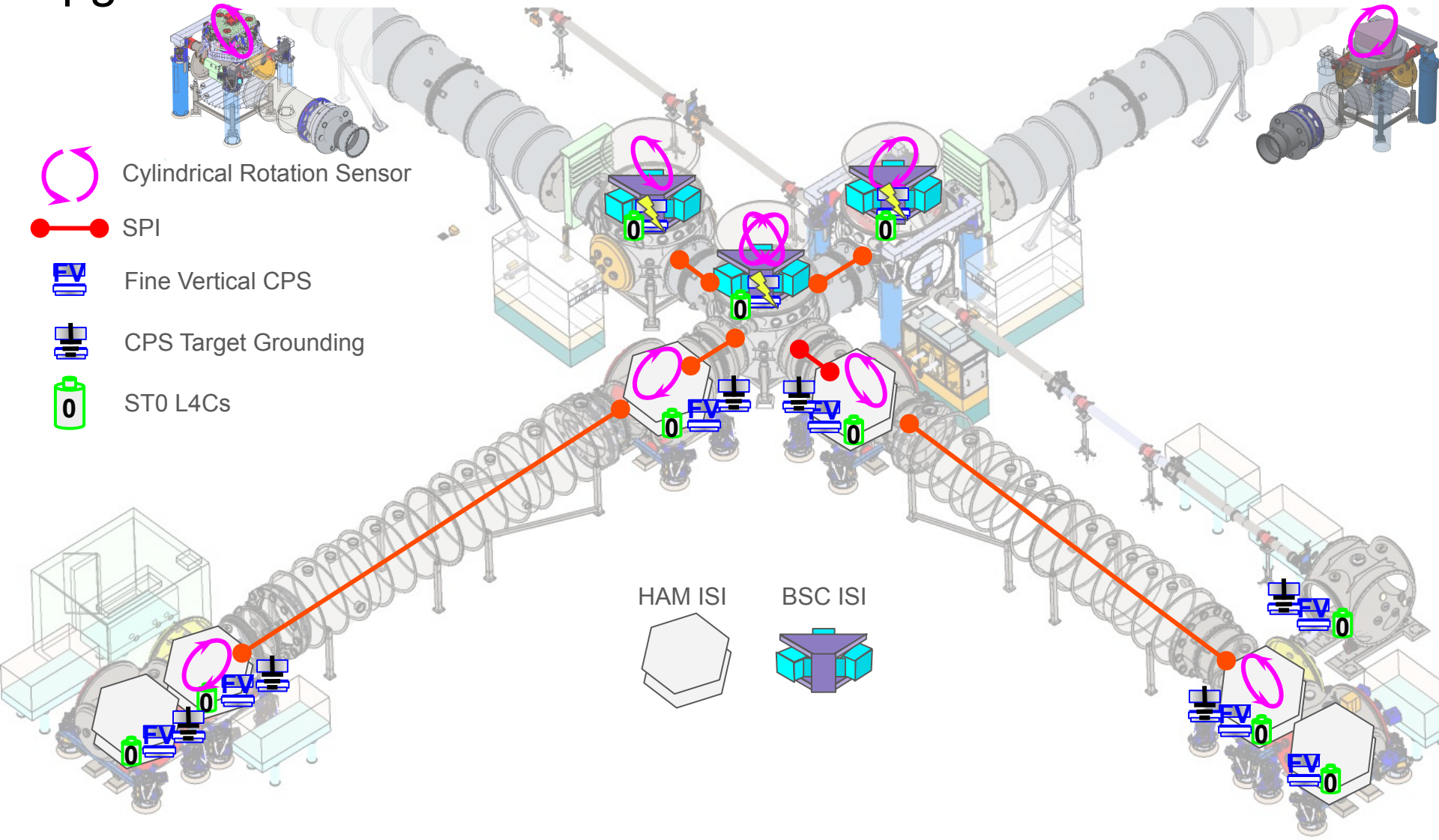
Seismic Platform Interferometer (SPI) Pathfinder Update (LVK 2026)

Joshua Freed, Jeff Kissel, Sina Koehlenbeck, Brian Lantz, Bram Slagmolen, Sheon Chua, Arnaud Pele, Eddie Sanchez, Jason Oberling, Matthew Heintze, Calum Torrie, Gabriele Vajente, Peter Fritschel, Michele Zanolin, Marc Pirello, …

G2600432

The SWG Dream: Integrated Collection of Sensor Upgrades



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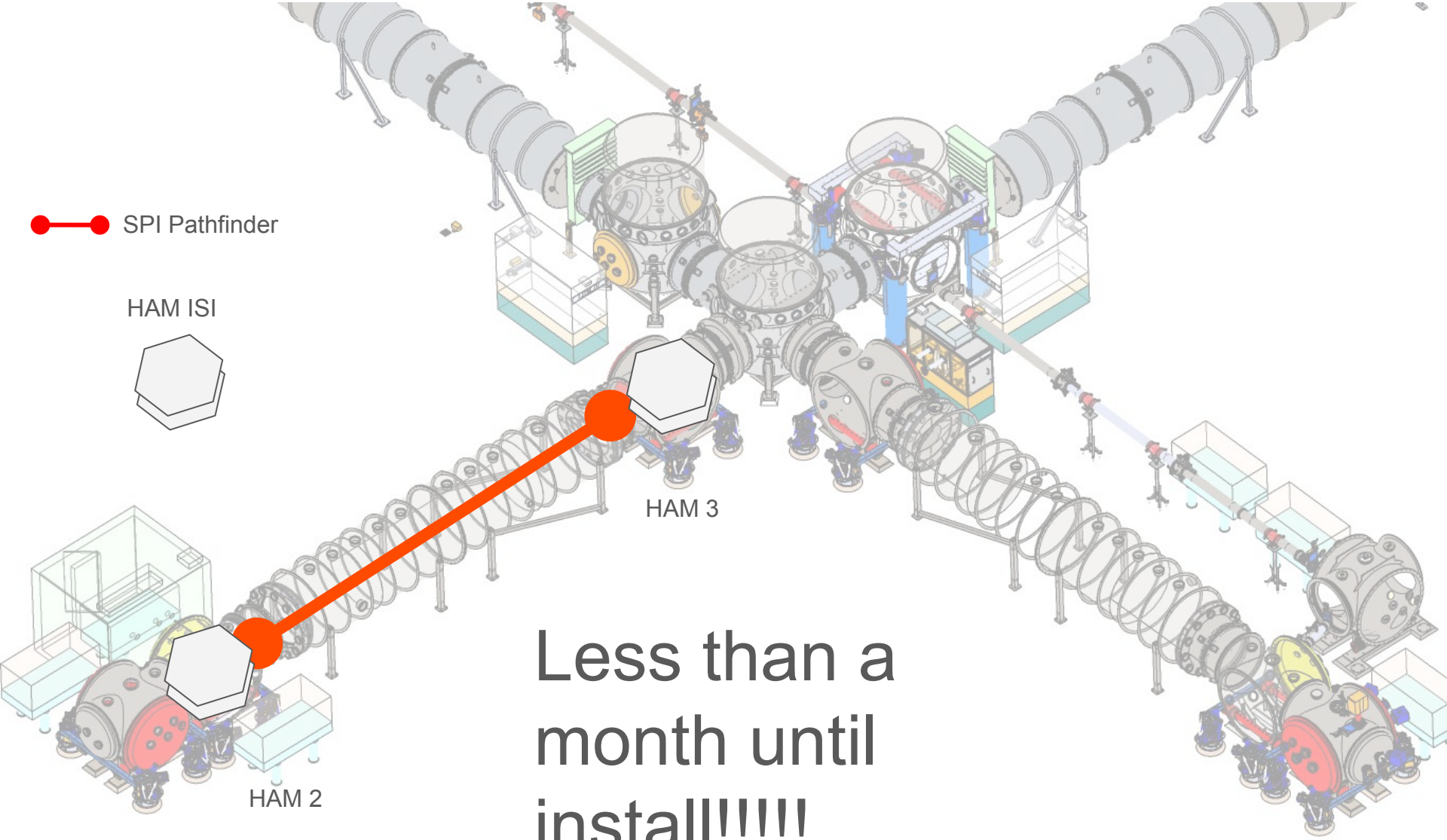
Next Step: **SPI Pathfinder** (Install Target March 30th 2026)

We have a final design doc! T2400145



Less than a month until install!!!!!

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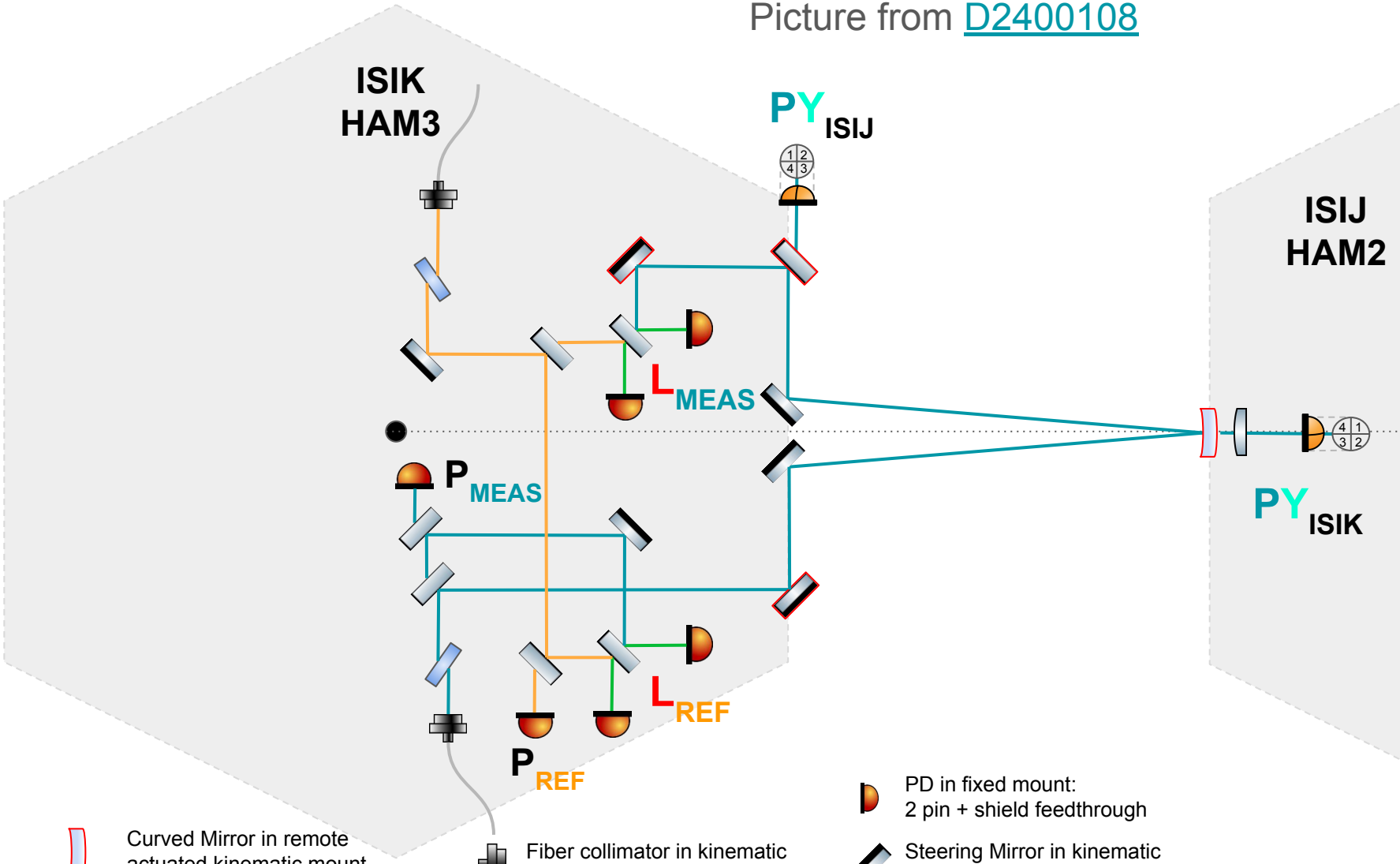
FINAL Optical Layout (Conceptually)

