Cosmic Explorer Intensity Noise Controllers

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CE Optical Design Call

Problem

Low frequency intensity noise may be a limiting noise factor for Cosmic Explorer gravitational wave sensitivity.

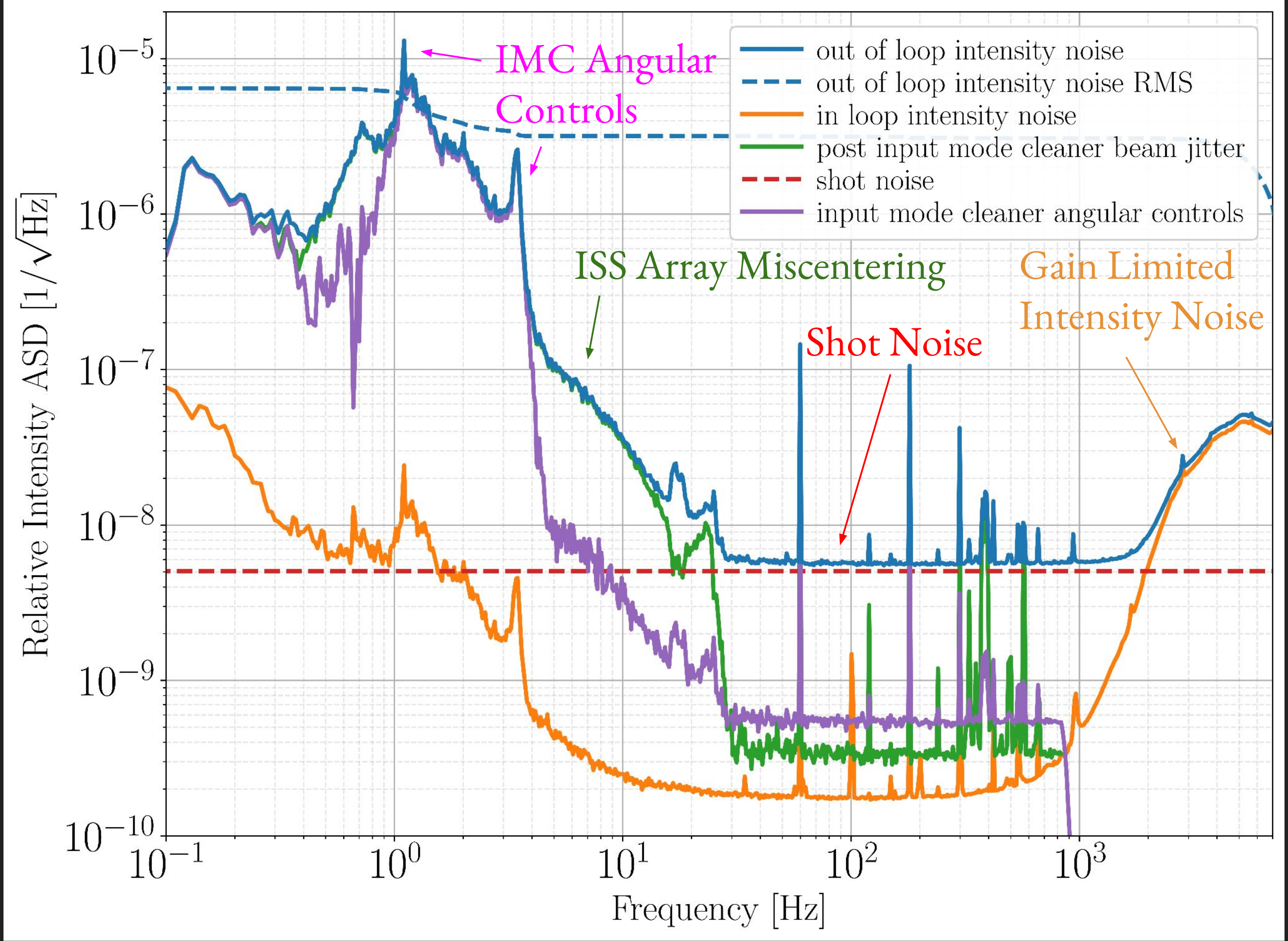
Particularly bad could be the intensity-to-frequency noise radiation-pressure-based cross-coupling.

