Laser Noise in Advanced LIGO and Cosmic Explorer

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on behalf of the CE Optical Design Team

XGCD call

June 24, 2024

Motivation

Laser noise is a technical noise source intrinsic to the stability of the laser output.

Without a laser, you're not going to detect much. The laser stores and carries the GW information as a coherent phase shift, which becomes power modulations at the dark port.

To be able to coherently store the tiny phase shifts imparted by the GW, the laser itself must be extremely stable in three ways:

- Frequency
- Intensity
- Spatially (also called beam jitter)

The native laser source will very likely still be the NPRO 1064 nm laser, barring significant design changes

Advanced LIGO coupling overview

Frequency Noise coupling to DARM

Frequency noise coupling to the dark port from Kiwamu's sideband picture derivations [15]

First order couplings only, ignores HOMs or cross-couplings. Same for Somiya [16].

Note the dependence on the DARM offset ϵ.

Arm reflectivity difference — Arm pole difference — Schnupp Asymmetry

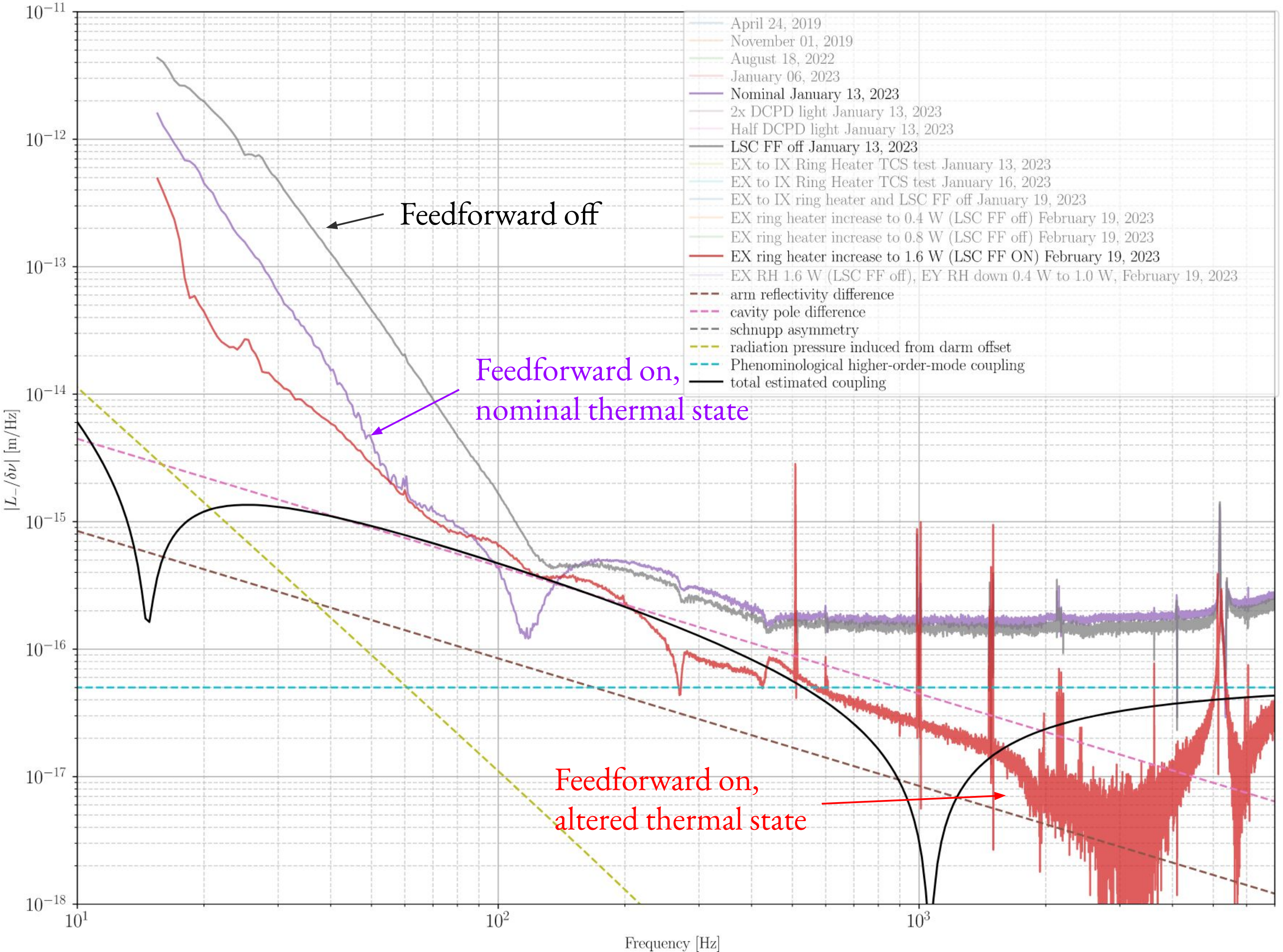
$$\frac{S^{(\mathrm{freq})}}{S_1} = \frac{(1+r_\mathrm{a})\,(g_\mathrm{p} g_\mathrm{s})^2\, r'_\mathrm{a}\epsilon}{(1+s_{cc})\,(1+s_\mathrm{rse})} \left[\underline{-\delta r_\mathrm{a}} - \underline{\frac{\delta\omega_\mathrm{c}}{\omega_\mathrm{c}}(1+r_\mathrm{a})} + \underline{\frac{l_\mathrm{sch}\omega_\mathrm{c} r_\mathrm{a}}{c}(1-s_c/r_\mathrm{a})\,(1+s_c)} \right] \left(\frac{2\pi\Delta f}{\omega_\mathrm{c}}\right)$$

$$+ \underline{4 g_\mathrm{p}^2 g_\mathrm{s}^2 r_\mathrm{a}'^2 \epsilon k \frac{1}{1+s_\mathrm{rse}} \left(\frac{\partial L_-}{\partial f}\right) \Delta f} \tag{29}$$

Radiation pressure coupling

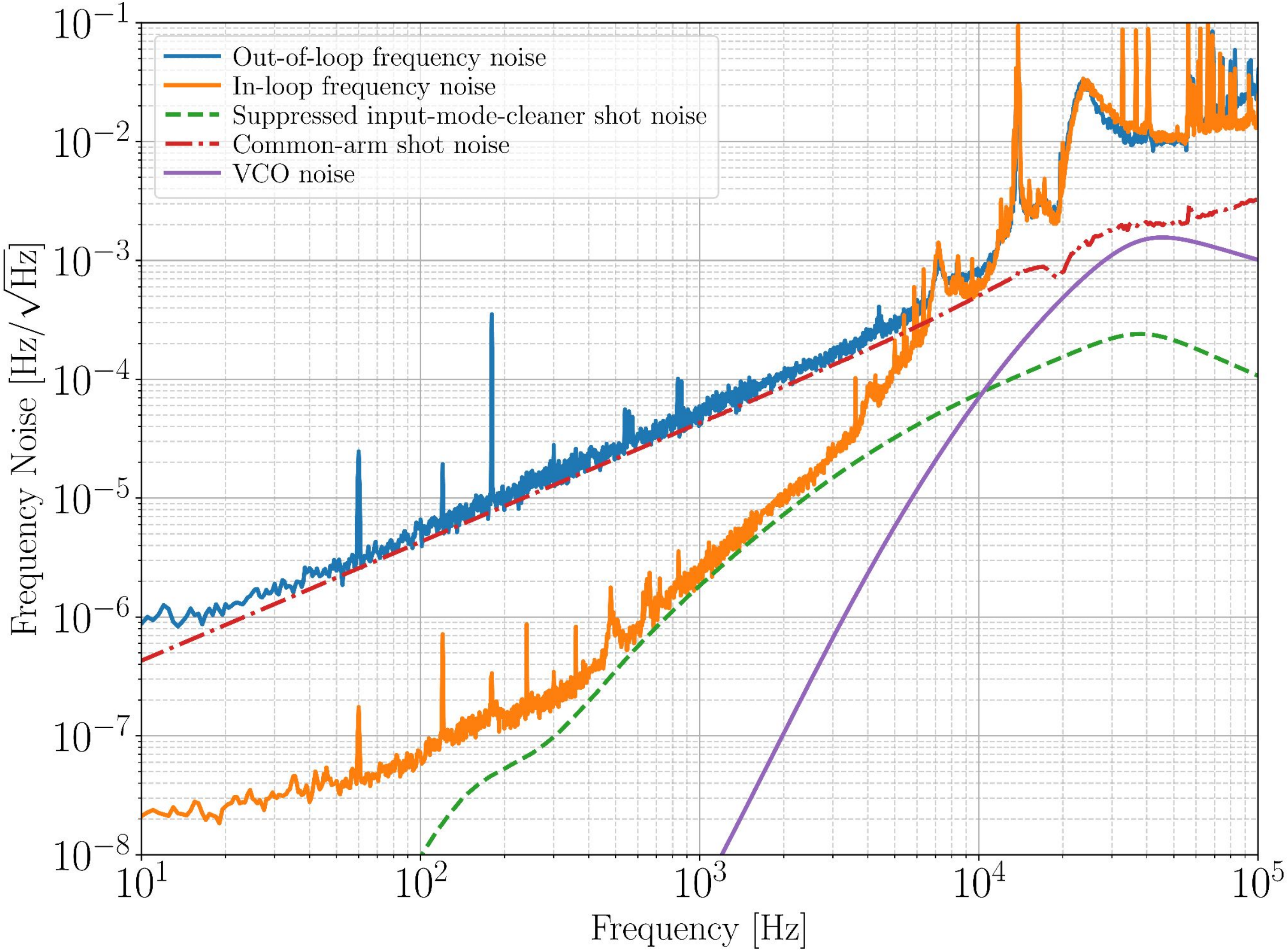
Frequency to DARM TF in O4

Analytic curves here plotted from Kiwamu Izumi analytic IFO analysis



Frequency noise in O3

Similar to O4



Intensity Noise coupling to DARM

Intensity noise coupling to the dark port from Kiwamu's sideband picture [15]

Again, HOMs and cross-couplings are ignored as too complicated.

