
   it is doubtful we could achieve Cosmic Explorer's laser noise limits
2. Hard to predict what true limits will be
   a. Cross couplings
   b. Thermal state
3. Upgrades are required for CE to achieve naive "aLIGO-based" limits
   a. Balanced Homodyne
   b. Heavier Suspensions (40 kg for IMCs, 400 kg for IFO)
   c. Mode sensing and control

More details on CE Optical Design

Posters

1. Paul Fulda - *Optical Layout of the Cosmic Explorer Interferometer*
2. Matt Todd - *Signal Recycling Cavity Design*
3. Nico O′Neill - *Deterministic DRMI*
4. Stefan Ballmer - *Trident WFS Sled for mode matching*

Open Questions related to Input Optics

1. How are we going to frequency stabilize without using CARM?

2. Are there clever ways to improve our usual stabilization technology?

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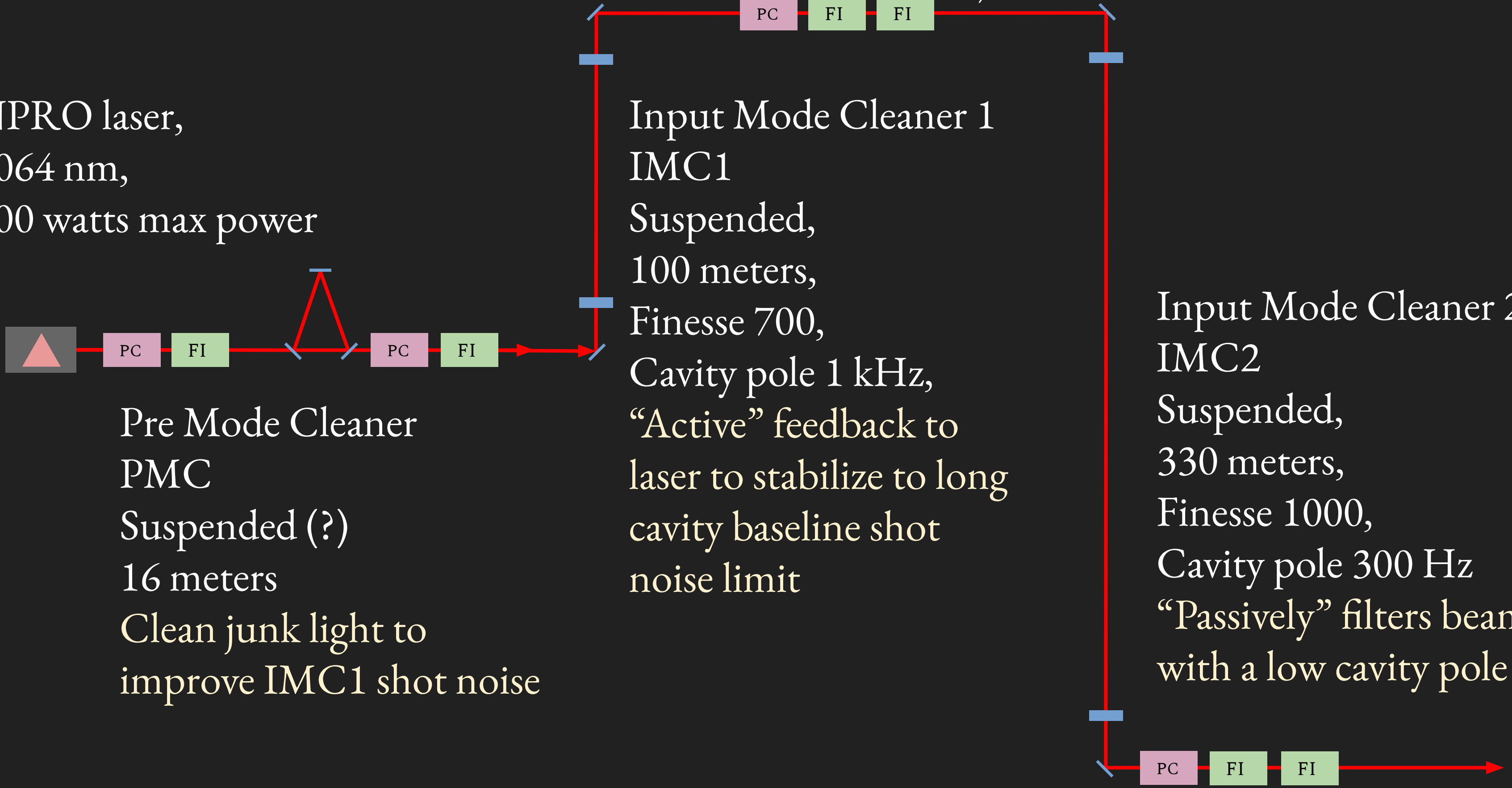
Extra Slides