This I2F cross-coupling has the ability to impose frequency noise in a low-frequency regime *using the input mode cleaners themselves*,
at a point in the input optics chain where we have little recourse to correct for it.

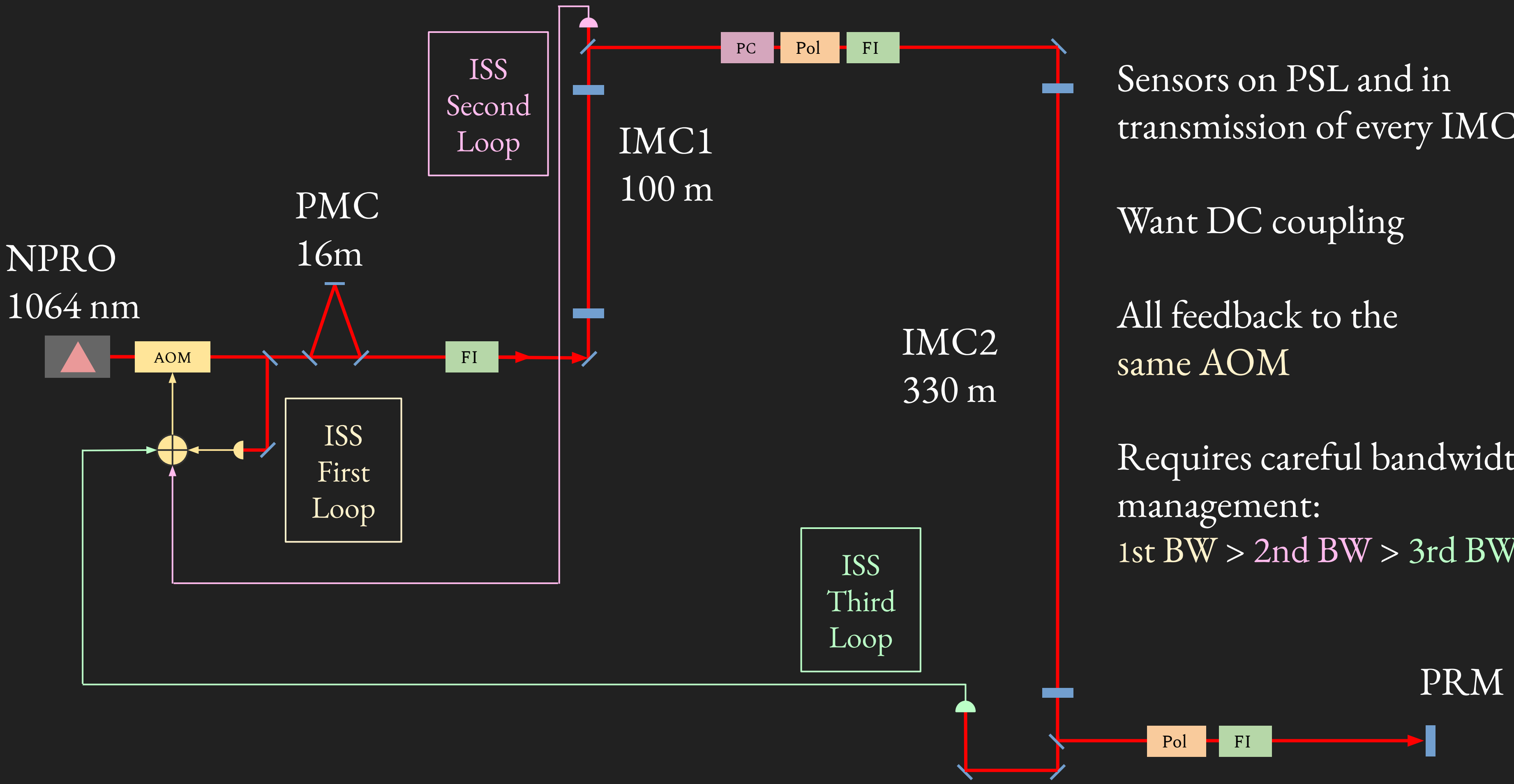
What are some options to combat intensity noise?