Arm reflectivity

Arm pole

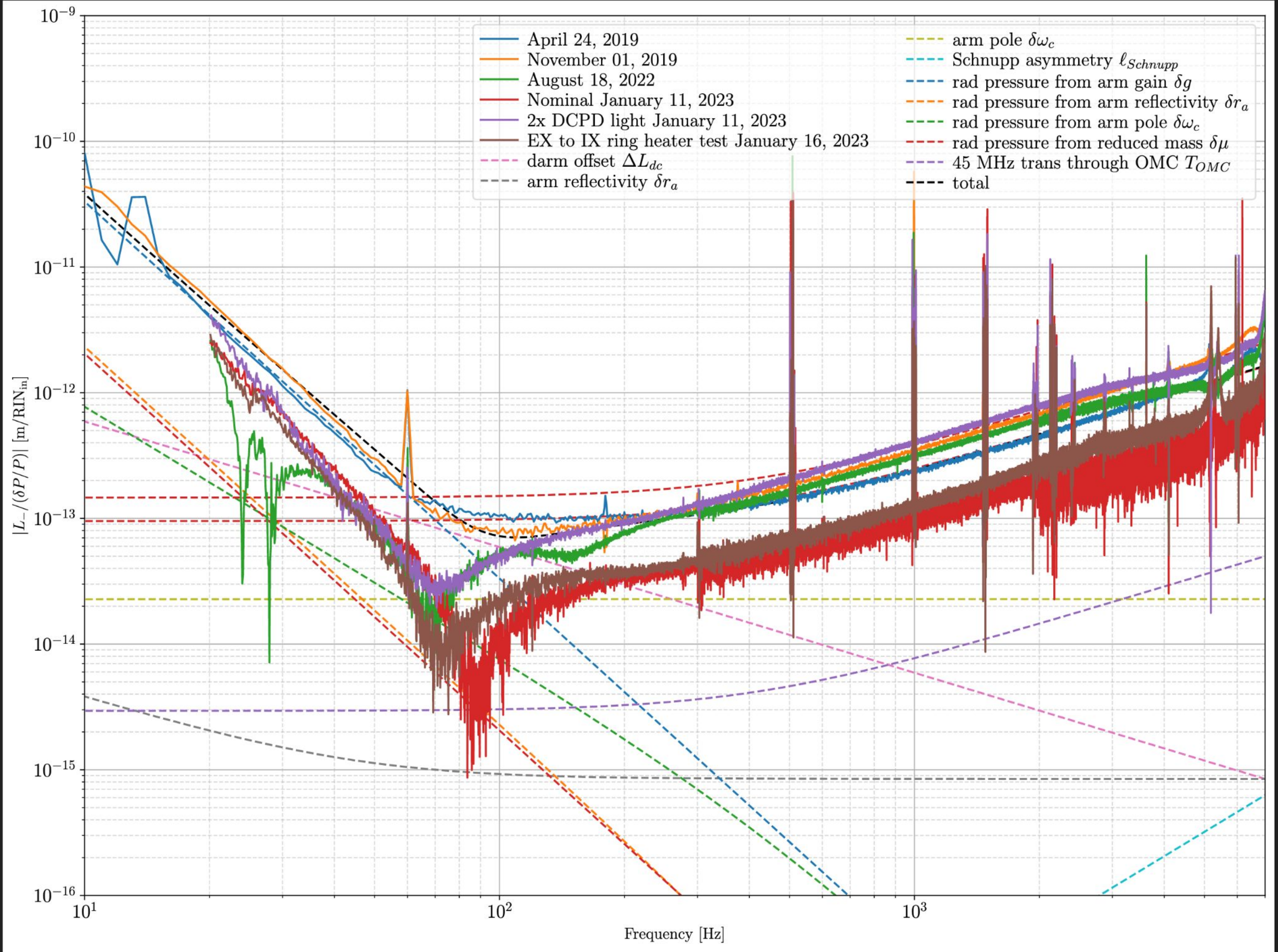
Schnupp Asymmetry

$$\frac{S^{(\mathrm{int})}}{S_1} = \Bigg\{ \frac{\left[\left(1+r_{\mathrm{a}}\right) g_{\mathrm{p}} g_{\mathrm{s}} r'_{\mathrm{a}} \epsilon\right]^2}{\left(1+s_{cc}\right)\left(1+s_{rse}\right)} + \frac{\left(g_{\mathrm{p}} g_{\mathrm{s}}\right)^2 \delta r_{\mathrm{a}}}{\left(1+s_{cc}\right)\left(1+s_{rse}\right)} \left[\delta r_{\mathrm{a}}\left(1+s_c\right) + \frac{\delta\omega_{\mathrm{c}}}{\omega_{\mathrm{c}}} s_c \left(1+r_{\mathrm{a}}\right) - \frac{l_{\mathrm{sch}}\omega_{\mathrm{c}}}{c} r_{\mathrm{a}} s_{\mathrm{c}} \left(1 - s_c/r_{\mathrm{a}}\right)\left(1+s_c\right)\right] + 2T_{\mathrm{omc}} \left(\frac{J_1}{J_0} g_{\mathrm{sb}} t_{\mathrm{sm}}\right)^2 + 4 g_{\mathrm{p}}^2 g_{\mathrm{s}}^2 r_{\mathrm{a}}'^2 \epsilon k \frac{1}{1+s_{\mathrm{rse}}} \left(A \frac{\partial L_-}{\partial A}\right) \Bigg\} \left(\frac{\Delta A}{A}\right). \tag{26}$$