Review of Cosmic Explorer Input Optics

1. CARM cannot be used in high-bandwidth feedback
   a. FSR = 3.8 kHz is too low
   b. CARM pole = 0.04 Hz means shot noise limit rising rapidly
2. Frequency noise requirement for Cosmic Explorer quite stringent
   a. Can probably solve frequency noise at f > 1 kHz with a low-bandwidth IMC2 lock
   b. f < 1 kHz frequency stabilization poses a difficult problem
3. Intensity noise requirements are also difficult to satisfy
   a. Especially at low frequency where intensity noise couples directly to mirror motion
4. Low-bandwidth length lock of IMC2 introduces unique solutions/challenges
   a. Avoids imposing sensing noise, and cleans input noise at $f > fpole$ = 30 Hz.
   b. Offers no input noise cleaning at $f < fpole$, and

Suspended Pre-Mode Cleaner Configuration (Evan's configuration)

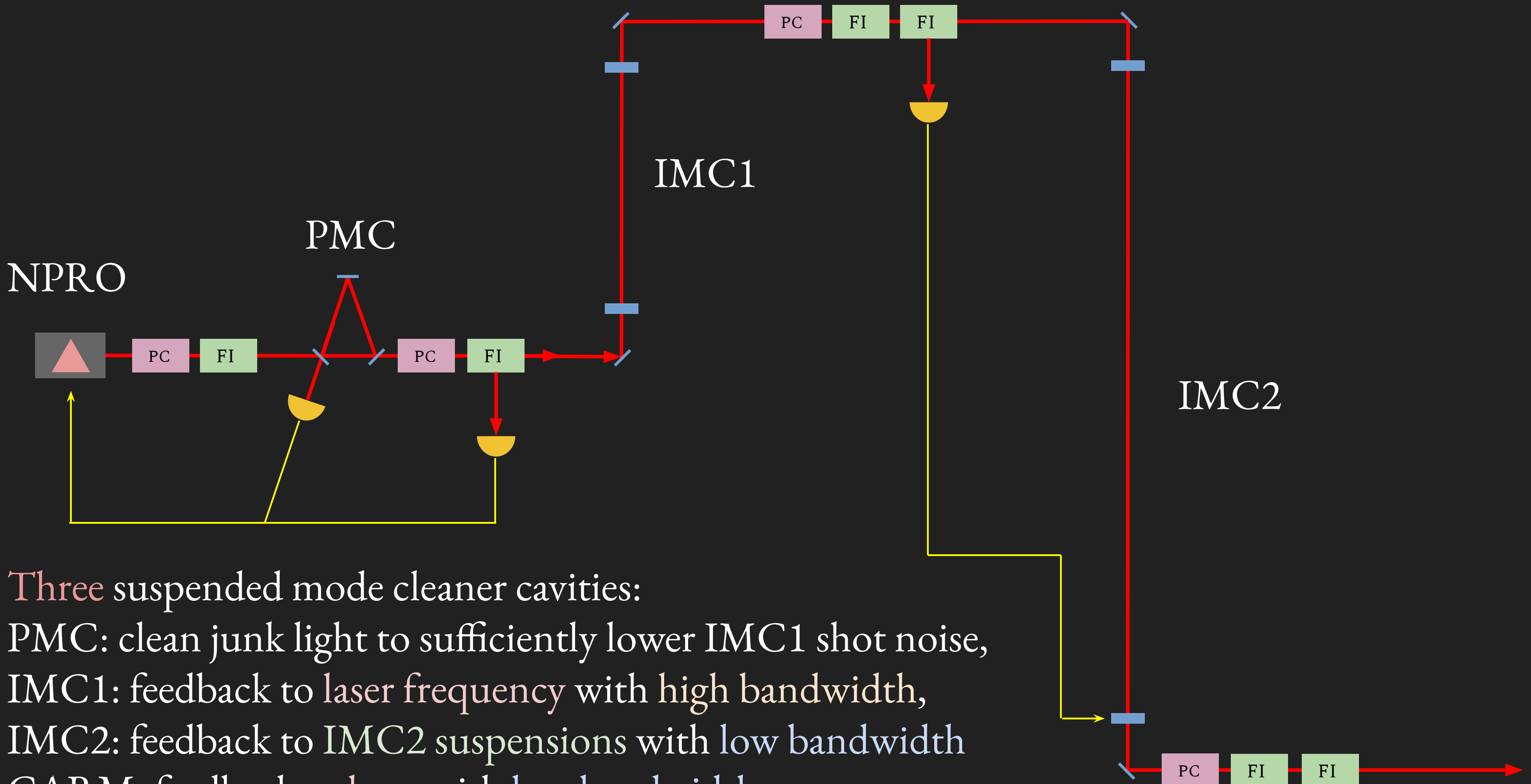


NPRO laser,
1064 nm,
200 watts max power

Pre Mode Cleaner
PMC
Suspended (?)
16 meters
Clean junk light to improve IMC1 shot noise

Input Mode Cleaner 1
IMC1
Suspended,
100 meters,
Finesse 700,
Cavity pole 1 kHz,
"Active" feedback to laser to stabilize to long cavity baseline shot noise limit

Input Mode Cleaner 2
IMC2
Suspended,
330 meters,
Finesse 1000,
Cavity pole 300 Hz
"Passively" filters beam with a low cavity pole



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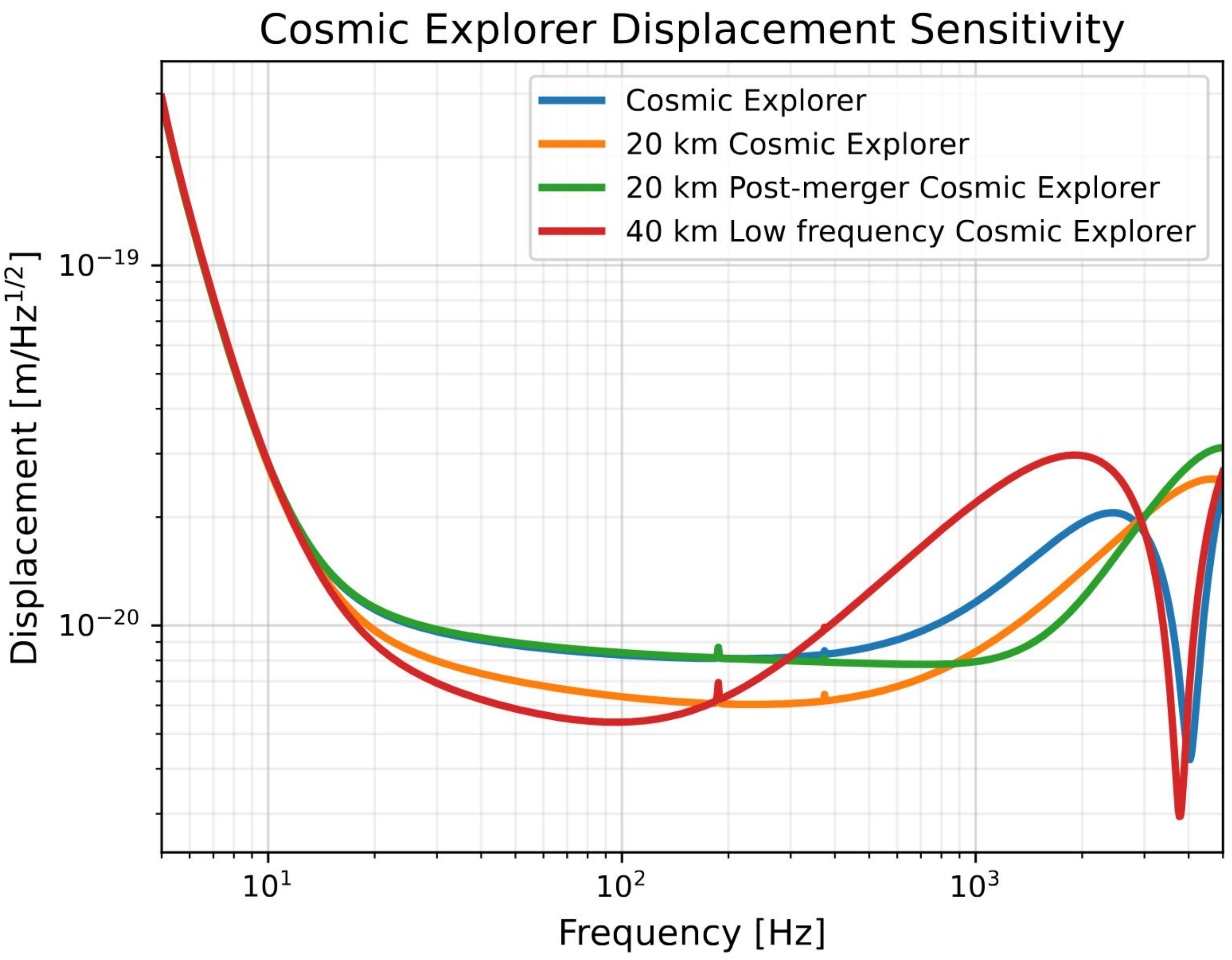
Baseline CE displacement