Intensity noise in O3

Similar to O4



Straightforward Hierarchical Intensity Control Scheme



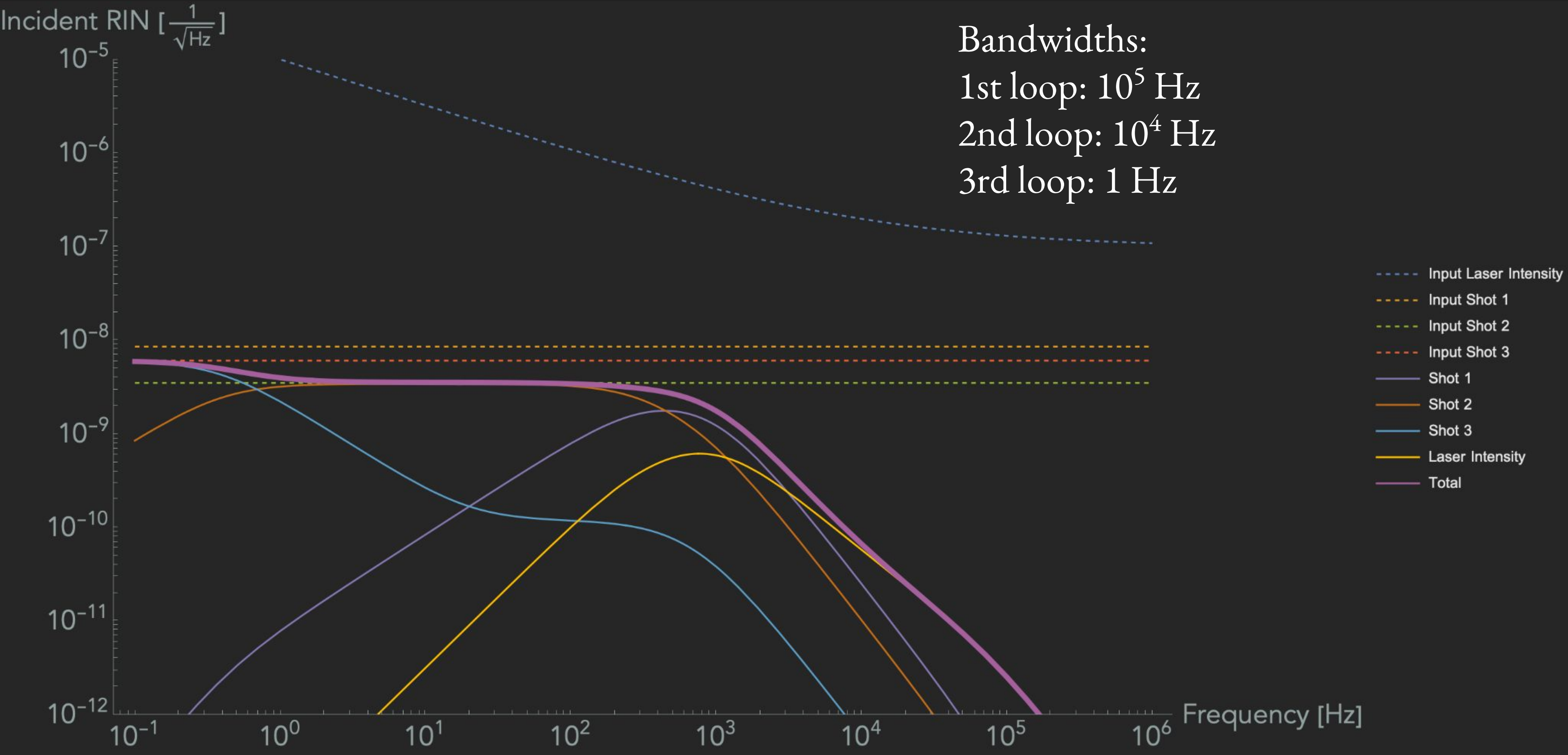
Sensors on PSL and in transmission of every IMC