Sideband trans through OMC

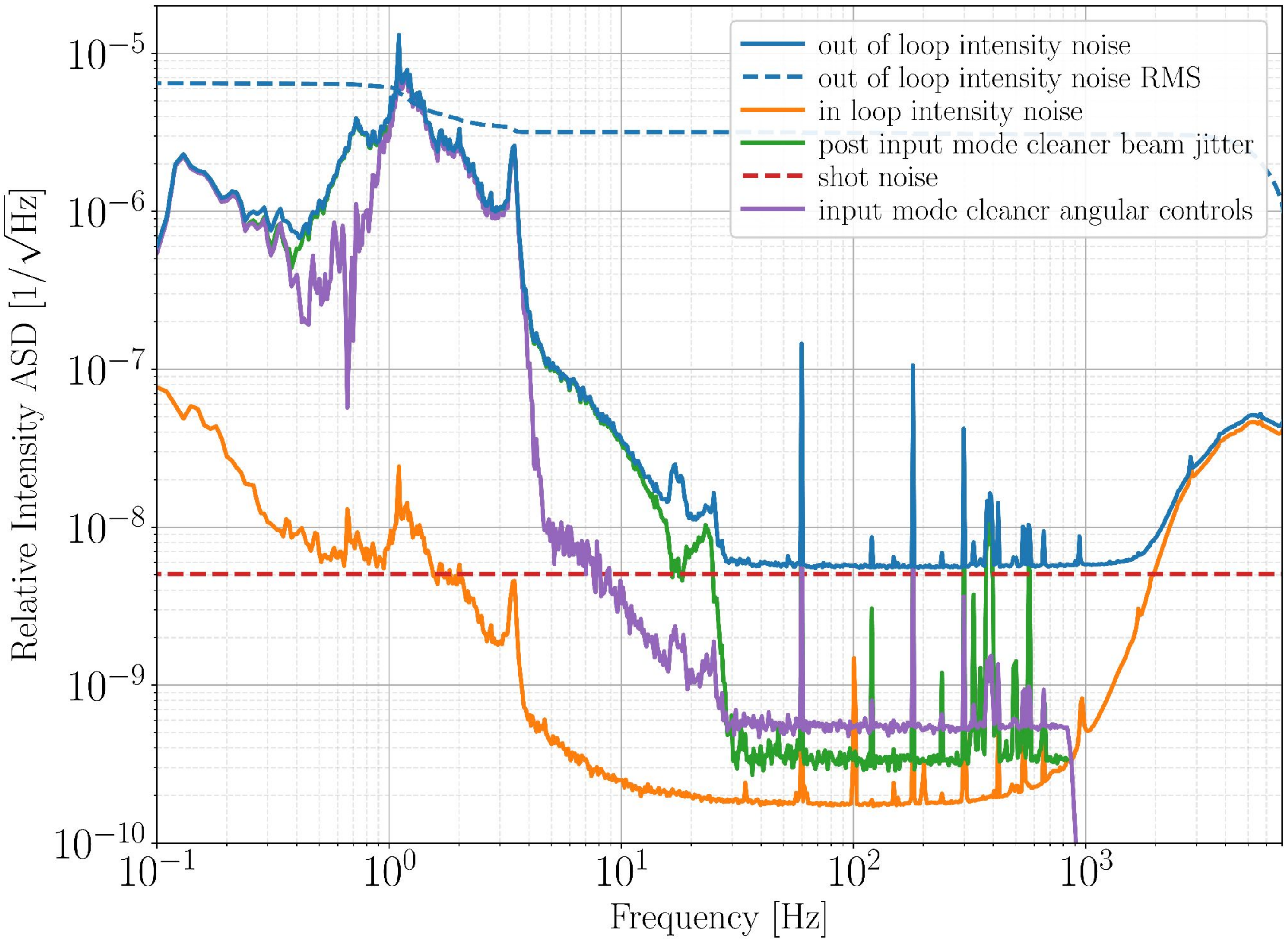
Radiation pressure coupling

Intensity to DARM TF in O4



Intensity noise in O3

Similar to O4



Beam jitter

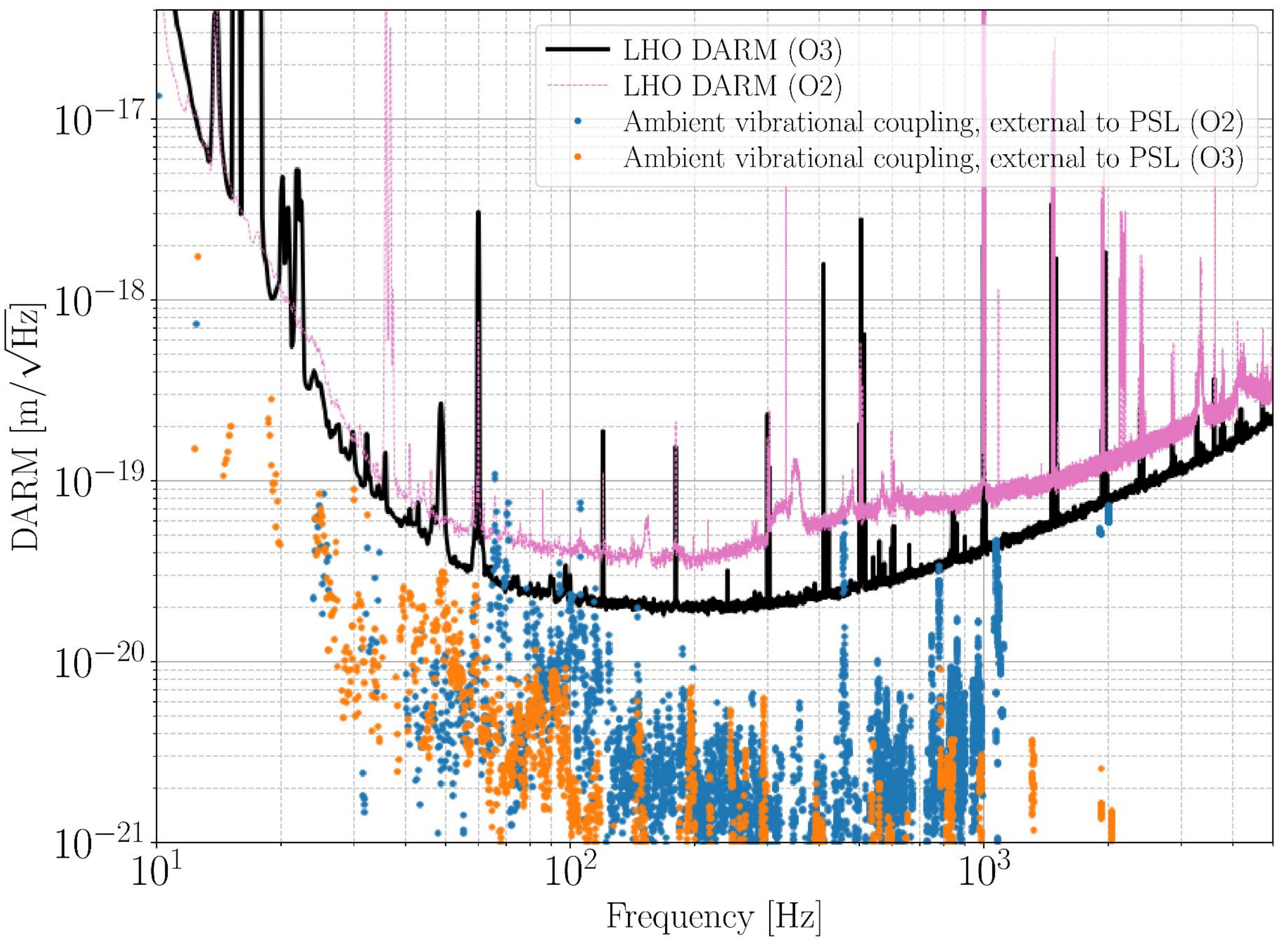
Would normally be rejected via common mode rejection.
Large sourced from PSL table motion, coupling to DARM via static misalignments in the IFO.

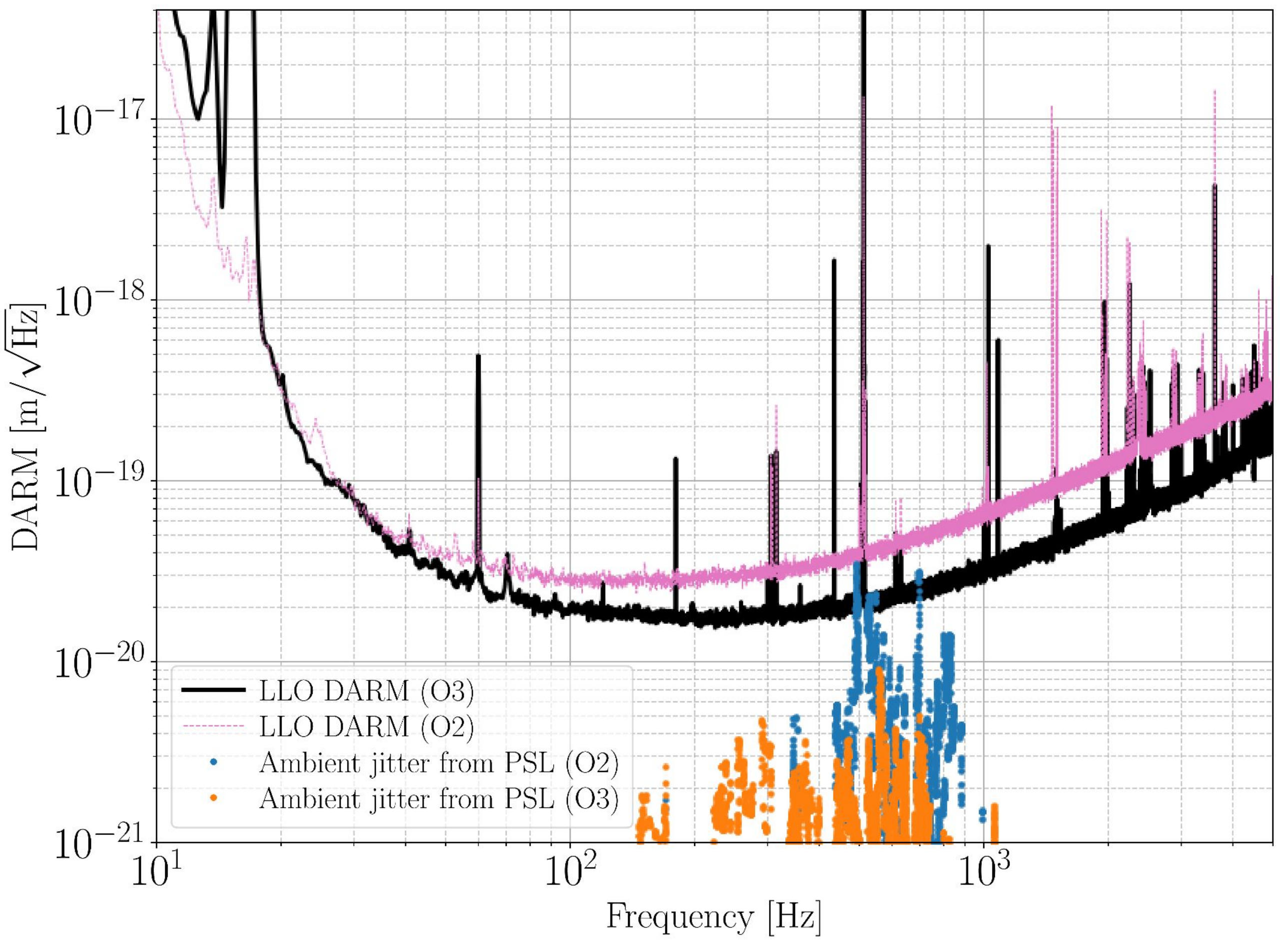
Major reduction between O2 and O3 due to High Power Oscillator removal.

Seems to become worse with high power (see Robert Schofield's alog 70808 [4])
1) Possibly due to worsening IFO thermal state increasing static misalignments?
2) "It might be caused by increased thermal distortion of test mass surfaces around coating defects, resulting in a greater fraction of light scattered and higher vibration coupling through retro-reflected scattered light."

Appears to be a major limiter of DARM in O4.