https://dcc.cosmicexplorer.org/CE-T2000017

Version 8

I used the blue curve here as a reference



O3 input RIN to DARM TF

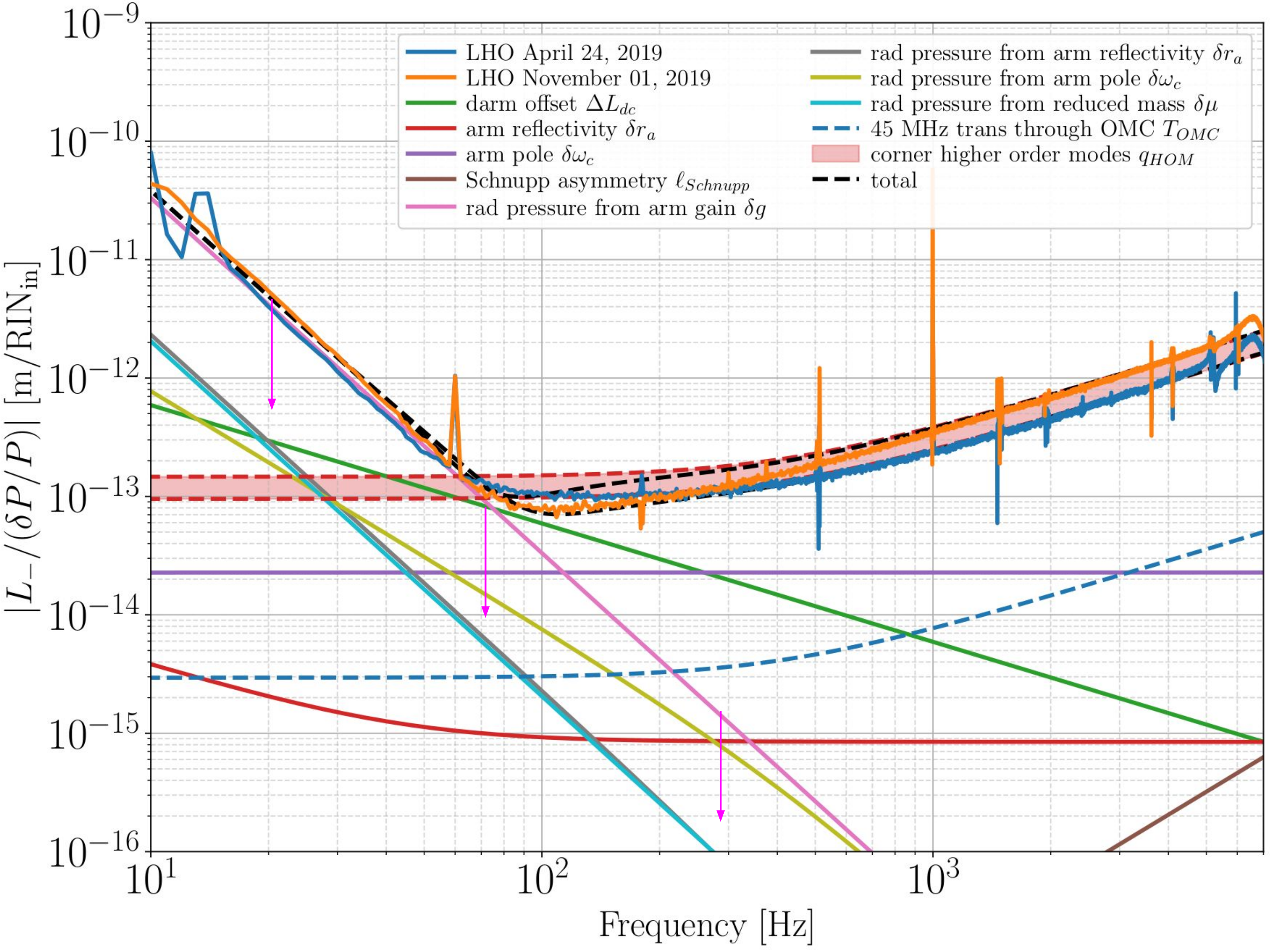
I also have some O4 traces here: [alog 66866]