Want DC coupling

All feedback to the same AOM

Requires careful bandwidth management:
1st BW > 2nd BW > 3rd BW

CE Intensity Noisebudget (first pass)



Bandwidths:
1st loop: 10^5 Hz
2nd loop: 10^4 Hz
3rd loop: 1 Hz

Optical AC Coupling

Idea: Reduce shot noise limit by detecting AC fluctuations above cavity pole directly.
Hurts sensitivity at low frequency

Derived in Patrick Kwee's thesis from AEI, studied by Kwee and Willke [2],[3], and measured at LIGO Livingston [4]

$$\frac{\mathrm{RIN}_{\mathrm{refl}}}{\mathrm{RIN}_{\mathrm{in}}} = \frac{1-(1-a)h(f)}{a}$$

where *a* is impedance matching
and *h(f)* is the normalized cavity pole TF
Cavity must be undercoupled, or else control loop is unstable

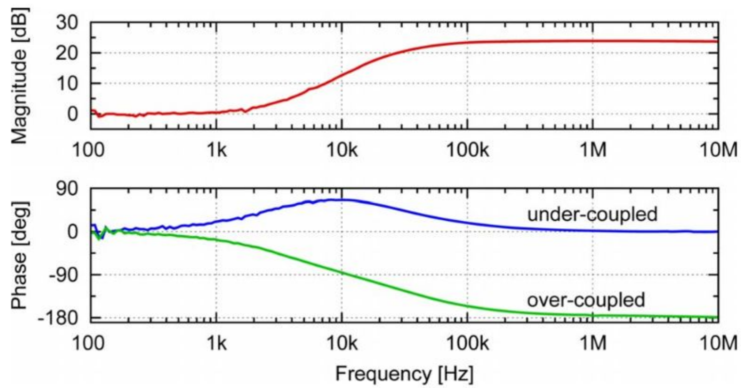


Fig. 2. (Color online) Measured transfer function $G(f)$ of RPN from the ACC input beam to the reflected beam using detectors HPD and LPD. The maximum gain was $|g| = 15.3$ with an upper corner frequency of $f_0 = 34$ kHz. The phase depended on the impedance matching of the ACC.

fluctuations A_{vac2} for frequencies above the resonator bandwidth. As the absolute power of $A_{ool,b}$ is again a factor of 2 smaller than the original beam power, the relative power noise of $A_{ool,b}$ is 3 dB above the power noise of A_{las} for high frequencies [Fig. 2(b)].

In a stabilization scheme with optical ac coupling [Fig. 1(c)] a better power stability can be achieved for frequencies above the ac-coupling resonator (ACC) bandwidth. The transfer function $G(f)$ from relative power fluctuations in front of the ACC to relative power fluctuation in reflection of the resonator was