We have a final design doc! T2400145

Picture from D2400108



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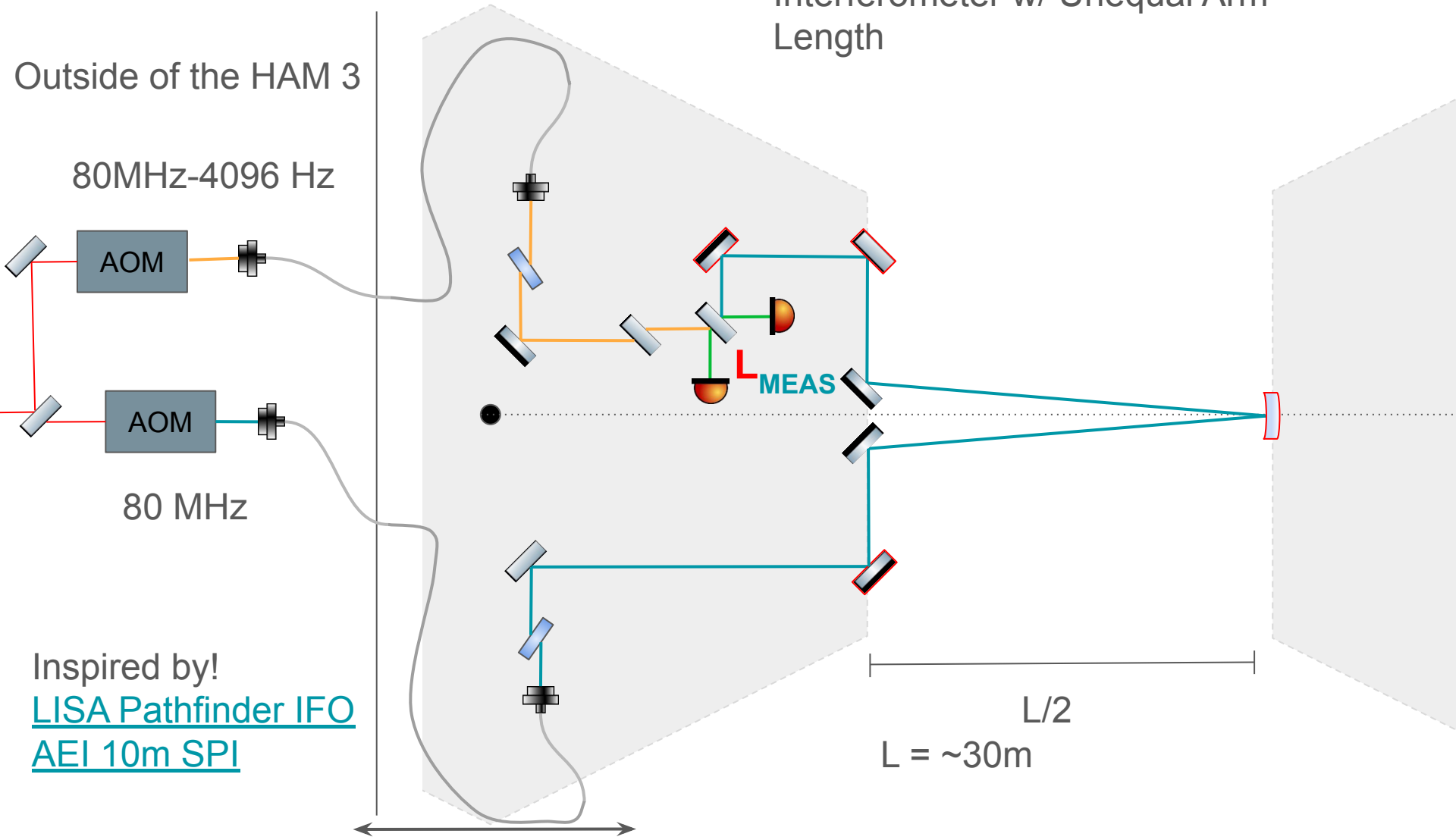
SPI LONG (Alone)

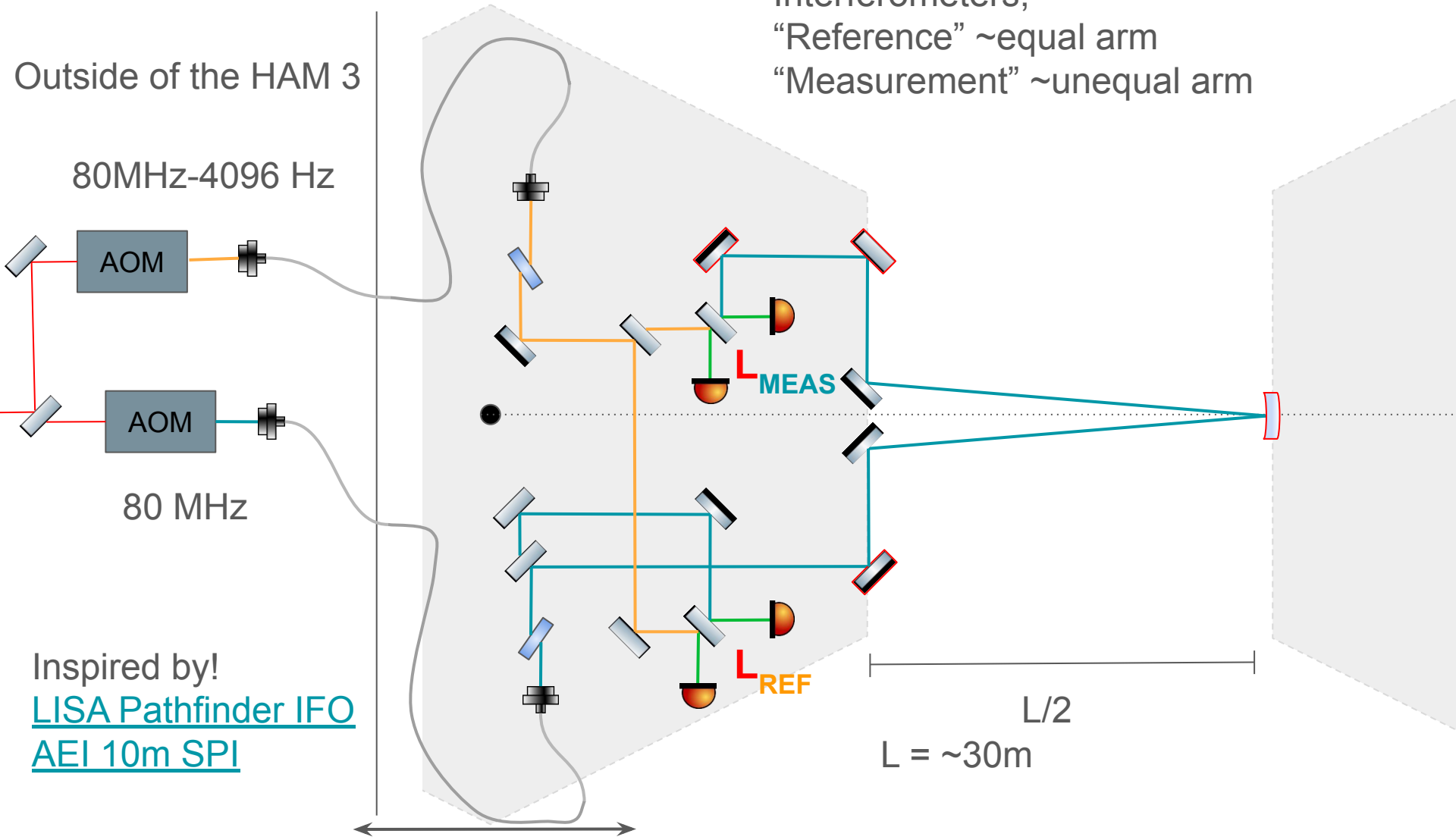
Heterodyne Mach-Zehnder Interferometer w/ Unequal Arm Length



Inspired by!
LISA Pathfinder IFO
AEI 10m SPI

SPI LONG (Alone)

Two Heterodyne Mach-Zehnder Interferometers,
“Reference” ~equal arm
“Measurement” ~unequal arm



Inspired by!
[LISA Pathfinder IFO]
[AEI 10m SPI]

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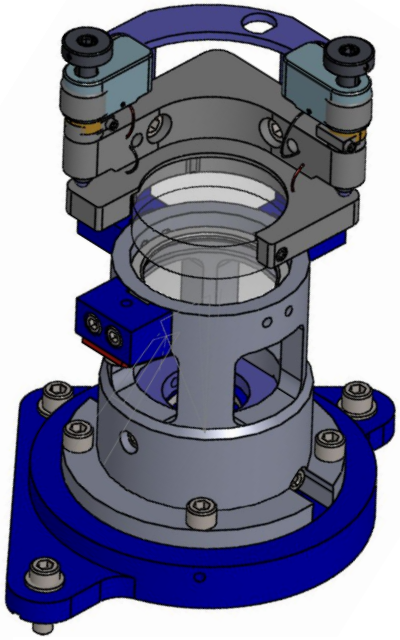
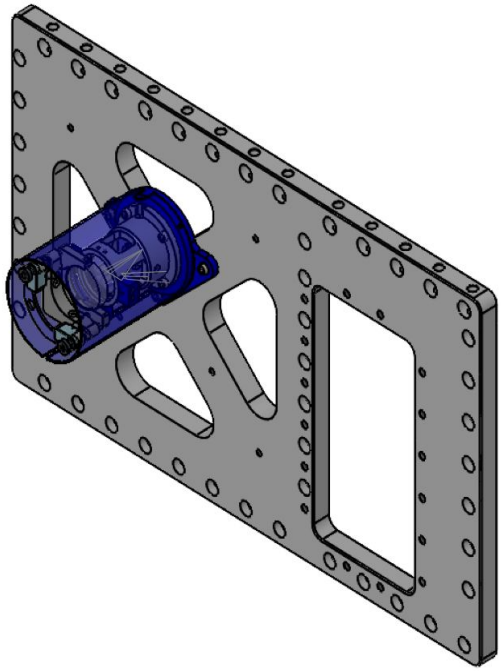
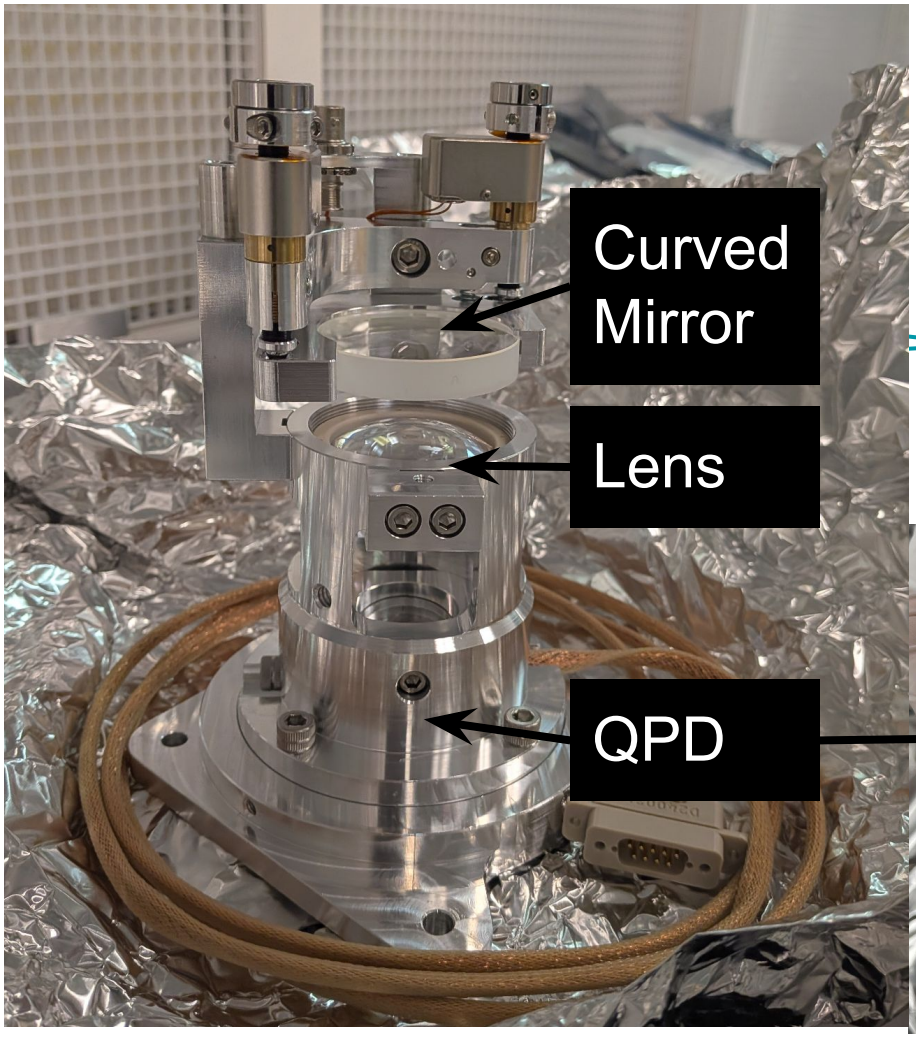
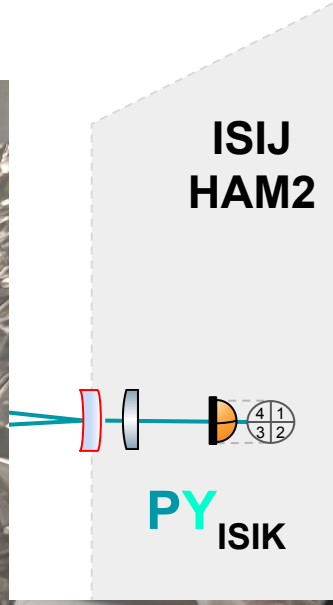
ISI J Design and Build D2400102

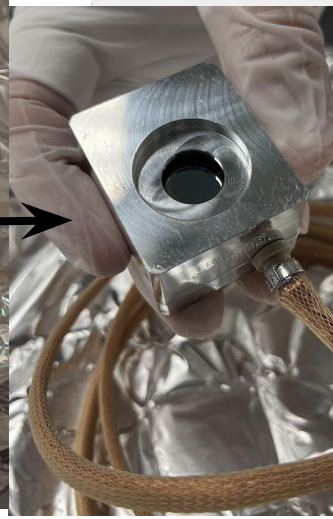


Spot size r = 5 [mm], ROC mirror = 15.472 [m]
f_lens = 17 [mm]
QPD sensitive area = 11 [mm]