Radiation pressure from diff arm gain:

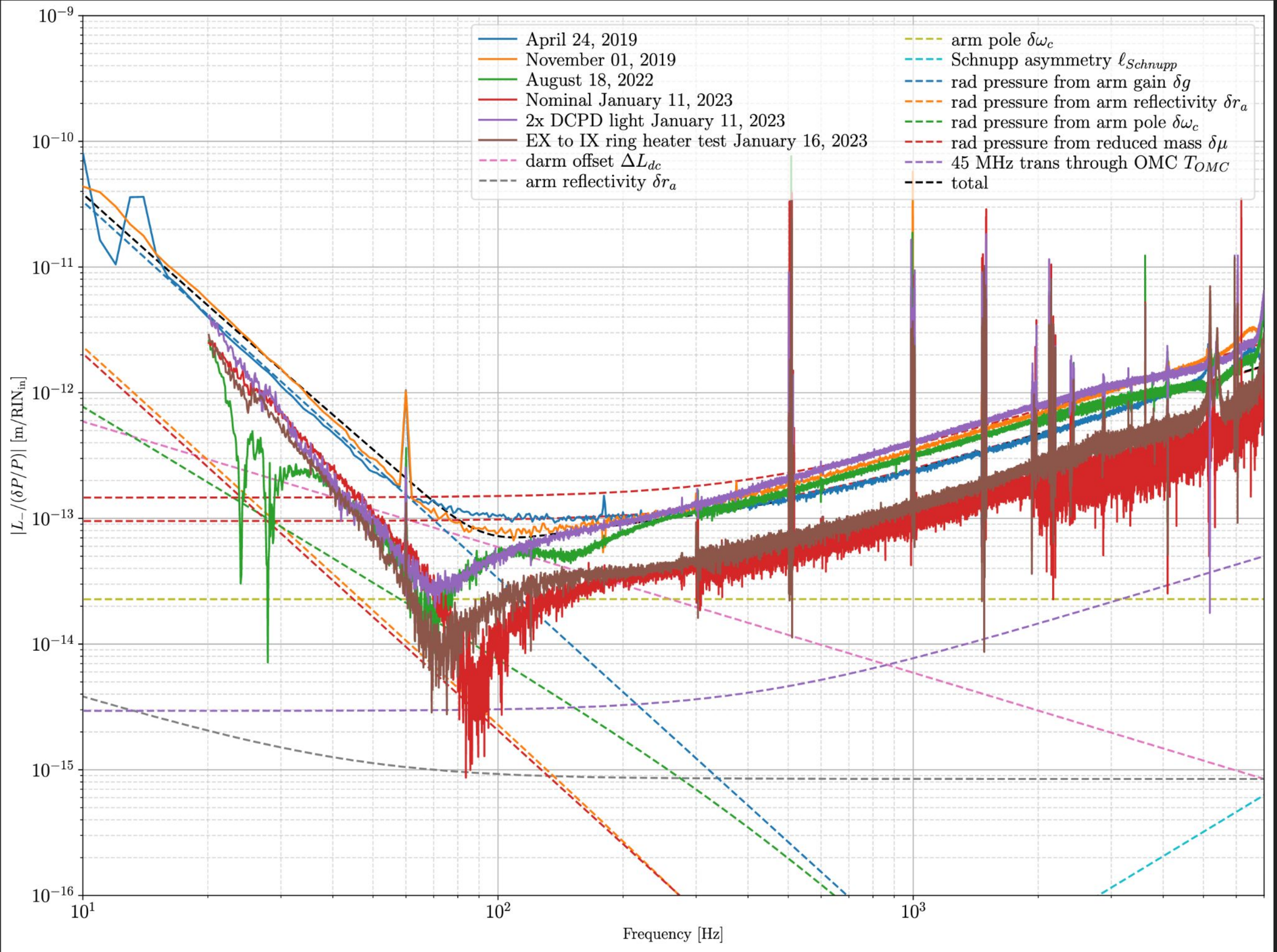
$$\frac{4\Delta P}{c m \omega^2}$$

ΔP = 5 kW

Should decrease by factor of 8 in CE.