Some wins: Removal of 120 Hz peak with SF2 Fan turned off alog 73403 [3]


LHO DARM (O3)
LHO DARM (O2)
Ambient vibrational coupling, external to PSL (O2)
Ambient vibrational coupling, external to PSL (O3)
DARM [m/√Hz]
Frequency [Hz]
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{1}
10^{2}
10^{3}

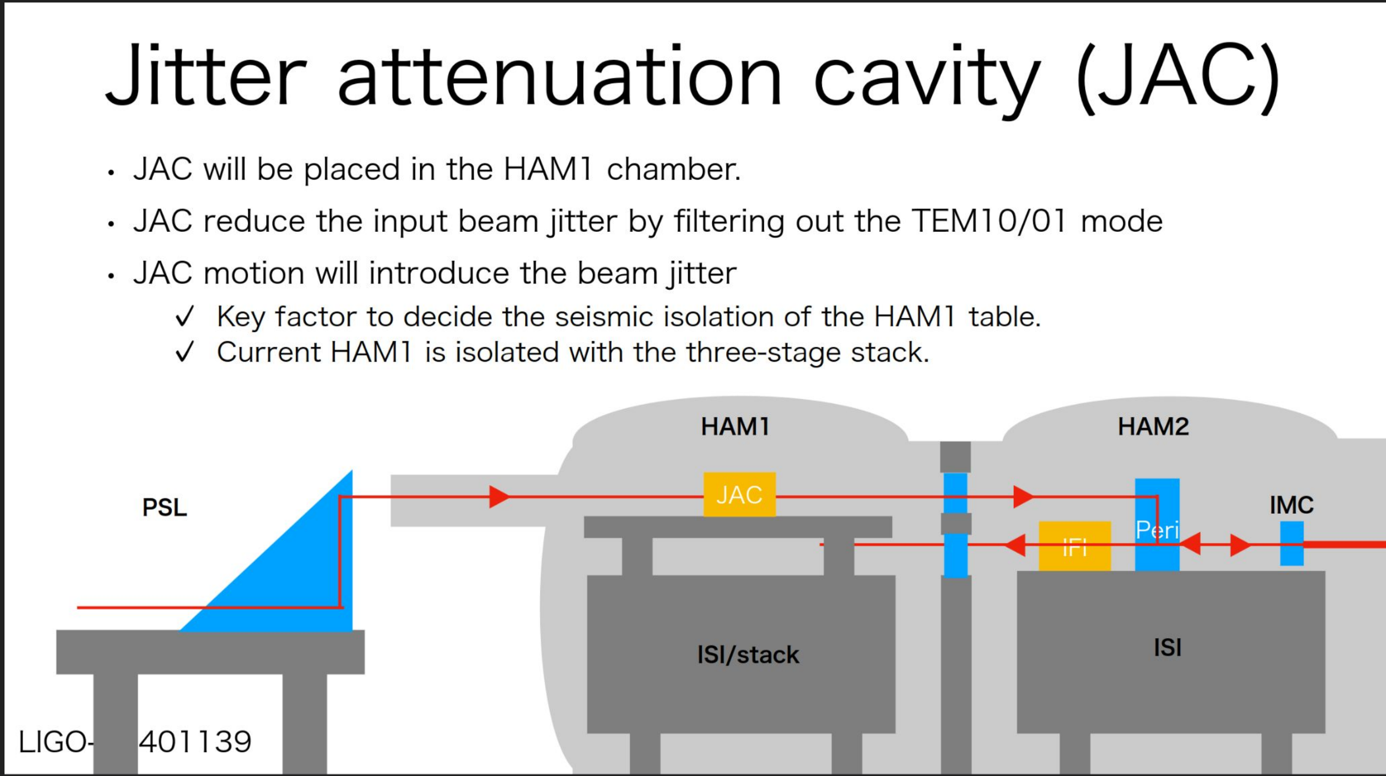


DARM [m/√Hz]
Frequency [Hz]
LLO DARM (O3)
LLO DARM (O2)
Ambient jitter from PSL (O2)
Ambient jitter from PSL (O3)

Jitter Attenuation Cavity (JAC)

Idea: Hang a fixed triangle cavity in HAM1 to which the PSL beam is locked. This should provide some 20 dB or more of jitter noise suppression coming from the PSL table, especially at Hanford.

Led by Masayuki Nakano at Caltech [13].



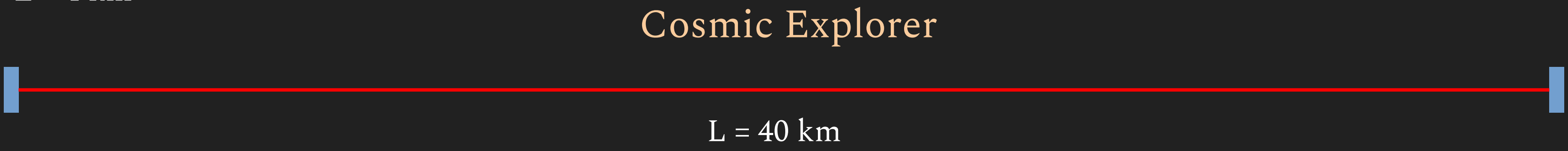
Cosmic Explorer current input optics design

Main problem

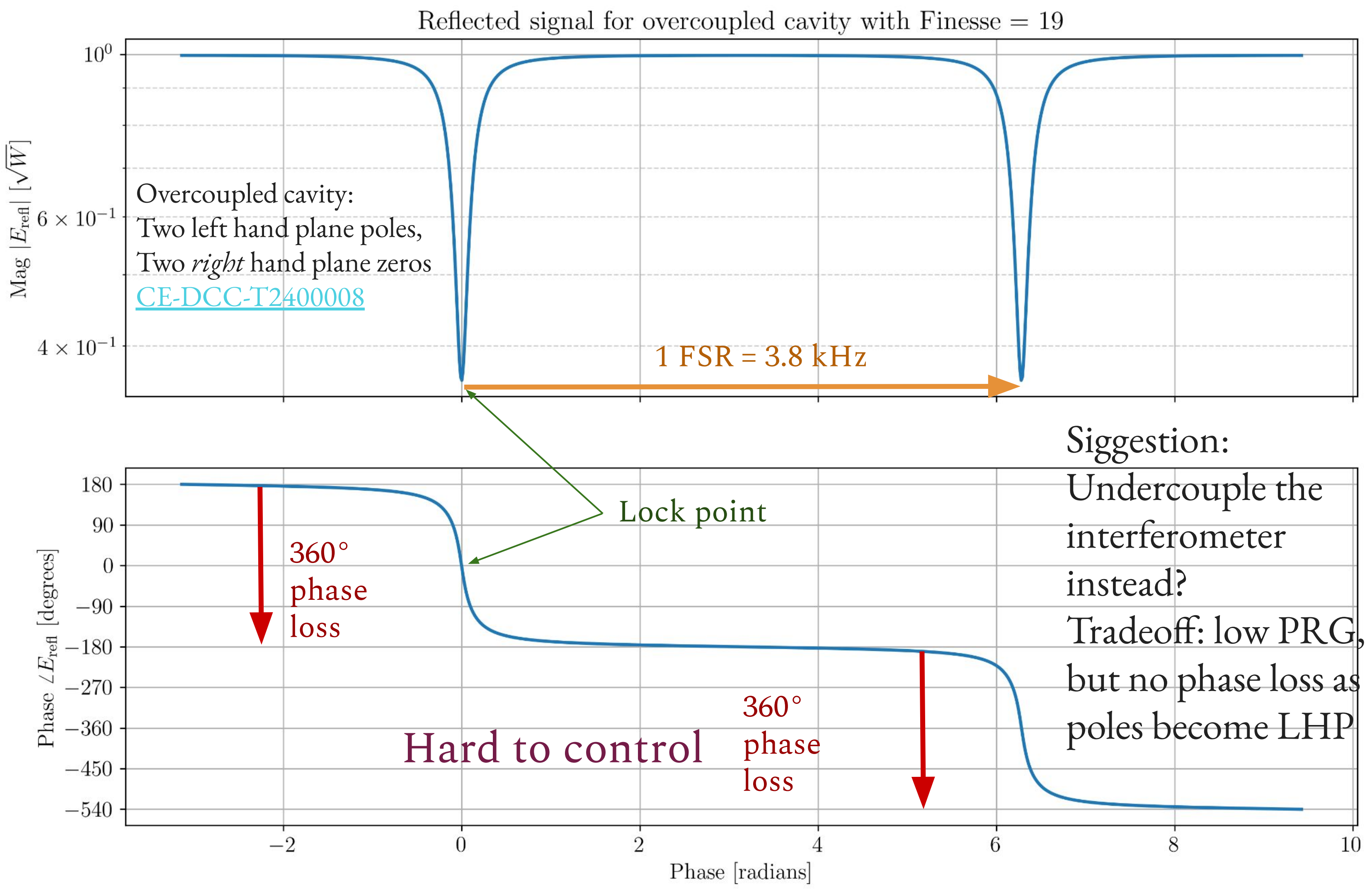
For Cosmic Explorer, the arms will be 40 km long.
The free-spectral range of LIGO is 38 kHz.
The free-spectral range of Cosmic Explorer is 3.8 kHz.