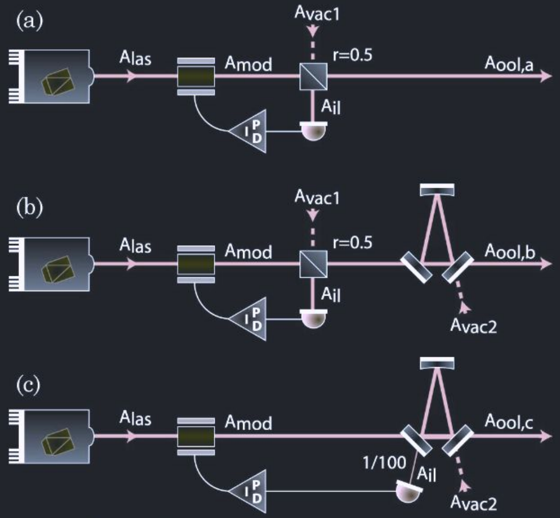


Fig. 1. (Color online) Models used for calculating the quantum noise limit of three different power stabilization schemes: (a) traditional power stabilization, (b) traditional power stabilization with additional resonator in the out-of-loop path, and (c) power stabilization with optical ac coupling. The relative power noise of the out-of-loop fields $A_{ool,a}$, $A_{ool,b}$, and $A_{ool,c}$ were calculated as functions of the input field A_{las} and the vacuum fields A_{vac}.

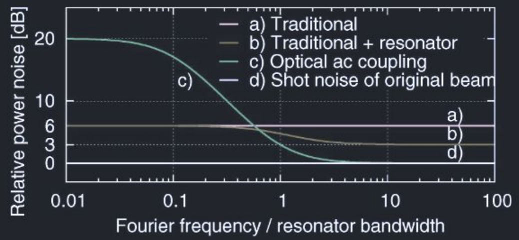


Fig. 2. (Color online) Shot-noise limit for different power stabilization schemes. The limits are given in relation to the relative shot noise of the original beam. Traditional power stabilizations are always 3 to 6 dB above this reference. A stabilization with optical ac coupling is very close to the relative shot noise of the original beam for Fourier frequencies above the resonator bandwidth.

Optical AC coupling only helps the shot noise limit at high frequencies above the cavity pole.

Not where we really want the improvement.

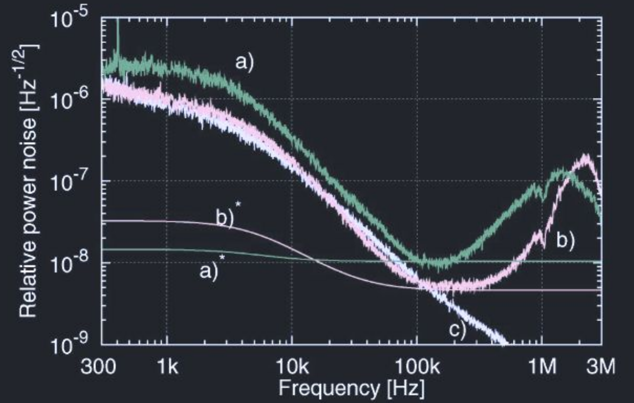
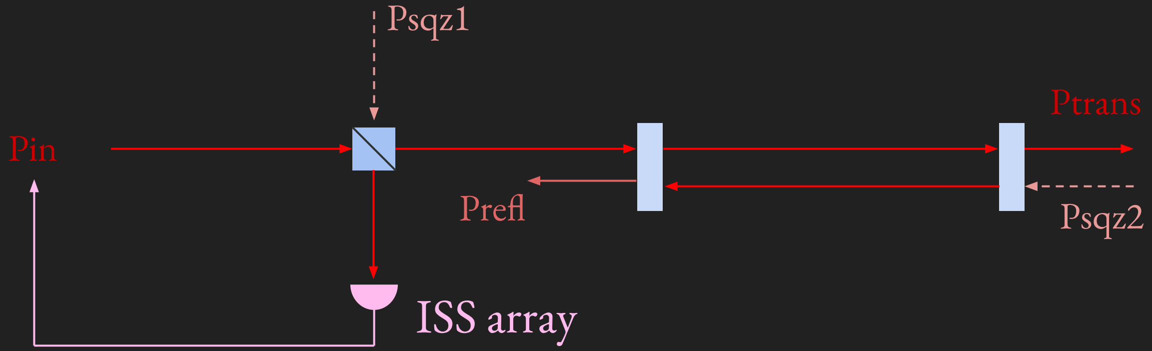


Fig. 5. (Color online) Typical out-of-loop power noise measurements performed with the HPD detector. Scattering to higher-order modes (curve a) or into the countercirculating fundamental mode (curve b) limited the power stability. The expected limits without any scattering are shown as smooth solid curve (curves a^*, b^*). For the case of scattering to the countercirculating fundamental mode, a projection of the power noise due to scattering is shown (curve c, see Subsection 4.B).