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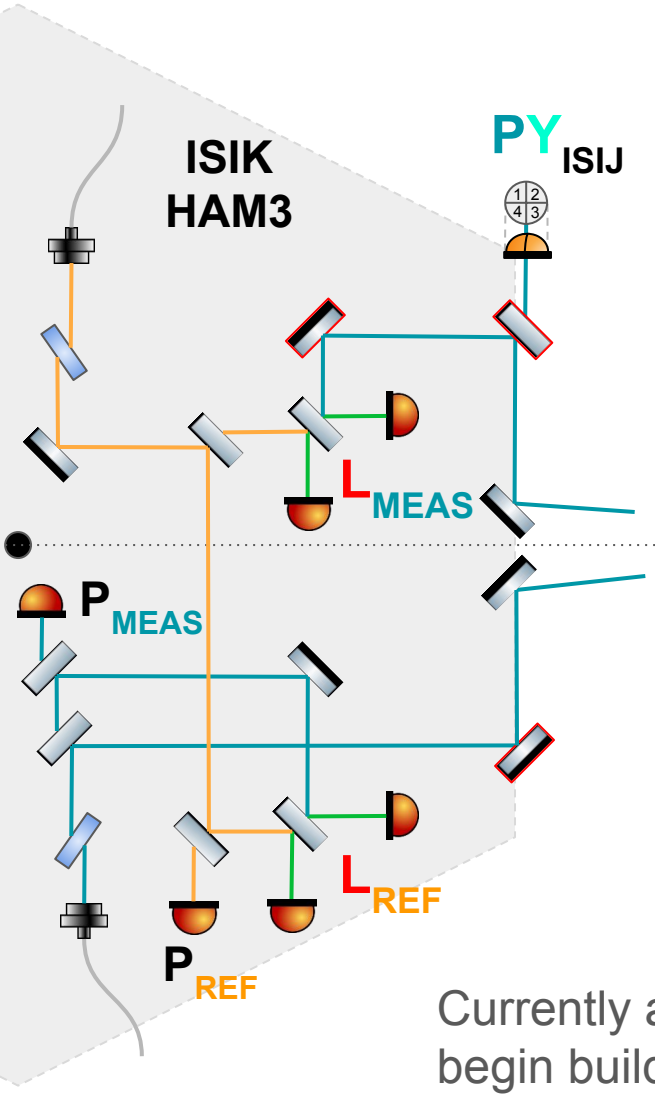
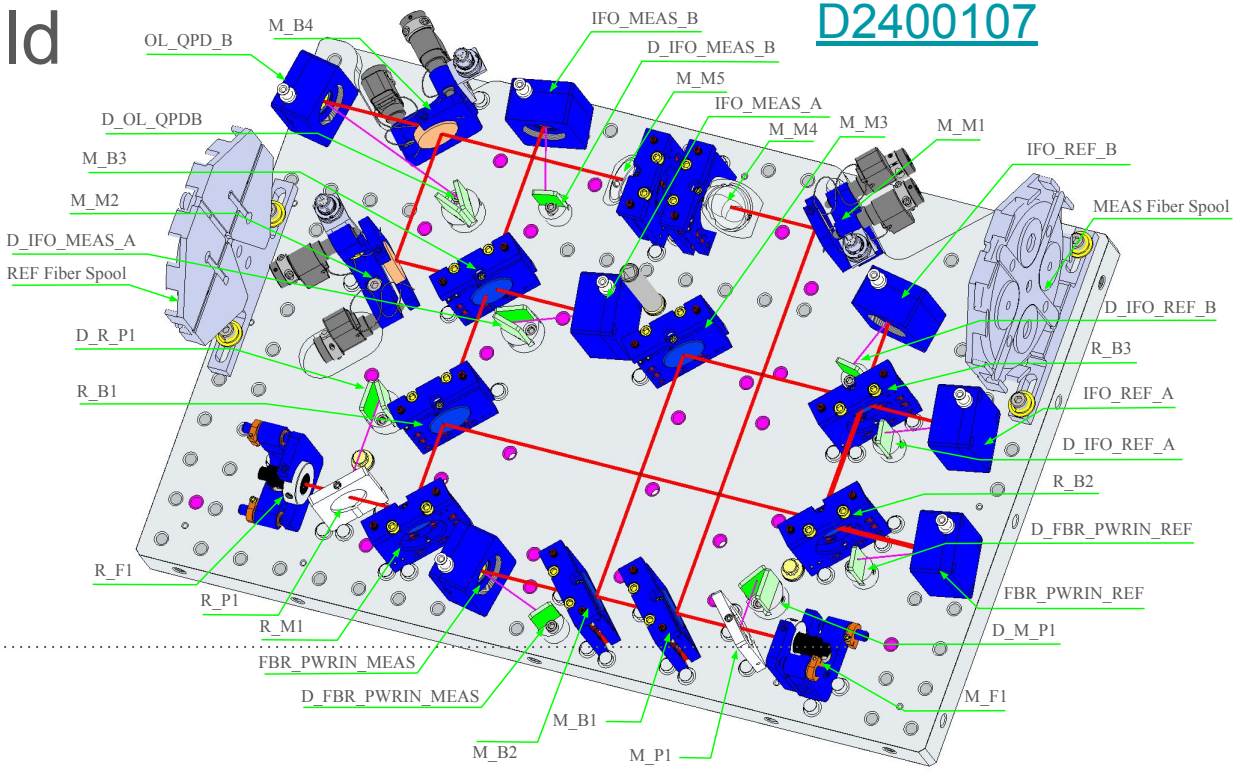
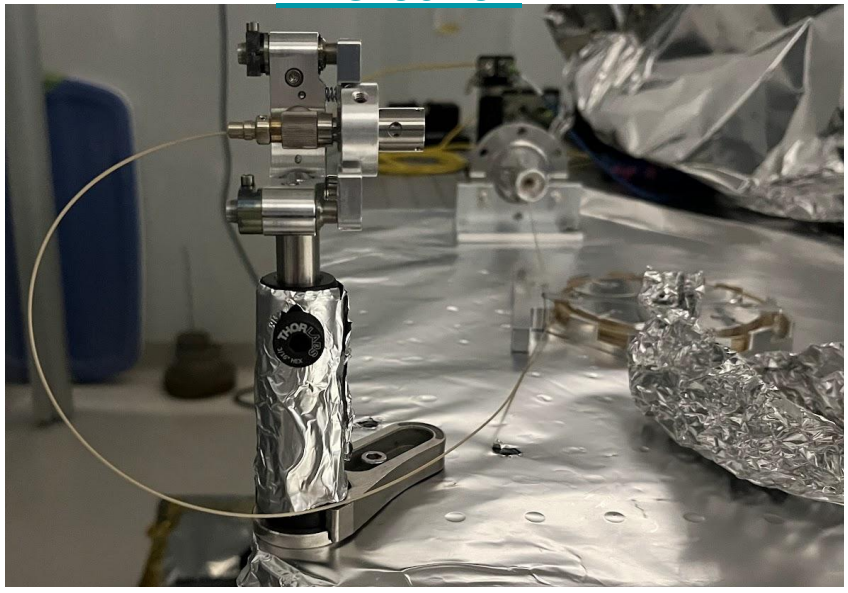
ISIK Design and Build



D2400107



LHO:89181



Currently about to begin building!

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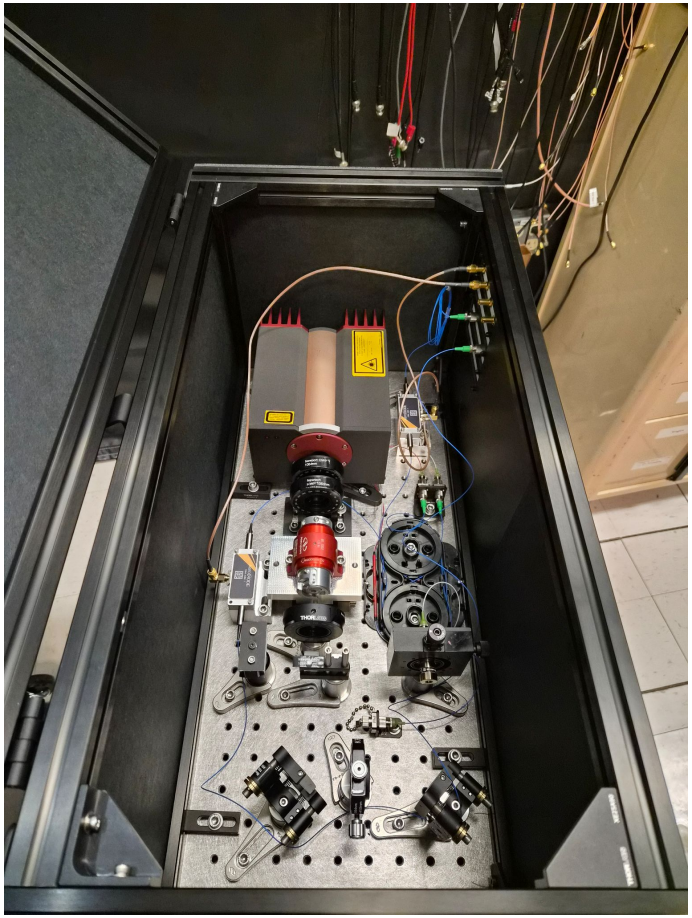
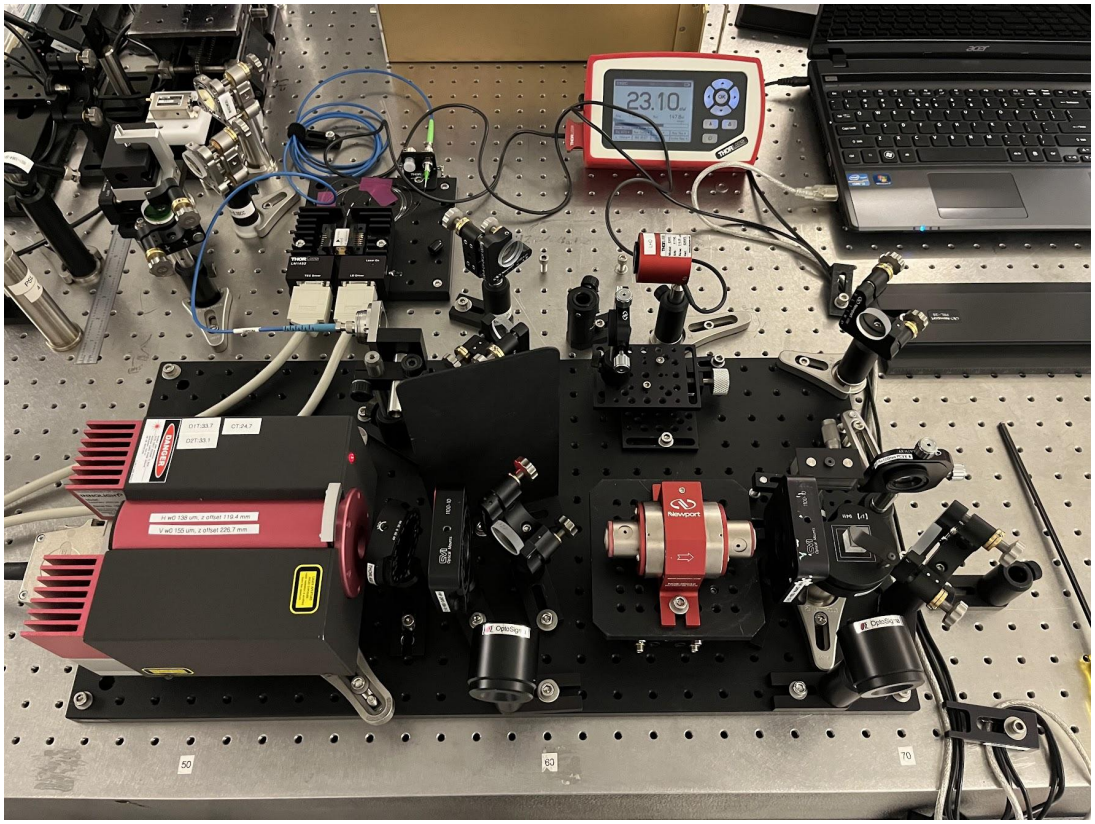
Picture of the NPRO Setup for seed in Optics Lab

Stanford build



Our current build



Started assembly on Feb 11, now mode matching into fiber collimator Mar 10!