	Advanced LIGO	Cosmic Explorer
Arm Length	4 km	40 km
FSR	38 kHz	3.8 kHz
CARM pole	0.4 Hz	0.04 Hz

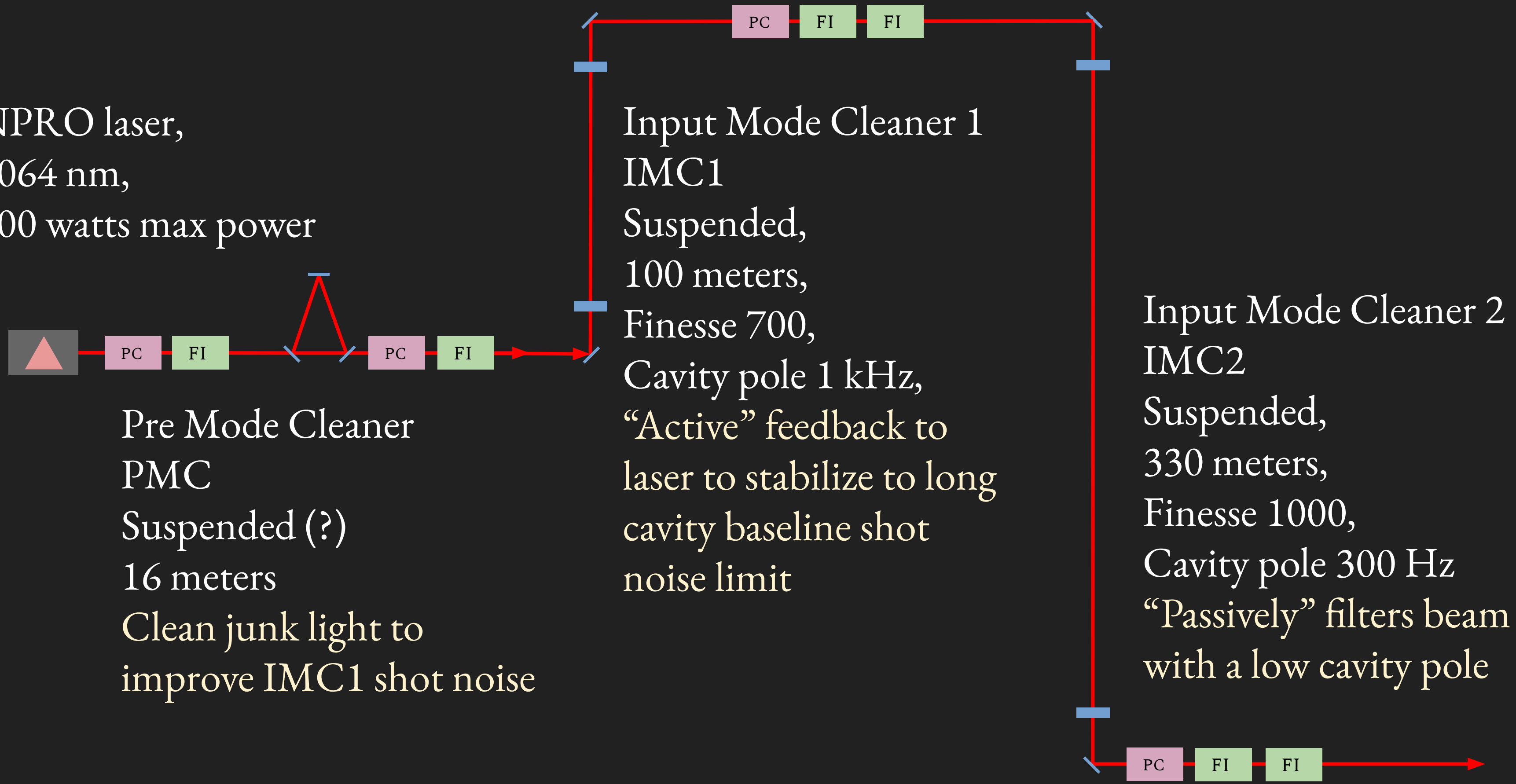
vs



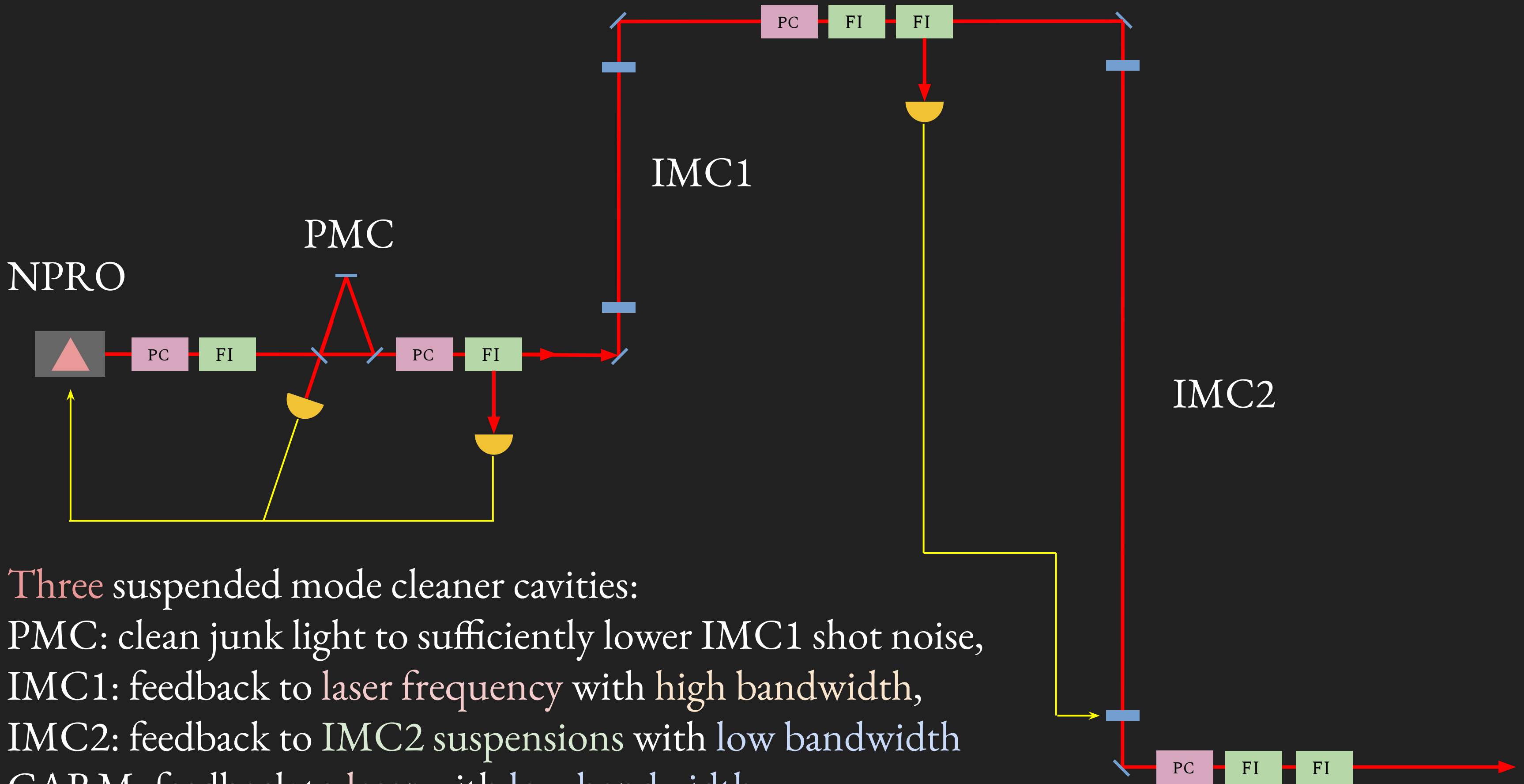
Problem: LIGO's current frequency stabilization bandwidth is around 30 kHz. However, the controller cannot extend beyond the FSR due to the cavity phase dynamics.
Additionally, the extremely low linewidth (0.04 Hz) makes the CE shot noise limit insufficient at 500 Hz.


Reflected signal for overcoupled cavity with Finesse = 19
Mag $|E_{\mathrm{refl}}|$ [$\sqrt{W}$]
10^0
6×10^{-1}
4×10^{-1}
Overcoupled cavity:
Two left hand plane poles,
Two *right* hand plane zeros
CE-DCC-T2400008
1 FSR = 3.8 kHz
Lock point
Siggestion:
Undercouple the interferometer instead?
Tradeoff: low PRG, but no phase loss as poles become LHP
Phase $\angle E_{\mathrm{refl}}$ [degrees]
180
90
0
−90
−180
−270
−360
−450
−540
360° phase loss
Hard to control
360° phase loss
−2
0
2
4
6
8
10
Phase [radians]

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

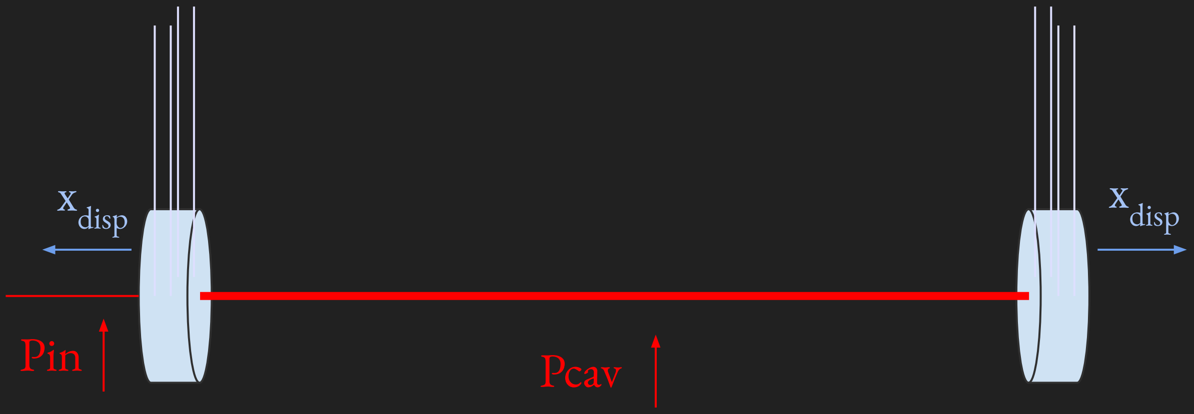


Suspended Pre-Mode Cleaner Configuration (Evan's configuration)