Squeezing and Intensity Noise



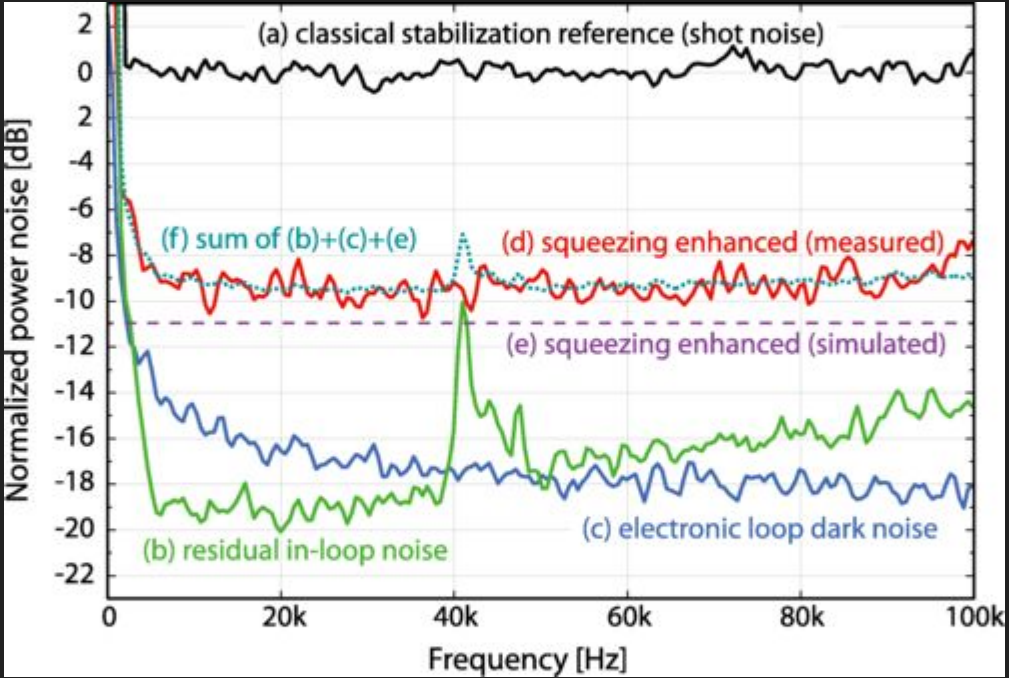
Can inject squeezing into the ISS improve the shot noise limit on Ptrans

Psqz1 is the main squeezed light path for reducing the intensity noise.
Psqz2 is another path by which quantum noise will be imposed upon Ptrans.

Proof of principle: Valbrutch et. al.
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.173601