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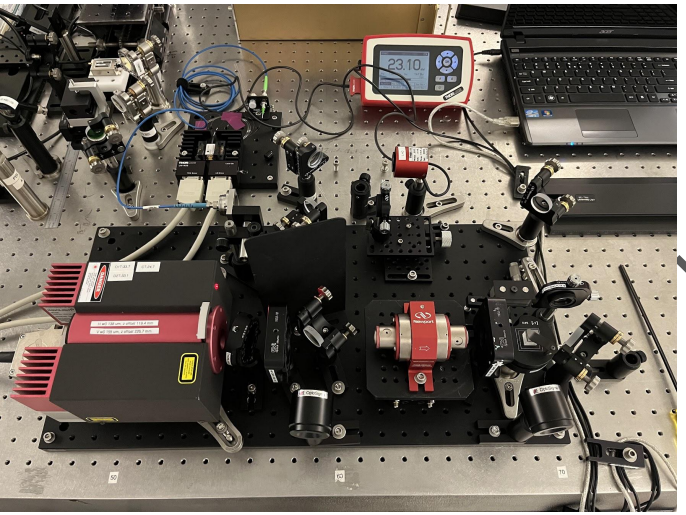
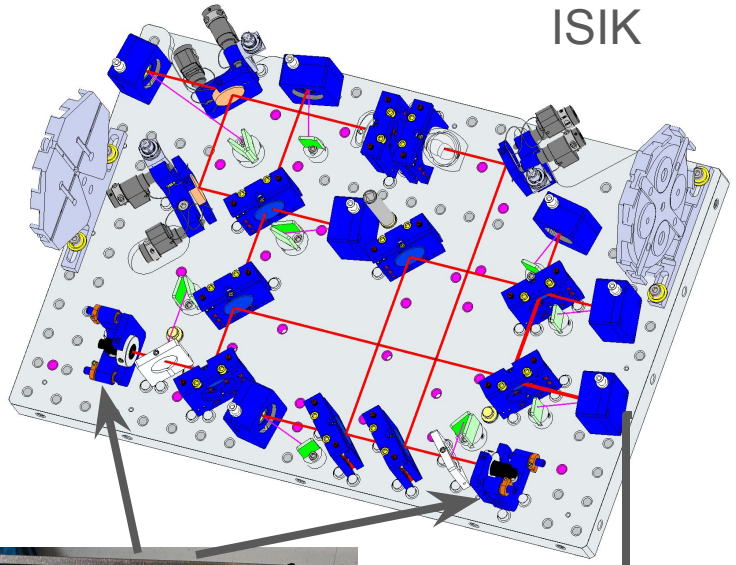
ISIK Build Testing so far…



Seed laser

ISIK



Laser Prep Chassis

Electronics

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Timeline

2025				2026				2027				2028	
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
O4b Observing run				Commissioning				IR1	Commissioning				

Final Design

Assemble and Installation pathfinder H1 HAM23

Evaluate Perform-ance with full IFO

Update design as needed, as well as expand the design to other HAMs

Build and install for H1 HAM45 L1 HAM23 L1 HAM45

L1 Staff visit to gain experience

We are here

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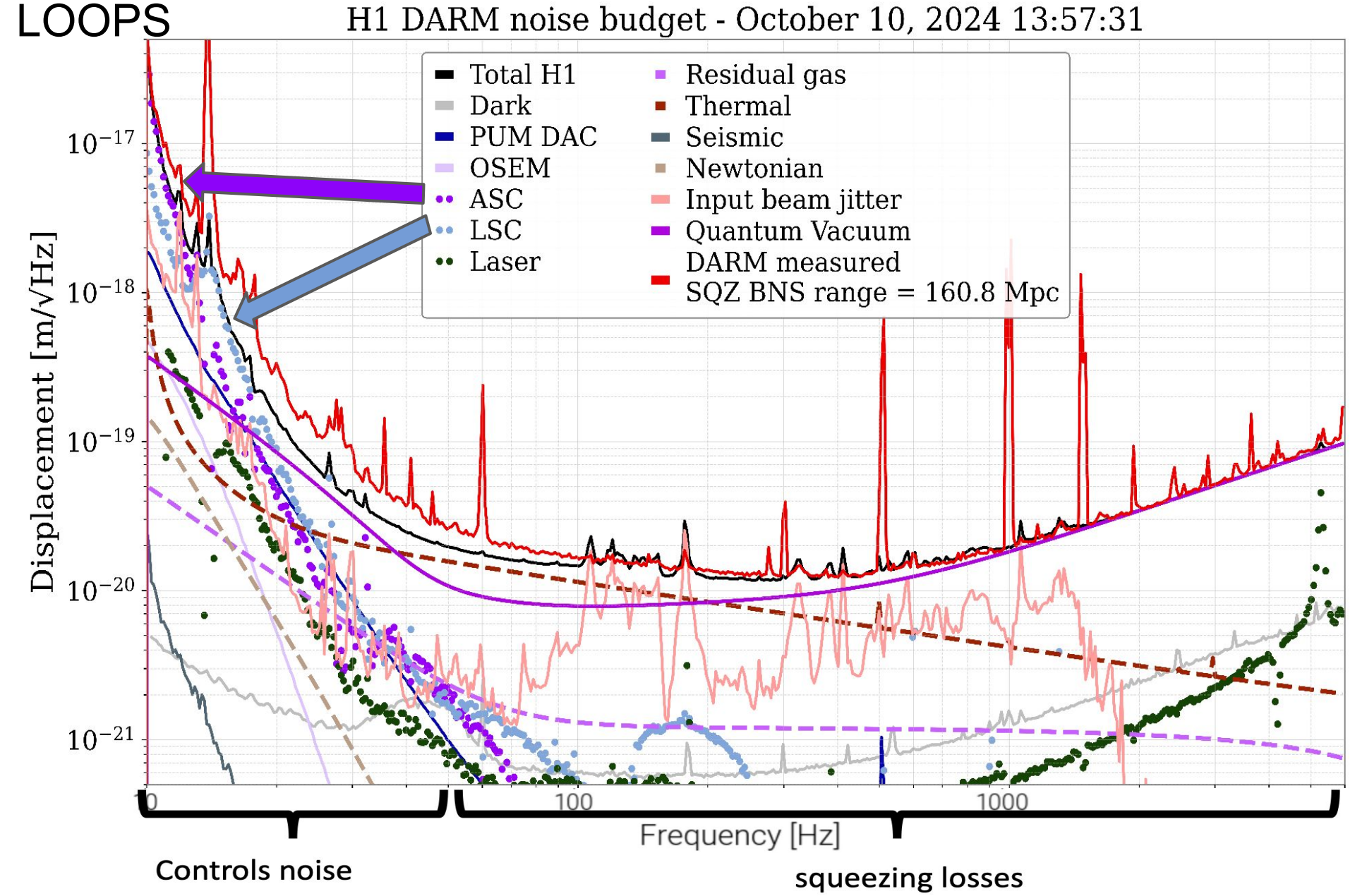
SPI's TARGET IS NOISE REDUCTION IN THE CONTROL LOOPS



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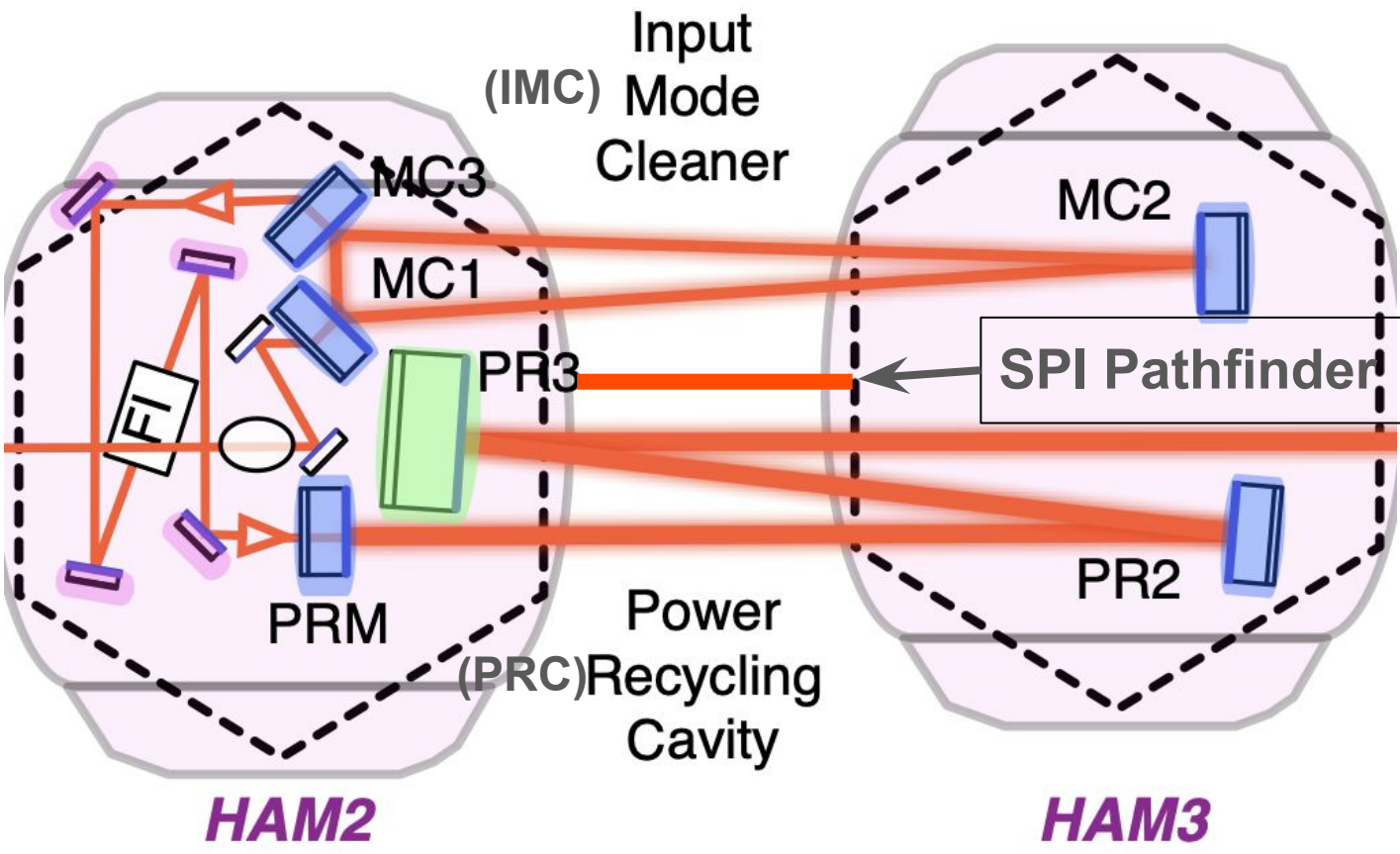
The IMC is an excellent witness for SPI Pathfinder, and vice versa

SPI Pathfinder is a **Singular** relative position sensor/optical lever combo

We do not expect to see DARM improvements with just pathfinder by itself



Using the IMC as a witness we can evaluate the performance SPI will bring. As well as, iterate the design that before a full rollout

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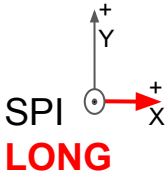
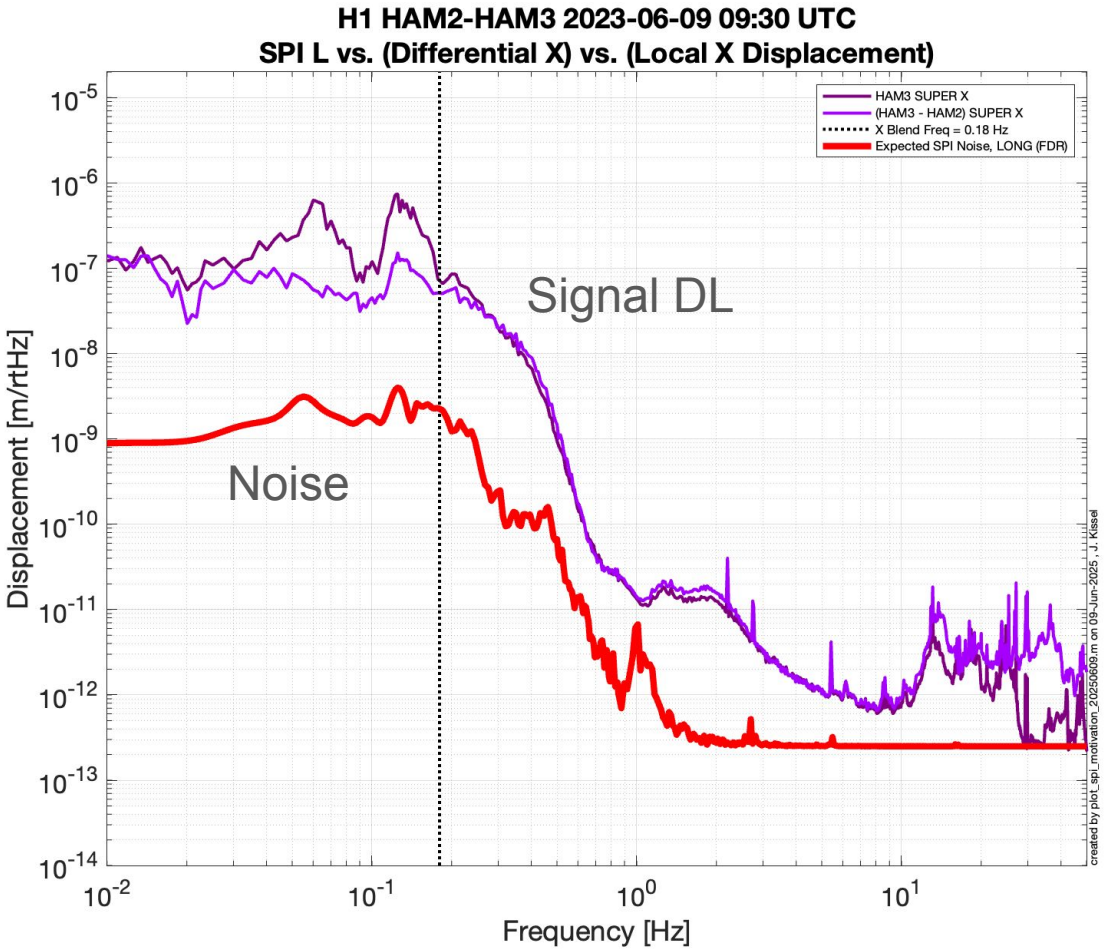
As a reminder Expected SPI **LONG** Performance



Local X

Differential X

SPI Sensor Noise



From final design doc!
T2400145

We won't be able to get all the way down to SPI LONG noise we'll still be limited by rolling off GS13 tilt noise, it'll still MUCH better than current performance.