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

Intensity noise to Frequency Noise in the input optics



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

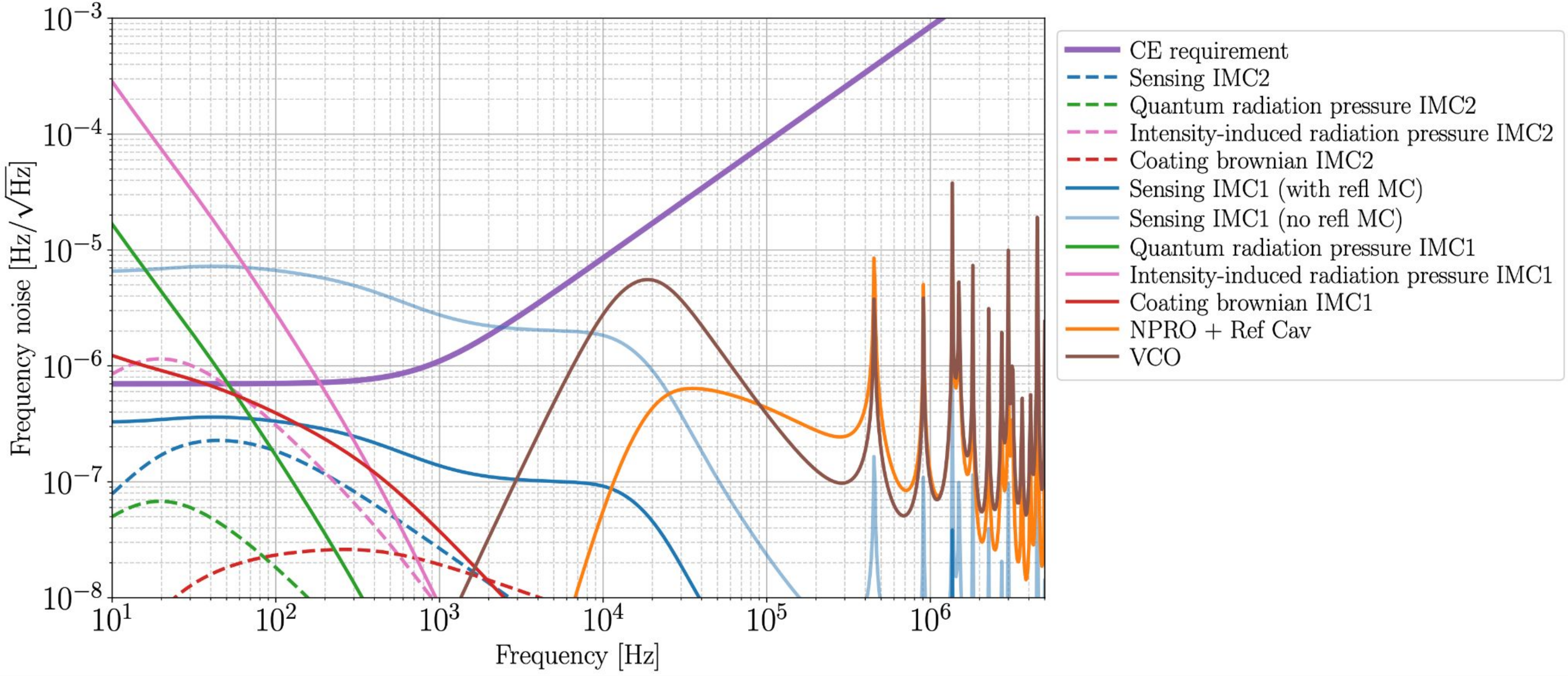
$$\sqrt{S_{\text{RIN}}} = \frac{\sqrt{S_{\text{shot}}}}{P_{\text{pd}}} \ [\frac{\text{W/W}}{\sqrt{\text{Hz}}}]$$

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

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

$$\sqrt{S_{\text{rin2freq}}} = \left(3\times 10^{-6}\left[\frac{\text{Hz}}{\sqrt{\text{Hz}}}\right]\right)\left(\frac{3\ \text{kg}}{m}\right)\left(\frac{100\ \text{Hz}}{f}\right)^2\left(\frac{P_{\text{cav}}}{100\ \text{kW}}\right)\left(\sqrt{\frac{30\ \text{mW}}{P_{\text{pd}}}}\right)$$

Double IMC frequency noisebudget (CE estimate, updated since [1])



Problems to consider

1) What are the requirements on the IMC lengths?
   a) Can we piggyback on the CE filter cavity beam tube to save on facilities costs?
2) What are the requirements on the IMC test masses?
   a) Are Advanced LIGO style triples sufficient? not enough?
3) Will we need mode sensing and control on the IMCs?
   a) Want to control the mode matching of IMCs to main IFO
   b) IMC2 will be especially susceptible to high power thermal transients
   c) Will beam jitter be a problem (currently is in Advanced LIGO)
4) What is an acceptable intensity servo?
   a) Will stabilizing to 100 mW be enough? Do we need AC coupling?
5) Are there ways we can improve lock acquisition?
   a) Three input RF sidebands (one non-resonant in the IFO)?
   b) In-vacuum, suspended, high-power EOMs?
      i) RF sidebands won't constrain IMC length, could avoid sideband FM-to-AM

Future Work

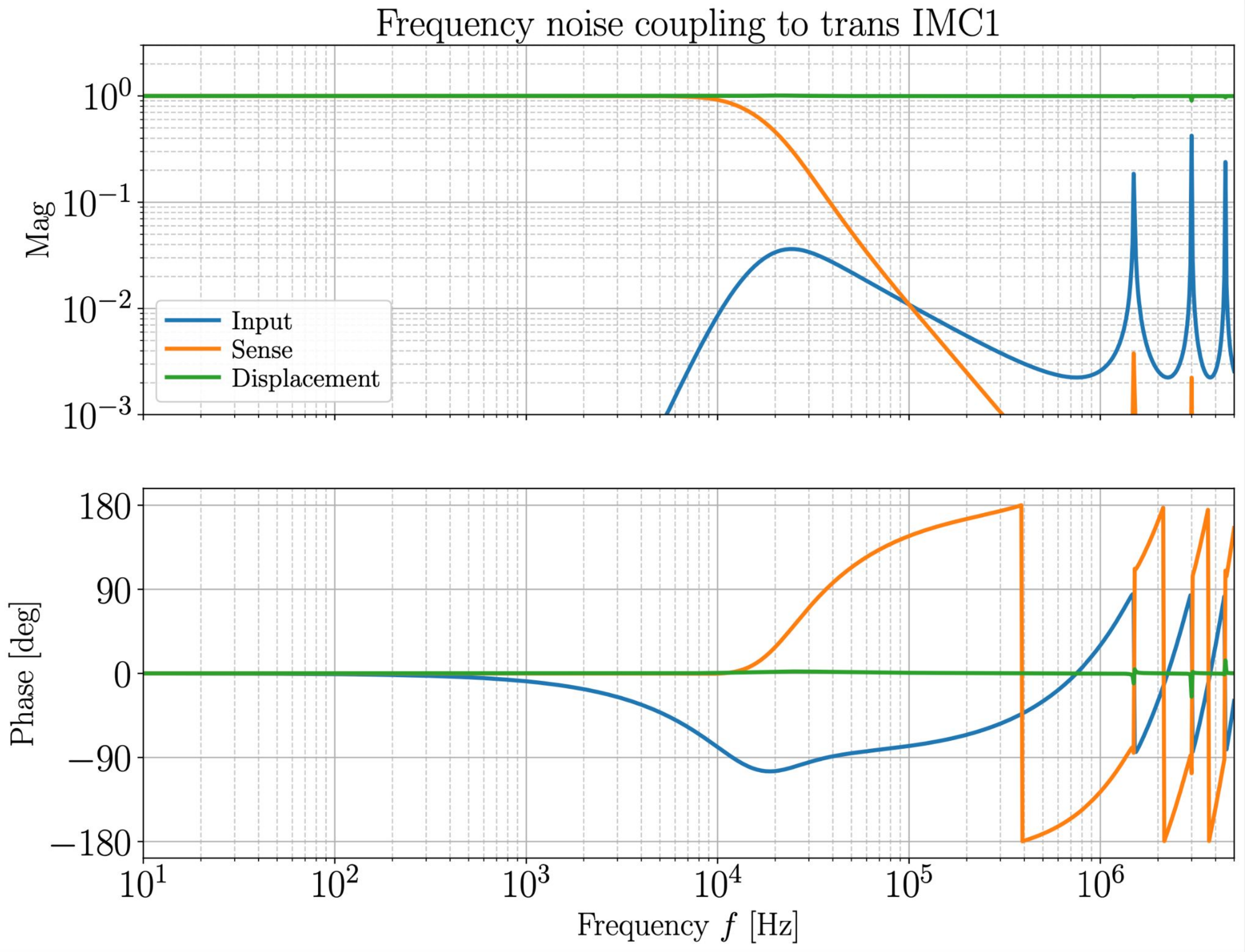
1. Model some of the competing designs for the input optics
2. Further investigate the impact of thermal compensation on laser noise coupling
3. Assuming some IFO, estimate transfer function noise requirements for:
    a. Frequency noise
    b. Intensity noise
    c. Jitter noise
    d. RF phase noise
    e. RF amplitude noise