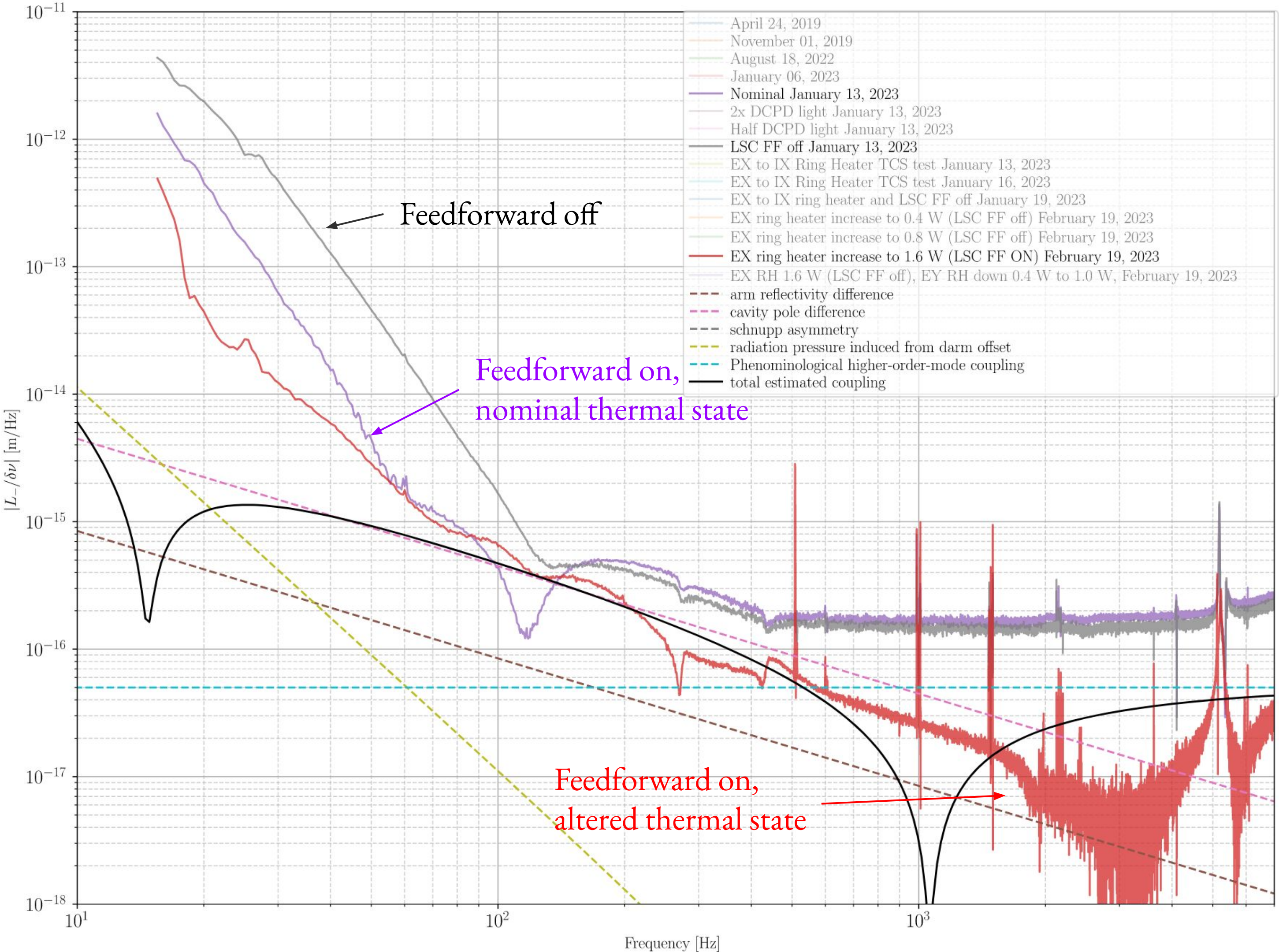


Intensity to DARM TF in O4



Frequency to DARM TF in O4

Analytic curves here plotted from Kiwamu Izumi analytic IFO analysis

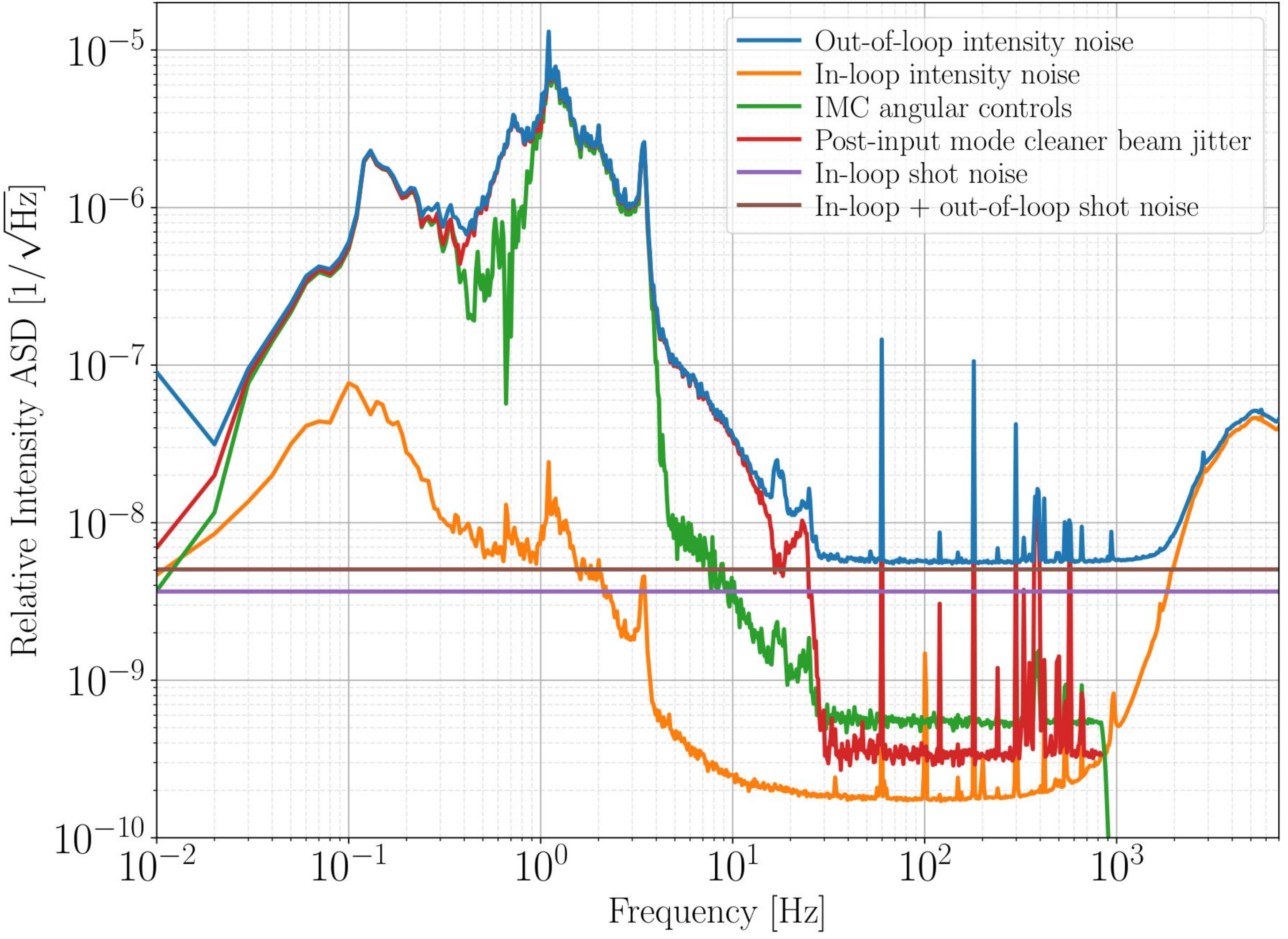


O3 intensity noisebudget

Achieving around

$$4 \times 10^{-9} \ \frac{\mathrm{RIN}}{\sqrt{\mathrm{Hz}}}$$

with the current two-loop ISS setup.



Frequency noise in O3

Similar to O4