The pathfinder's job is to quantify HOW much better.

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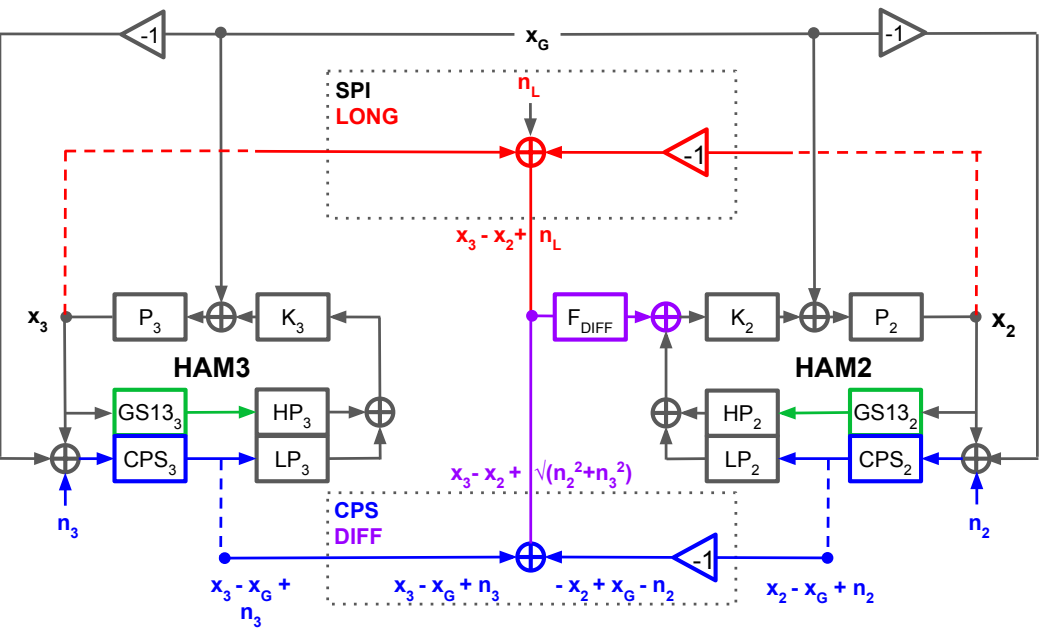
Controls? Yes! But SPI is a **Relative** Position Sensor

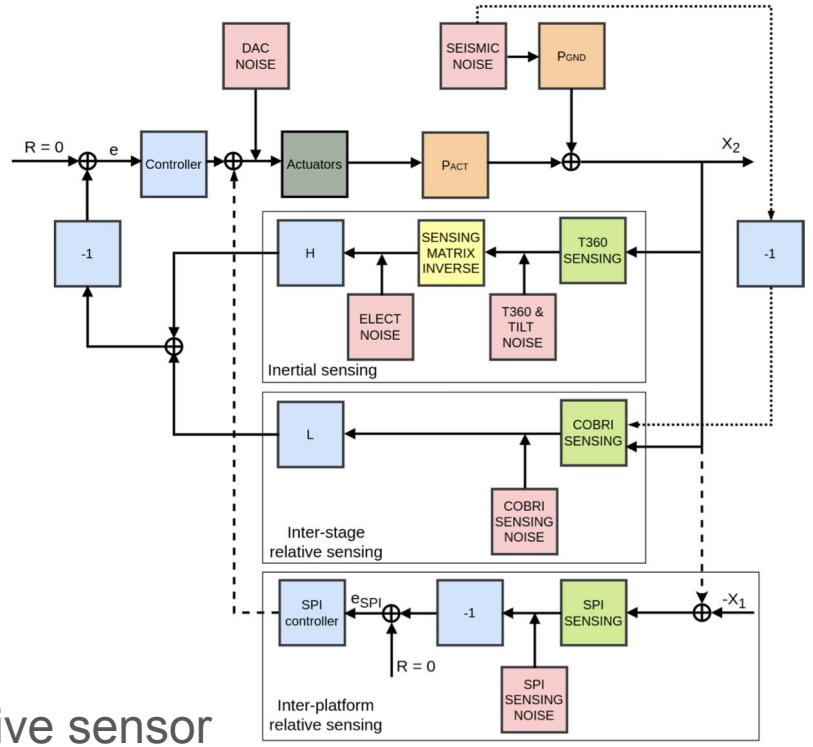
SPI Pathfinder Integration at Hanford



G2402139

CPS DIFF would be turned off (or blended in at much lower frequency), but shown here to provoke thoughts of similarity, and to convey where sensor noises get in

SPI Integration in GEMINI



https://arxiv.org/abs/2509.04730

Careful thought must be put into integrating a relative sensor between 2 platforms vs. what IFO needs

Baseline plan is using a similar topology to LIGO's CPS DIFF (CQG 42.4 (2025): 045019), but also considering "GEMINI" topology (arxiv:2509.04730).

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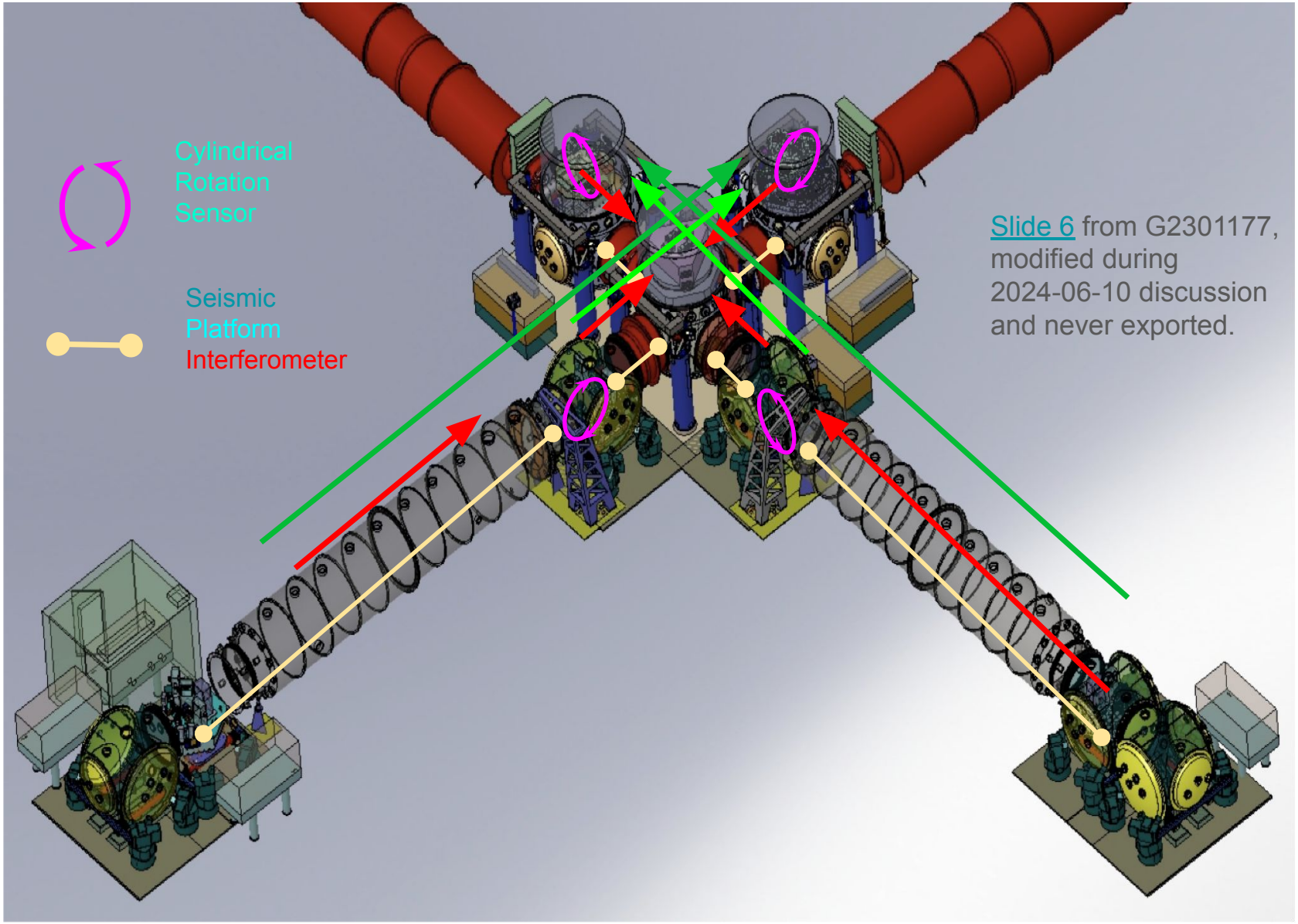
But what about when we have to link more than two platforms together?



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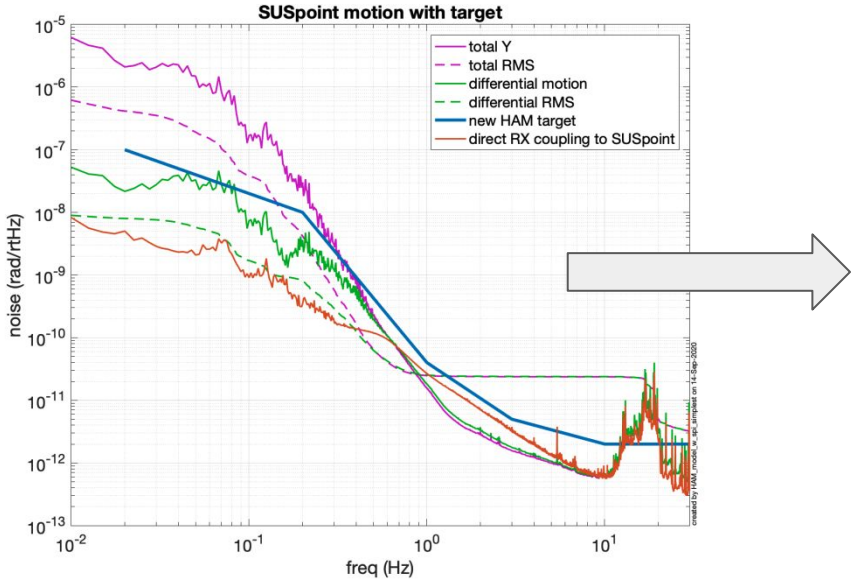
Josh's (aka Me) Goals for Controls

- (Right Now) Reproduce and update Brian's SRCL performance with SPI improvement from G2001539 >> update for HAM2 / HAM3 and the IMC or PRC.



- Improve SPI noise with latest knowledge
- Change H45 to H23 performance
- Consider YAW instead of just LP
- Update Blend Filters

- (Definitely) Consider different two-platform control topologies for ease of design and IFO integration
- (Definitely) Motivate the need for CRSs and where
- (Stretch Goal) Model linking / CRS'ing the whole corner station and its performance.

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Recap

- We have a final design doc! T2400145
- Installation readiness has been reviewed G2600020
- SPI document tree: E2400121

- SPI Pathfinder will be installed in a few weeks!!!!

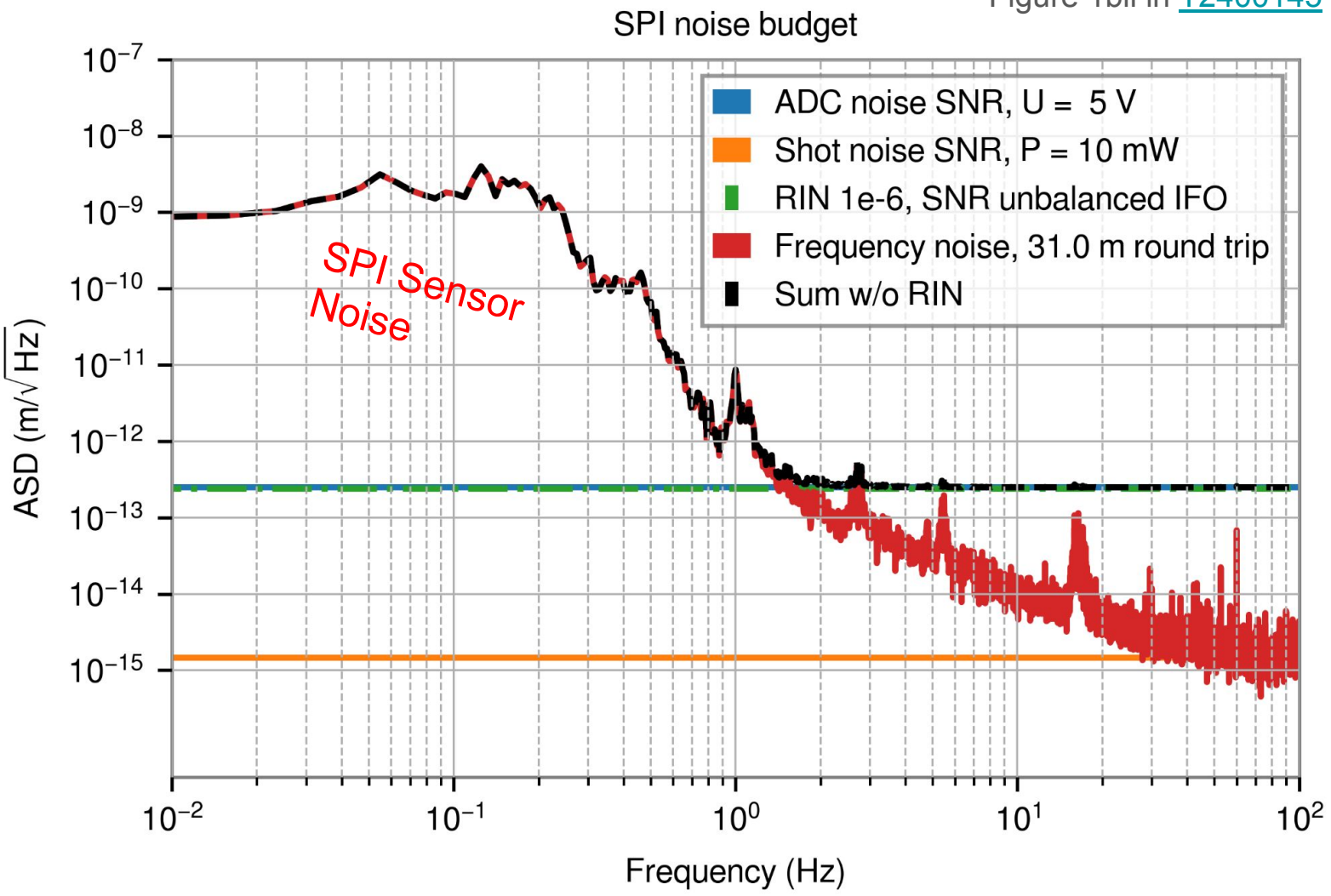
- The next steps after installation involve evaluating performance using IMC as a witness

Thank you!