Bibliography

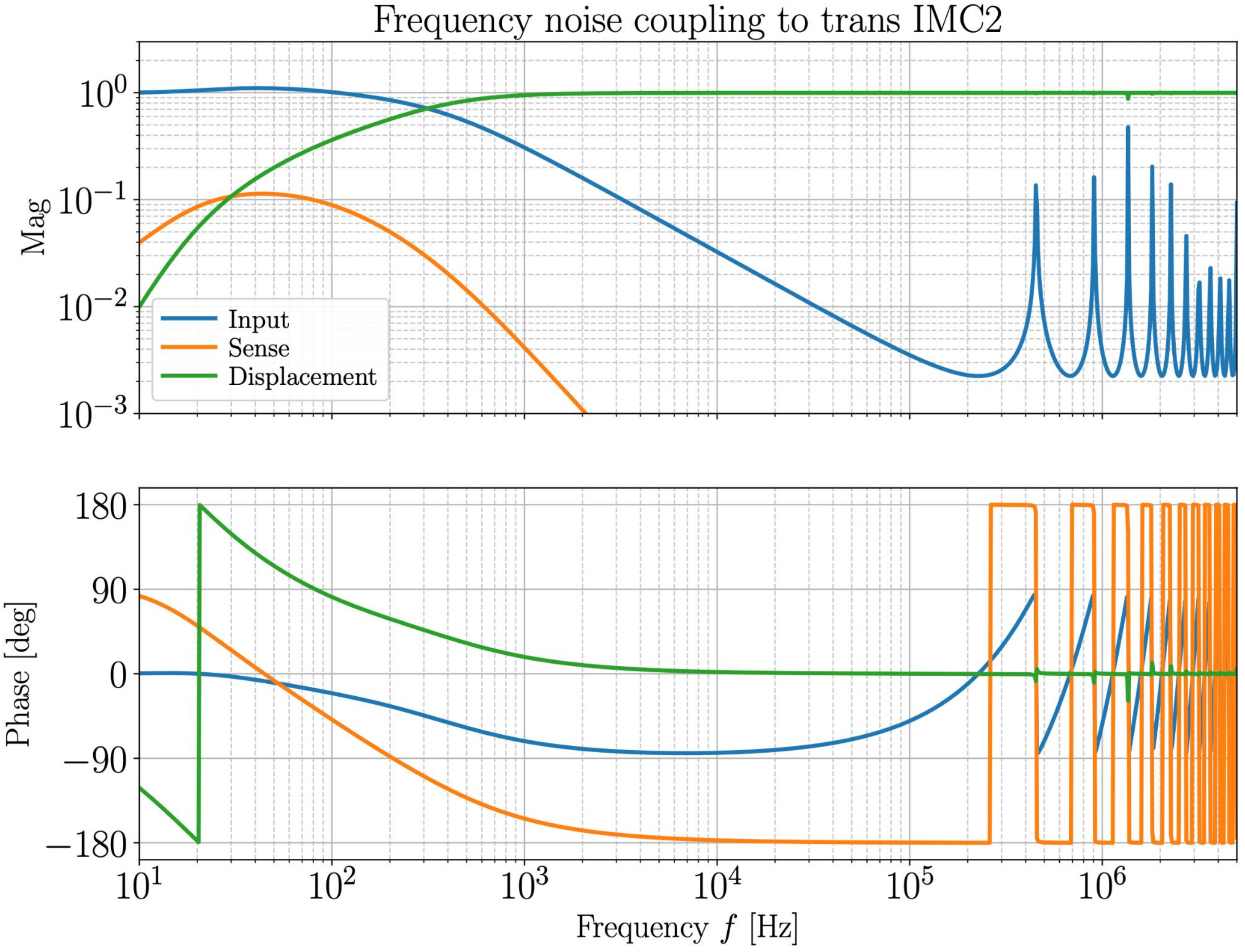
[1] Craig Cahillane, Georgia Mansell, Daniel Sigg, "Laser frequency noise in next generation gravitational-wave detectors" https://doi.org/10.1364/OE.439253
[2] Arai, Koji "Finesse simulation for the alignment control signal of the aLIGO input mode cleaner" https://dcc.ligo.org/LIGO-T1300074
[3] T. Akutsu, "Input optics systems of the KAGRA detector during O3GK" https://arxiv.org/abs/2210.05934
[4] B. Willke, "Spatial and temporal filtering of a 10-W Nd:YAG laser with a Fabry–Perot ring-cavity premode cleaner" https://opg.optica.org/ol/fulltext.cfm?uri=ol-23-21-1704&id=62753
[5] C. Mueller, "The Advanced LIGO input optics" https://pubs.aip.org/aip/rsi/article/87/1/014502/367353/The-advanced-LIGO-input-optics
[6] Gabriele Vajente, "Frequency noise coupling through ISC loops", https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=67871
[7] Craig Cahillane, "Frequency and intensity to DARM TFs (January 2023)" https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=66866
[8] Robert Schofield, "Broad 120 Hz peak no longer in DARM after PSL periscope tuning and shutdown of SF2" https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=73403
[9] Robert Schofield, "Does vibration coupling tend to increase with main laser power? Coupling dropped at PSL by roughly two and at EX by three when power was dropped from 75W to 60W" https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=70808
[10] Daniel Sigg, "Interferometer Mode Matching and Reflectivity" https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=70985
[11] Kiwamu Izumi, "Beam size jitter coupling" https://dcc.ligo.org/LIGO-T1700353
[12] Daniel Sigg, "Jittery Presentation" https://dcc.ligo.org/LIGO-G1602269
[13] Masayuki Nakano, "Jitter attenuation cavity (JAC) and PSL+" https://dcc.ligo.org/LIGO-G2401139
[14] Craig Cahillane, "Interferometer reflection and the right-half-plane zero" https://dcc.cosmicexplorer.org/CE-T2400008
[15] Kiwamu Izumi, "Frequency Response of the aLIGO Interferometer: part3" https://dcc.ligo.org/LIGO-T1500559/public
[16] Kentaro Somiya, et al. "Frequency noise and intensity noise of next-generation gravitational-wave detectors with RF/DC readout schemes" https://doi.org/10.1103/PhysRevD.73.122005

Extra Slides

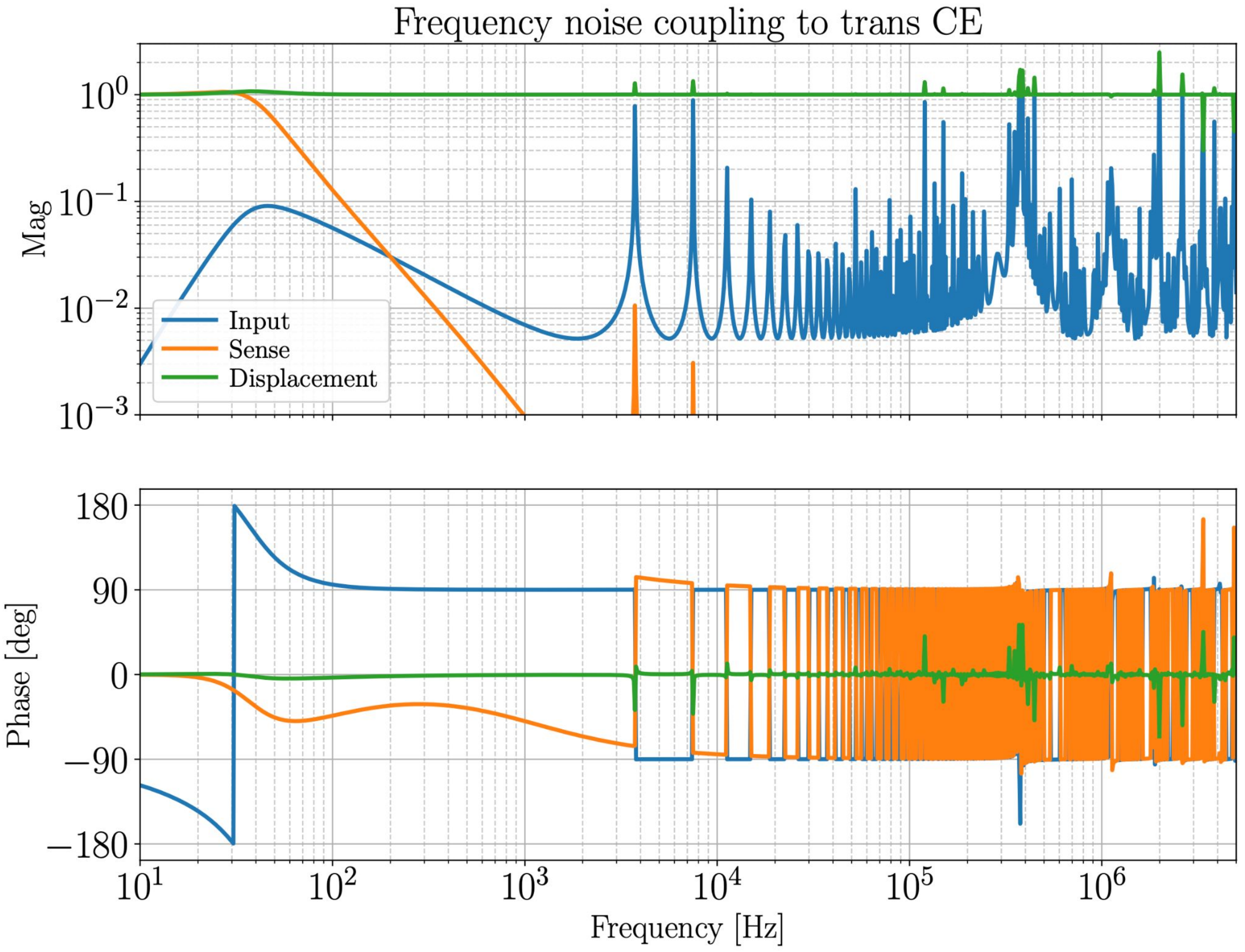
Coupling Functions for noise through IMC1