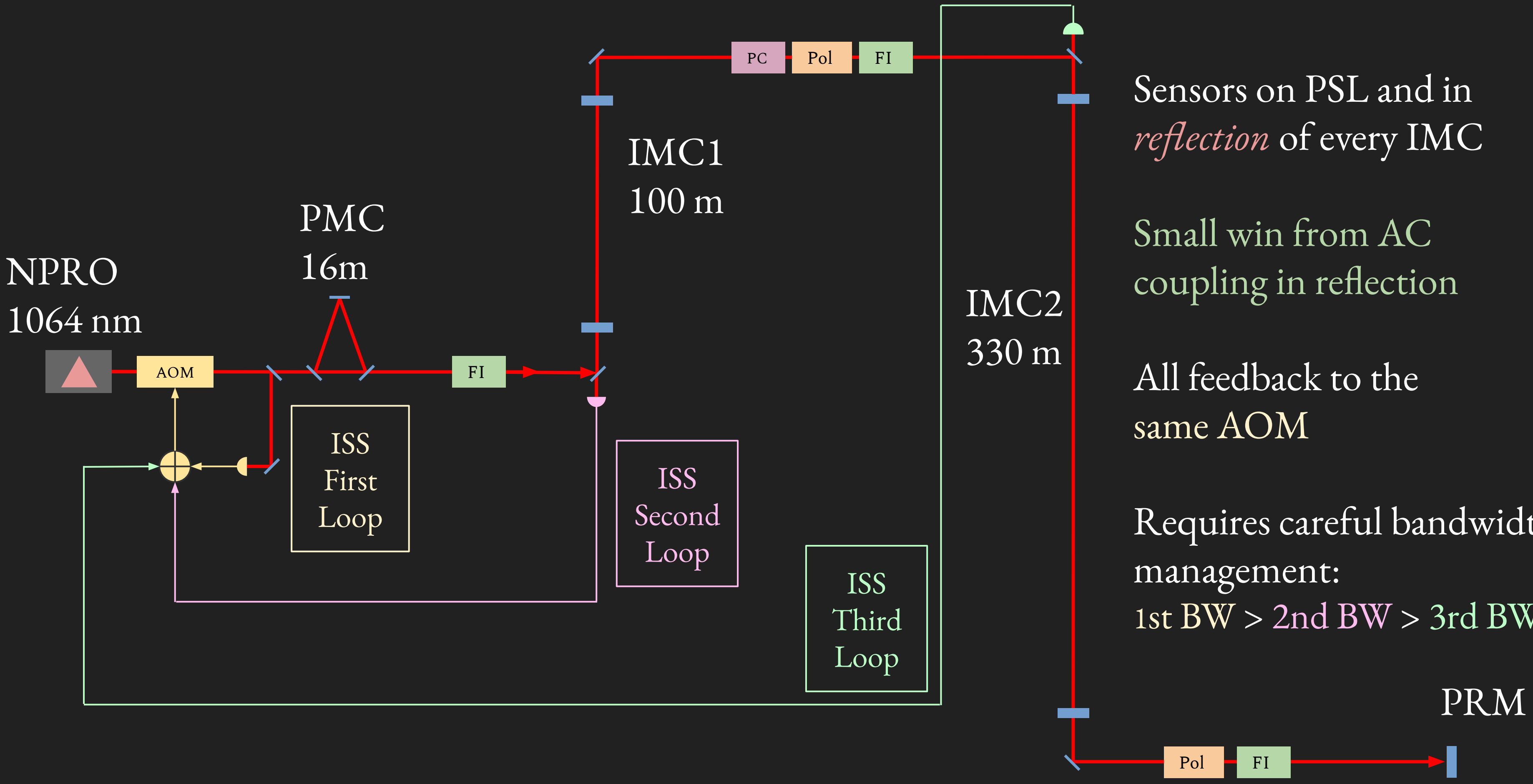
Advantages of Squeezed intensity loop:

1. Improves low frequency intensity noise (if shot noise limited)
2. Easy to implement (for LIGO)
3. Lots of experience in LIGO
4. Don’t necessarily have to use