Extra Slides (If time permits)

Expected SPI **LONG** Budget

Figure 1bii in T2400145



SPI **LONG** is currently limited by Laser Frequency Noise up to ~2Hz then ADC Noise past ~2Hz

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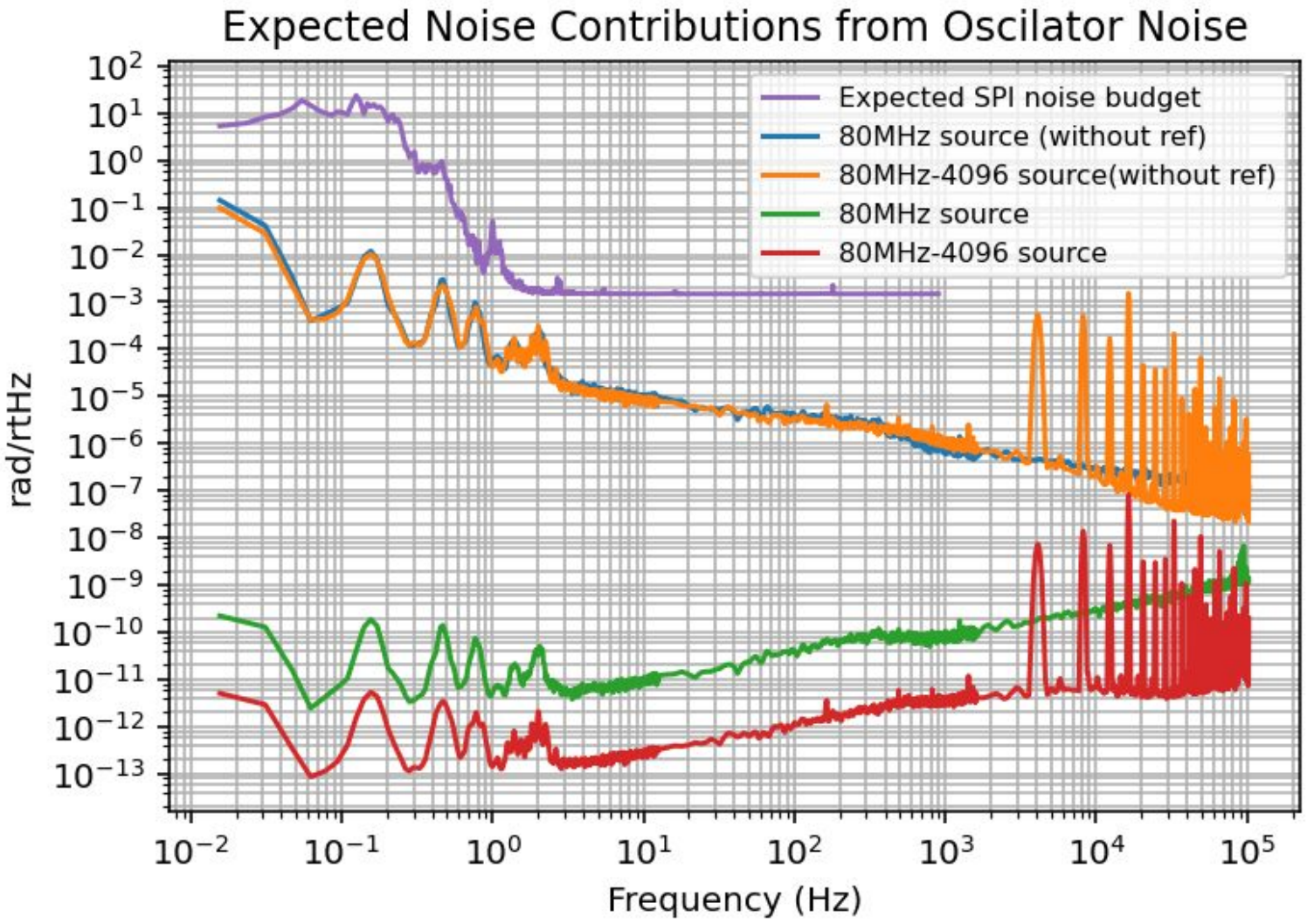
A Reference Interferometer Massively reduces differential noise between the Meas/Ref arms

In particular the Ref arm see's the most reduction in noise so the noisier signal should be on it.



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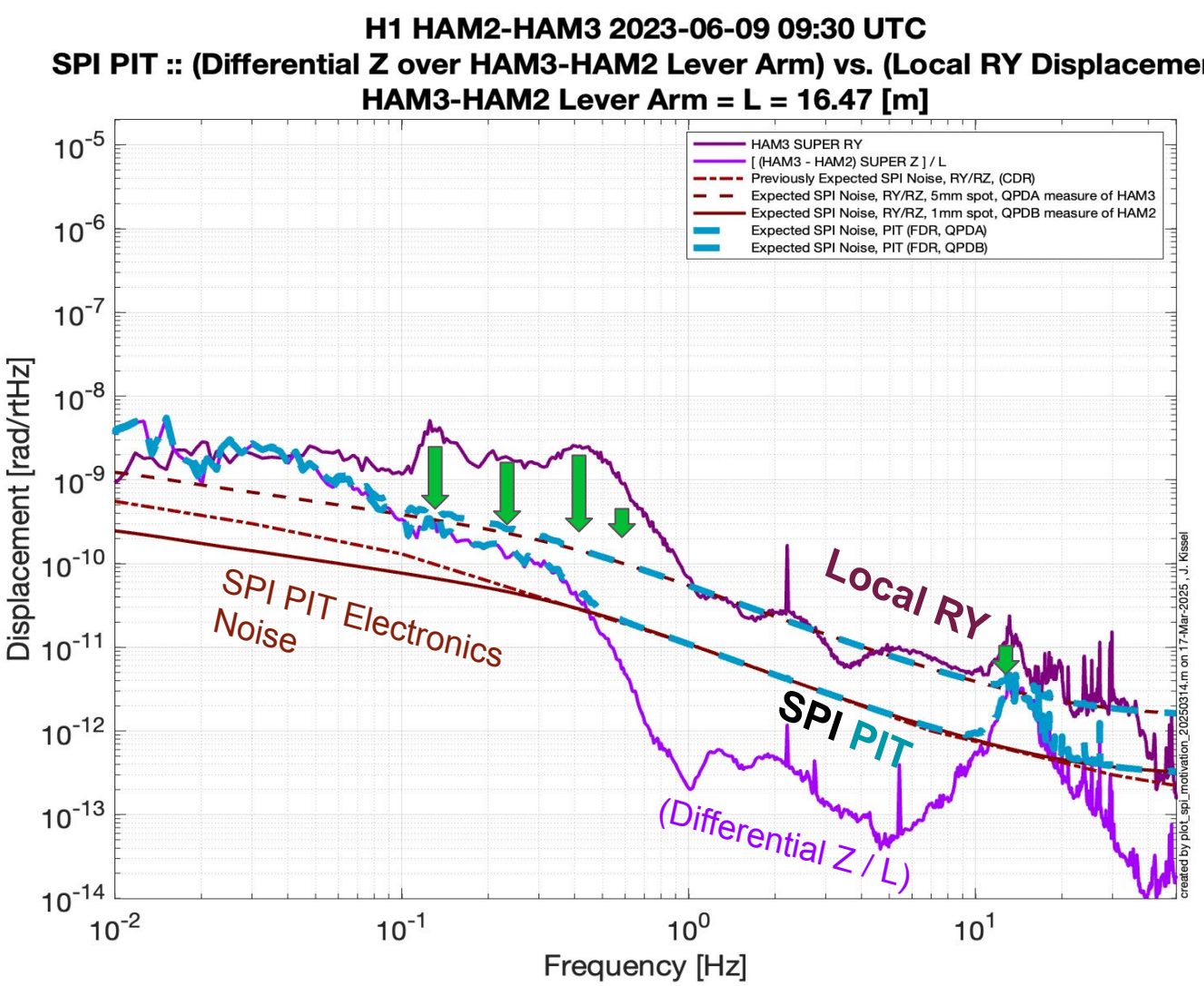
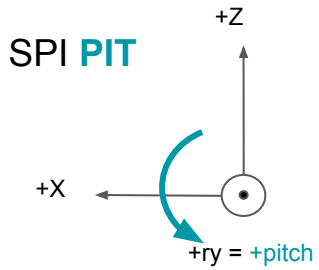
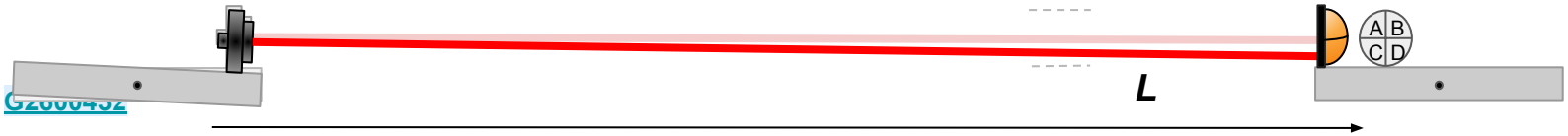
Expected SPI PIT Performance