Coupling Functions for noise through IMC2



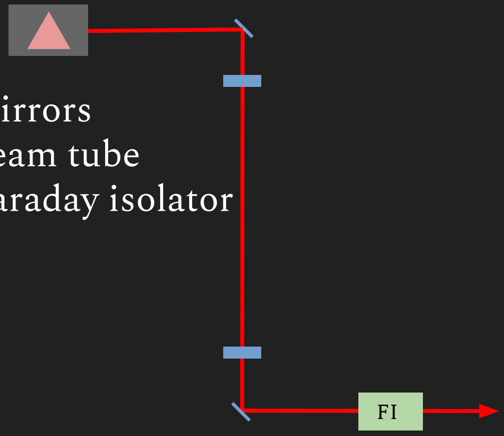
Coupling Functions for noise through CE



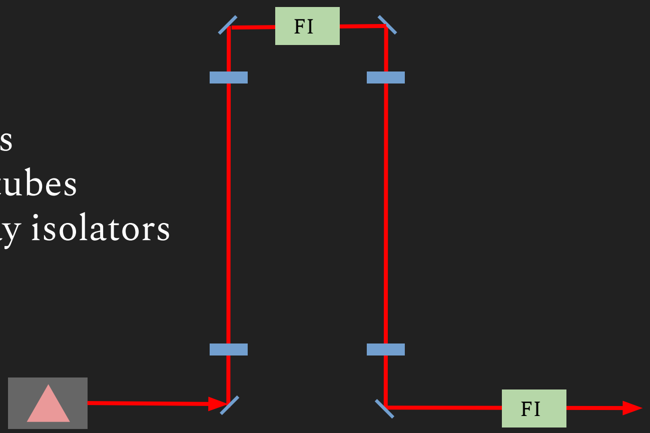
Configurations

One IMC | Two IMCs

Fabry-Pérot



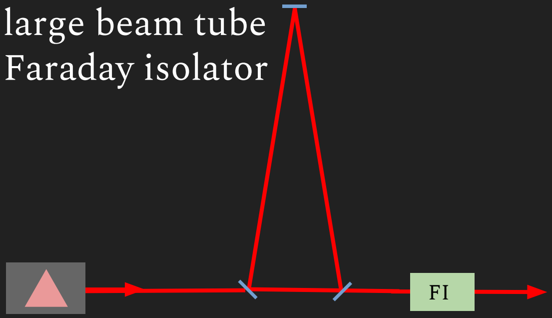
2 mirrors
1 beam tube
1 Faraday isolator



4 mirrors
2 beam tubes
2 Faraday isolators

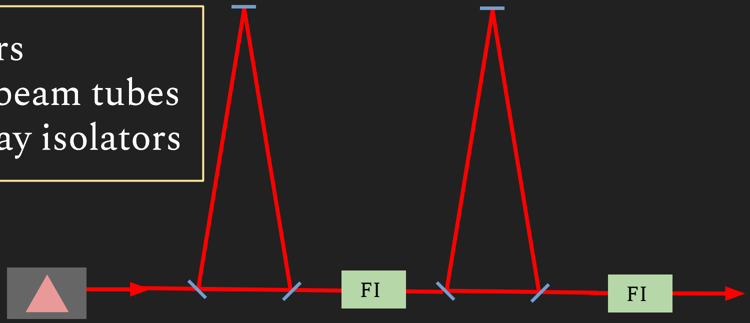
Triangular

3 mirrors
1 large beam tube
1 Faraday isolator



Most expensive

6 mirrors
2 large beam tubes
2 Faraday isolators



Intensity Noise

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

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

In Advanced LIGO we stabilize to 30 mW of power.

We anticipate finesse ~ 1500 for IMC2.

With 200 W of input power, we get around 100 kW of power in IMC2.
Shot noise limited RIN:

RIN = 3 x 10^{-9} (W/W)/rtHz

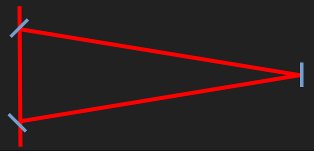
Displacement noise from radiation pressure in IMC2:

IN = 2 RIN Pcav/(m c) = 1 x 10^{-12} m/rtHz

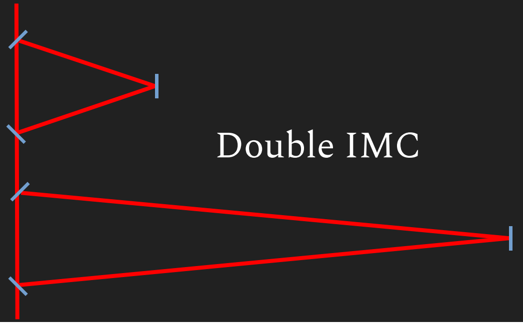
Can induce significant radiation pressure displacement noise for an IMC with 3 kg mirrors, and we have no control authority in IMC2 (thanks to Benno Willke for asking us about this)

CE frequency noise requirement:
Determined by the O3 observed
HOM frequency to DARM coupling

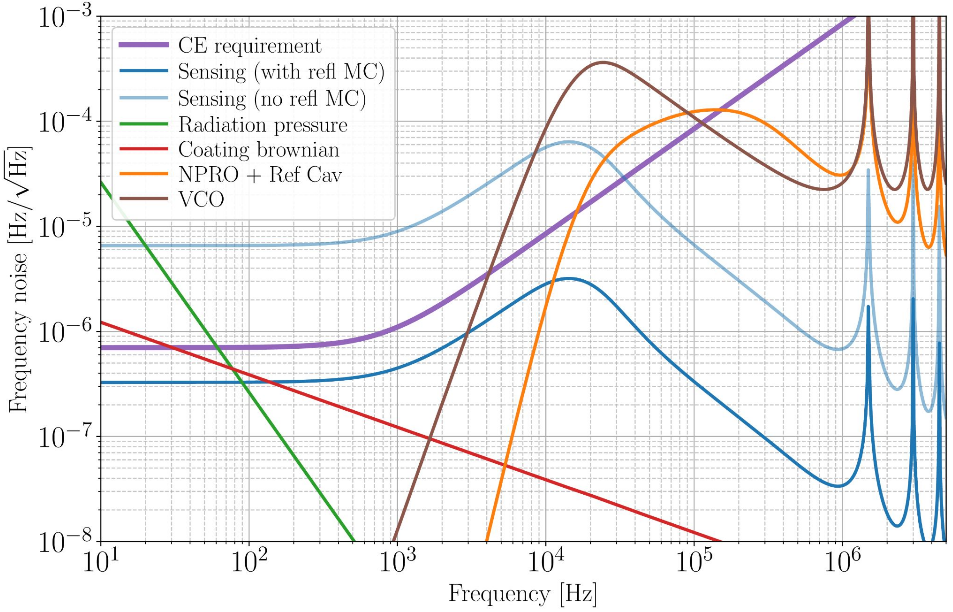
- Finesse = 700
- L_{imc1} = 100 m
- L_{imc2} = 330 m
- FSR_{imc1} = c/(2L) = 1.5 MHz
- FSR_{imc2} = c/(2L) = 450 kHz
- IMC1 pole = 1 kHz
- IMC2 pole = 500 kHz

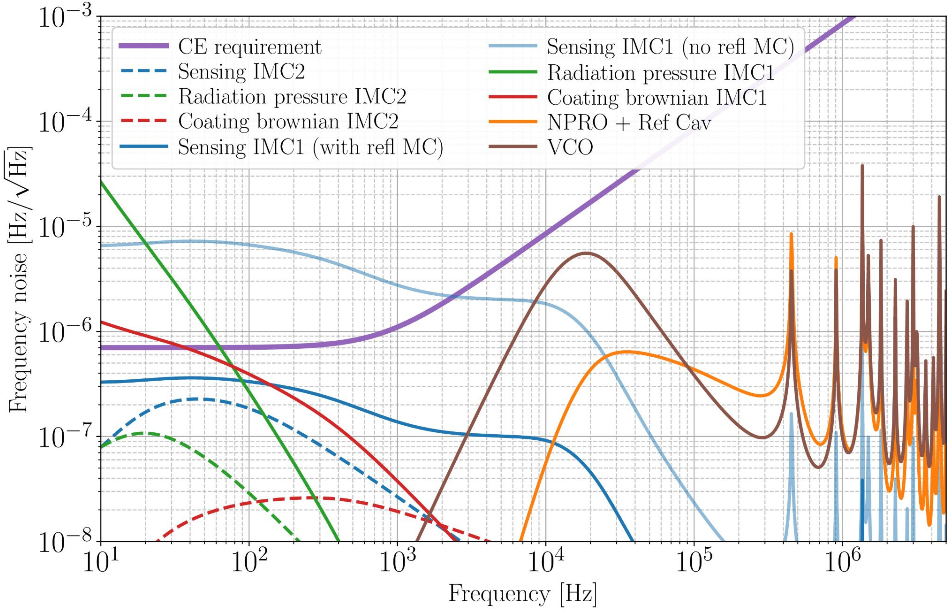


Single IMC



Double IMC





Single IMC noisebudget