Valbrutch et. al. FIG. 3

Optical AC Coupling Hierarchical Intensity Control Scheme



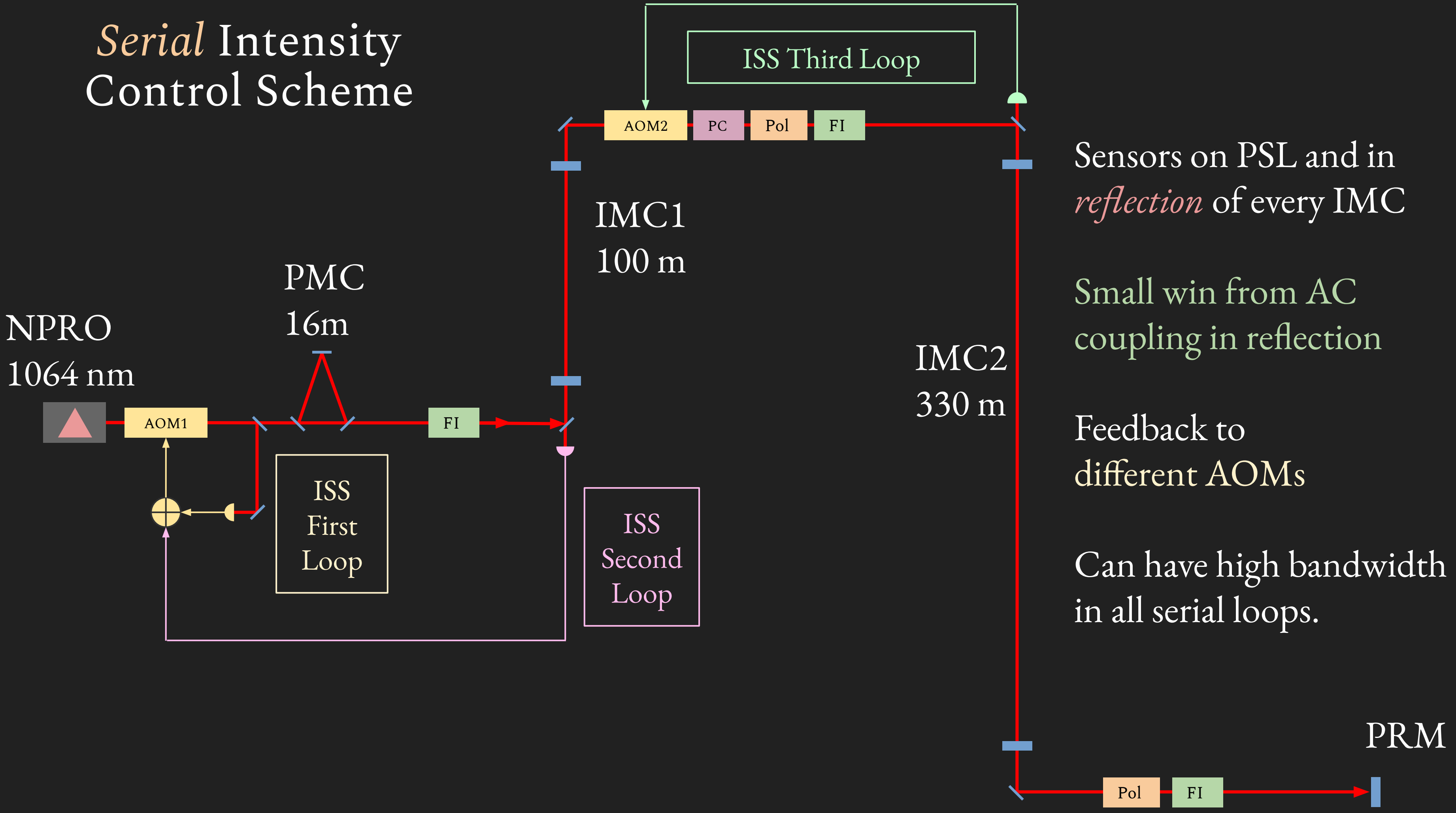
Sensors on PSL and in *reflection* of every IMC

Small win from AC coupling in reflection

All feedback to the same AOM

Requires careful bandwidth management:
1st BW > 2nd BW > 3rd BW

Serial Intensity Control Scheme



Sensors on PSL and in *reflection* of every IMC

Small win from AC coupling in reflection

Feedback to different AOMs

Can have high bandwidth in all serial loops.

Conclusions

Options to combat intensity noise

1. Push down IMC angular control resonances to be < 1 Hz to avoid limiting CE at 5 Hz.
    a. Will aLIGO quad suspensions be enough? Probably close enough.
2. Make ISS array easier to align
    a. Can investigate ultra-high power photodiodes, see if they can perform for 10000 hours with 100 mW incident.
3. Squeezed light injection into main ISS array