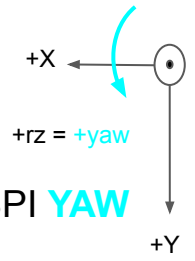


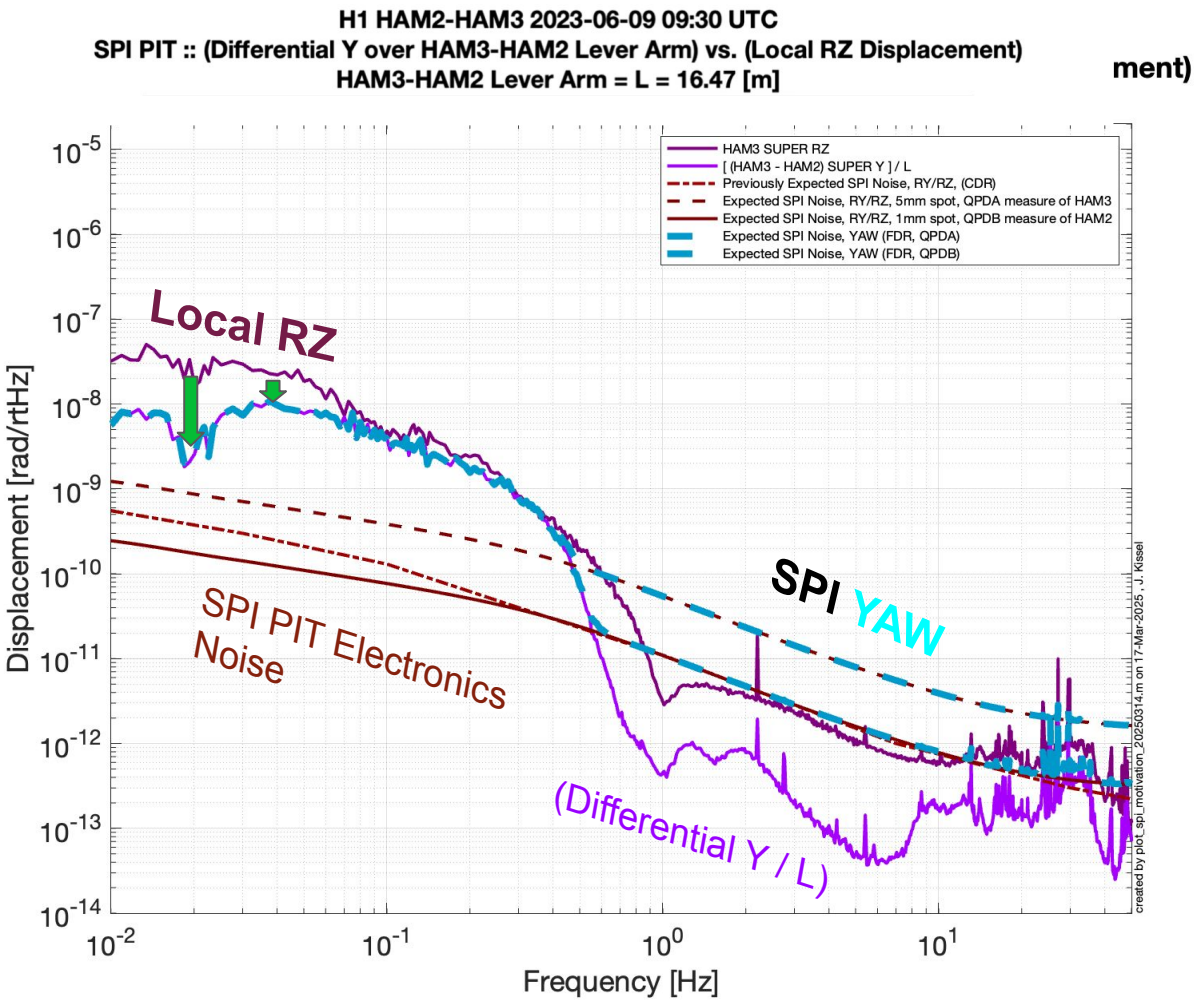


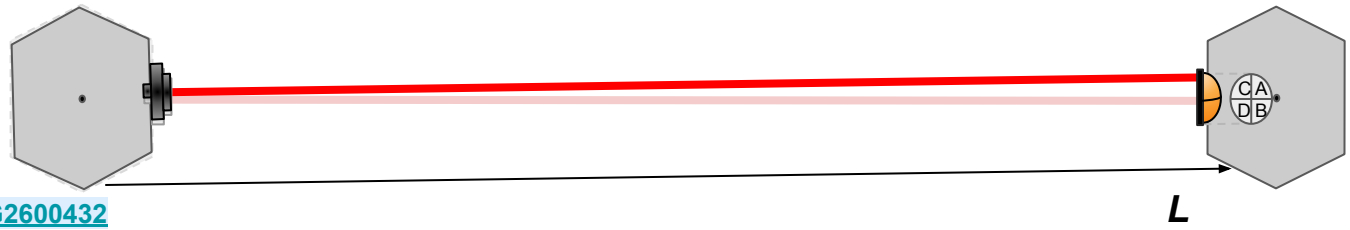
We expect improve platform RY performance by as much as 10-50x between 0.08 - 10 Hz with SPI PIT.



Expected SPI YAW Performance







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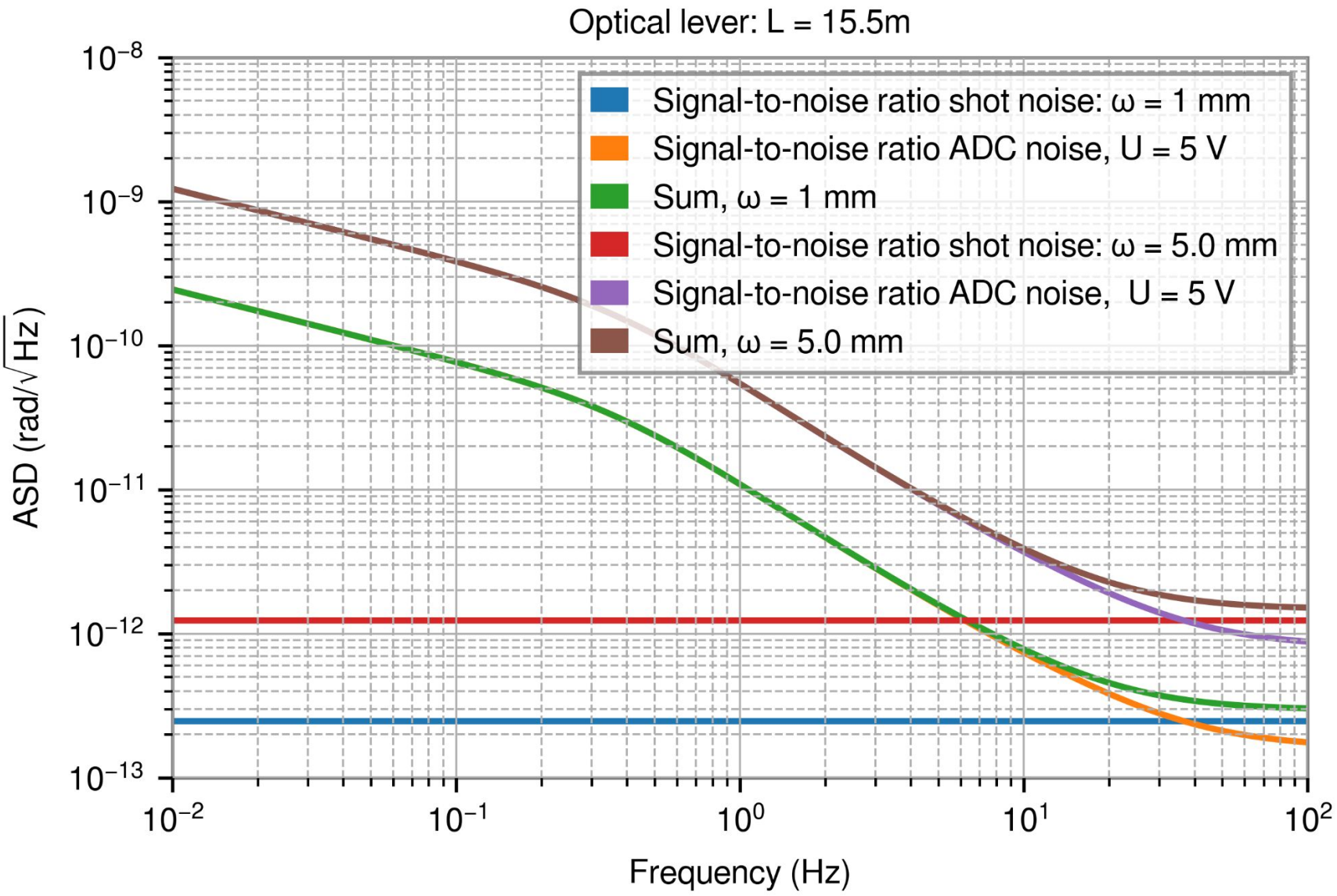
It is unclear if the Differential Y / L noise limit for **SPI YAW** is better than **Local RZ**

But that is what the pathfinder is for!!

Optical Lever Noise Budget



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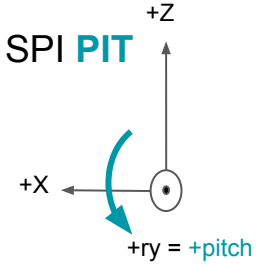
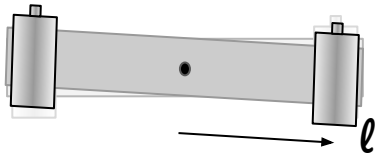
SPI **PIT**



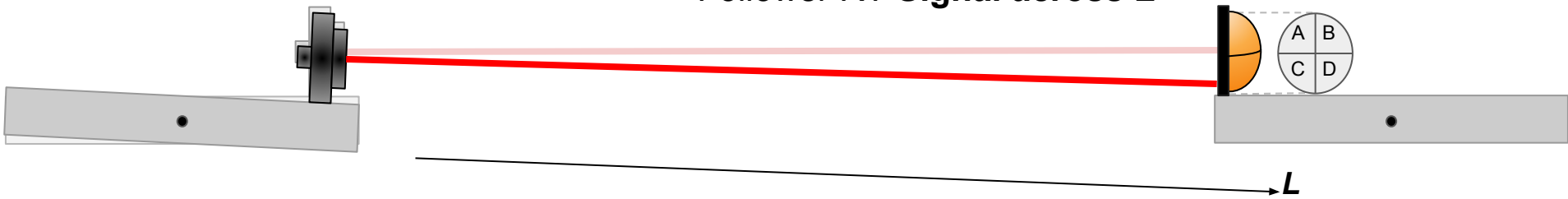
HAM3
“ISIK”



Local RY Signal:
Differential Z across ℓ

HAM2
“ISIJ”

Follower RY **Signal across L**



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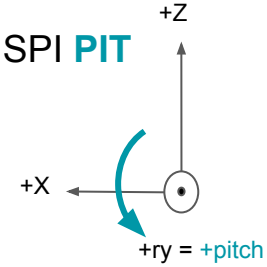
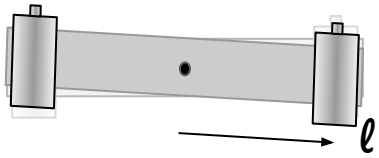
SPI **PIT**

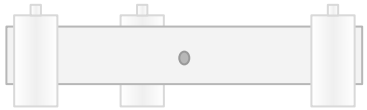


HAM3
“ISIK”

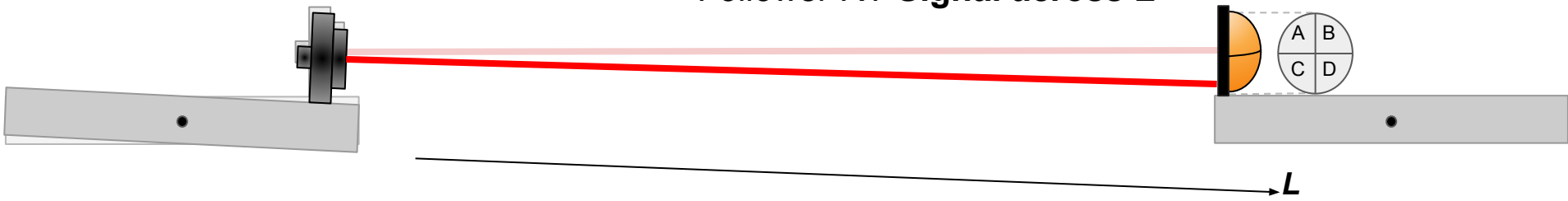


Local RY Signal:
Differential Z across ℓ

HAM2
“ISIJ”

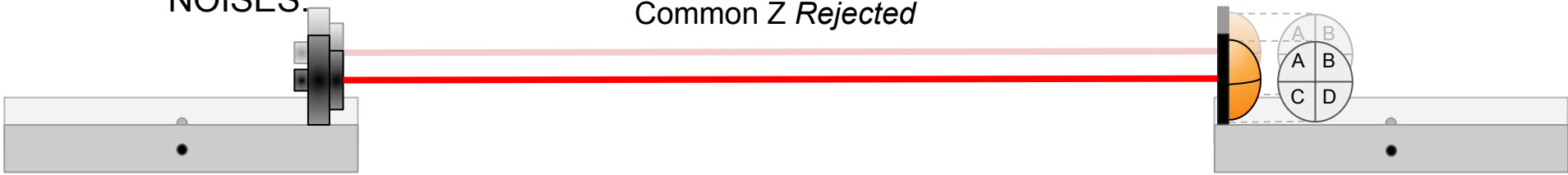


Follower RY **Signal across L**



NOISES:

Common Z *Rejected*



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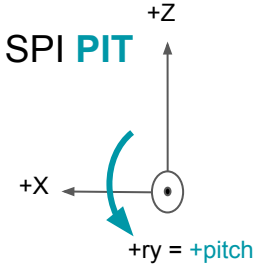
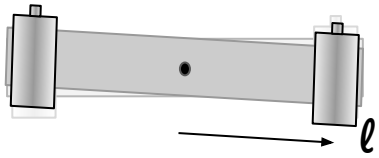
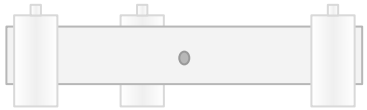


HAM3
"ISIK"

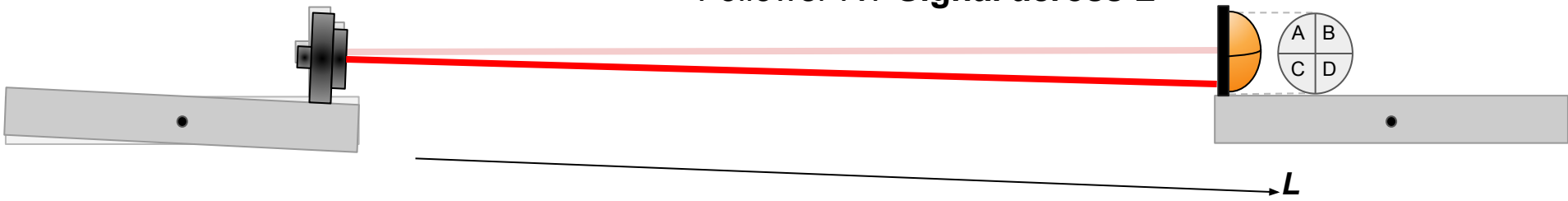


Local RY Signal:
Differential Z across ℓ

HAM2
"ISIJ"



Follower RY **Signal across L**



NOISES:

Common Z *Rejected*

Differential Z *across L* is a Noise Limit

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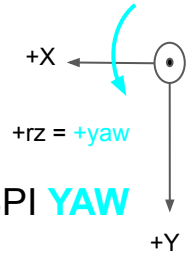
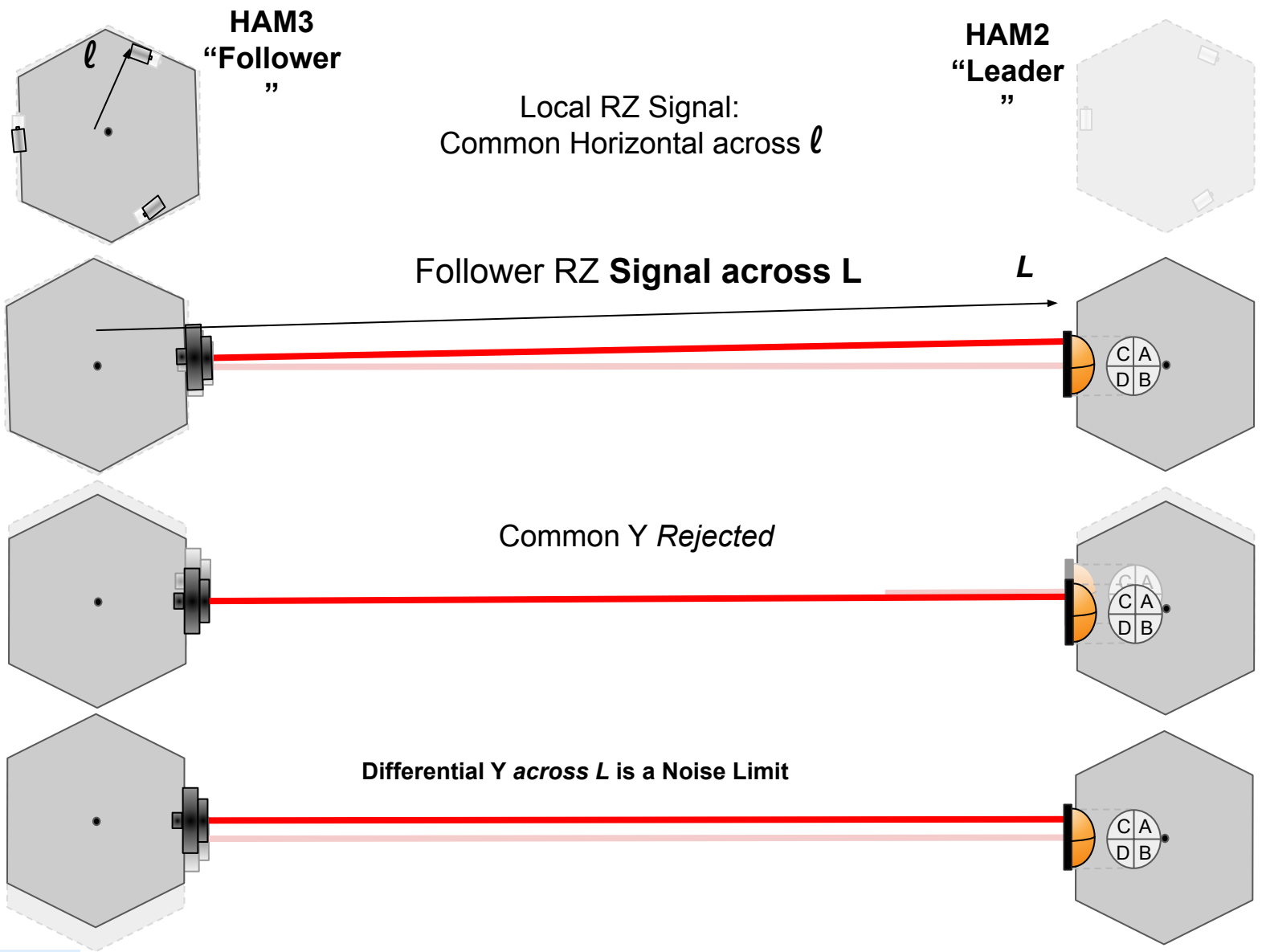
Measuring YAW w/ ONE-WAY Optical Lever





Since we are using QPDs we also get the YAW "for free"

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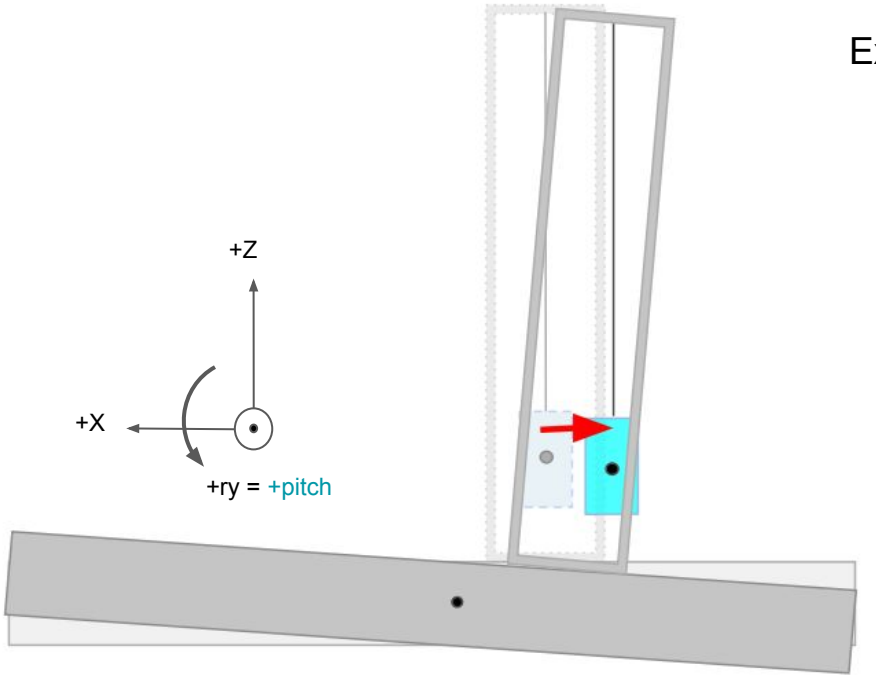
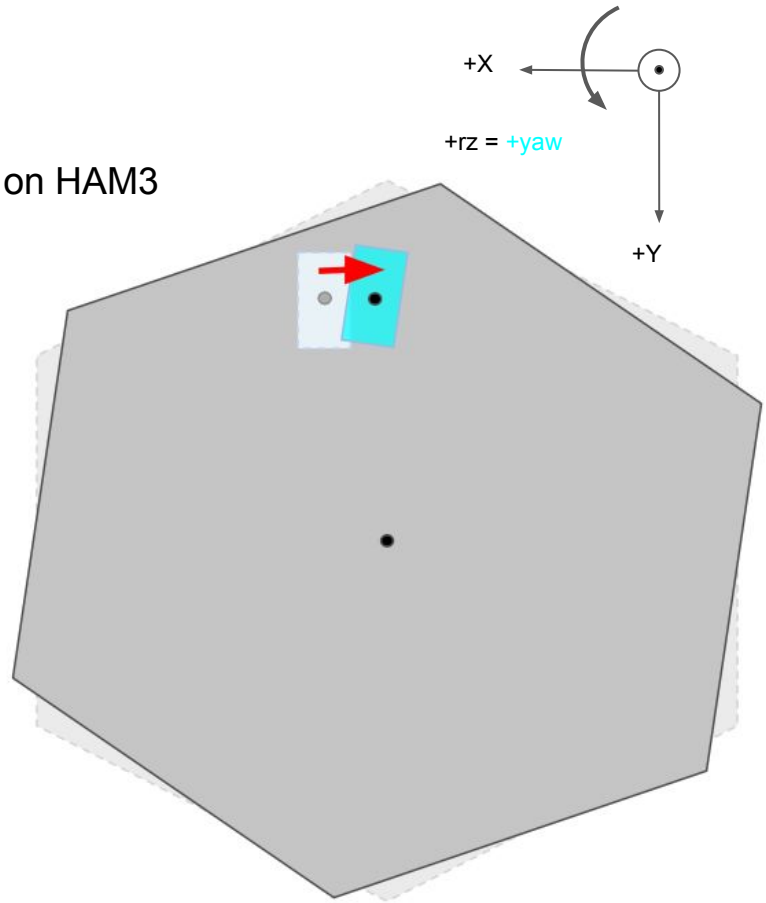
Tilt-to-Length Coupling



Example PR2 on HAM3



https://dcc.ligo.org/LIGO-G2400623

HAM: Horizontal Access Module (Vacuum Chamber)

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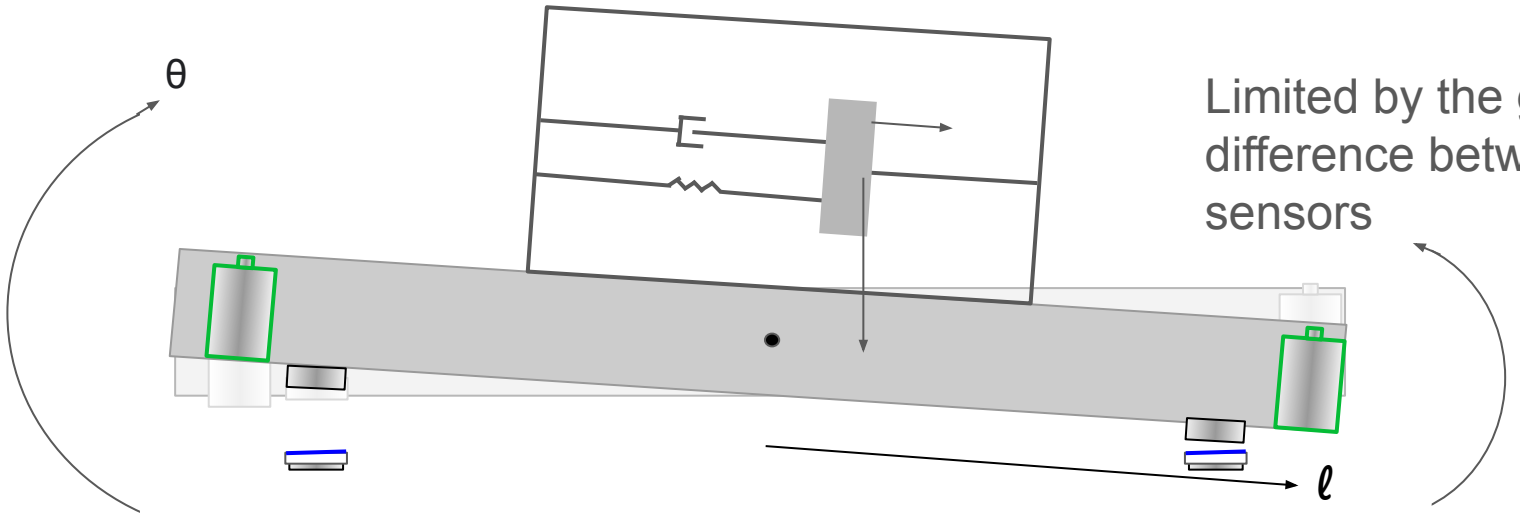
Tilt-to-Horizontal Coupling

Tilt is interpreted as Horizontal Motion in seismometers

$F = -mg\theta$



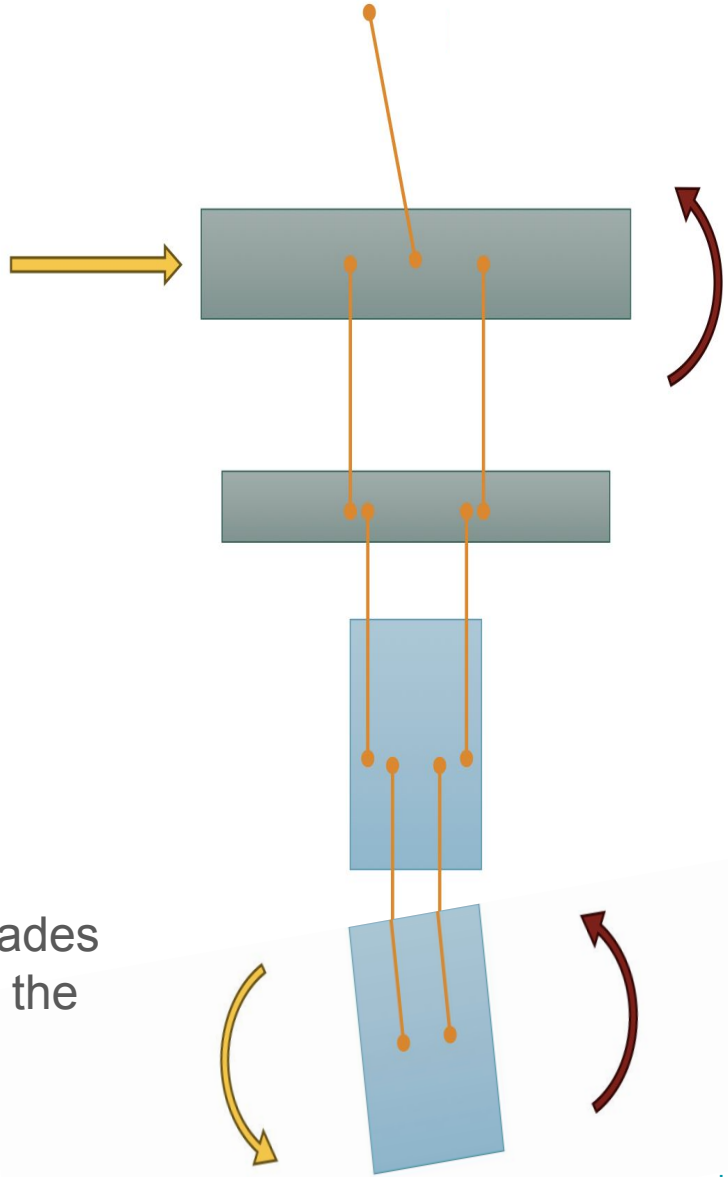
Limited by the gain difference between sensors

GS13s – Inertial Sensors

CPS – Displacement Sensors

Sensor Noise because lever is very short $\ell \approx 1$m

Length-to-Tilt Coupling



Driving in length causes pitch in top mass

This cascades down into the test mass

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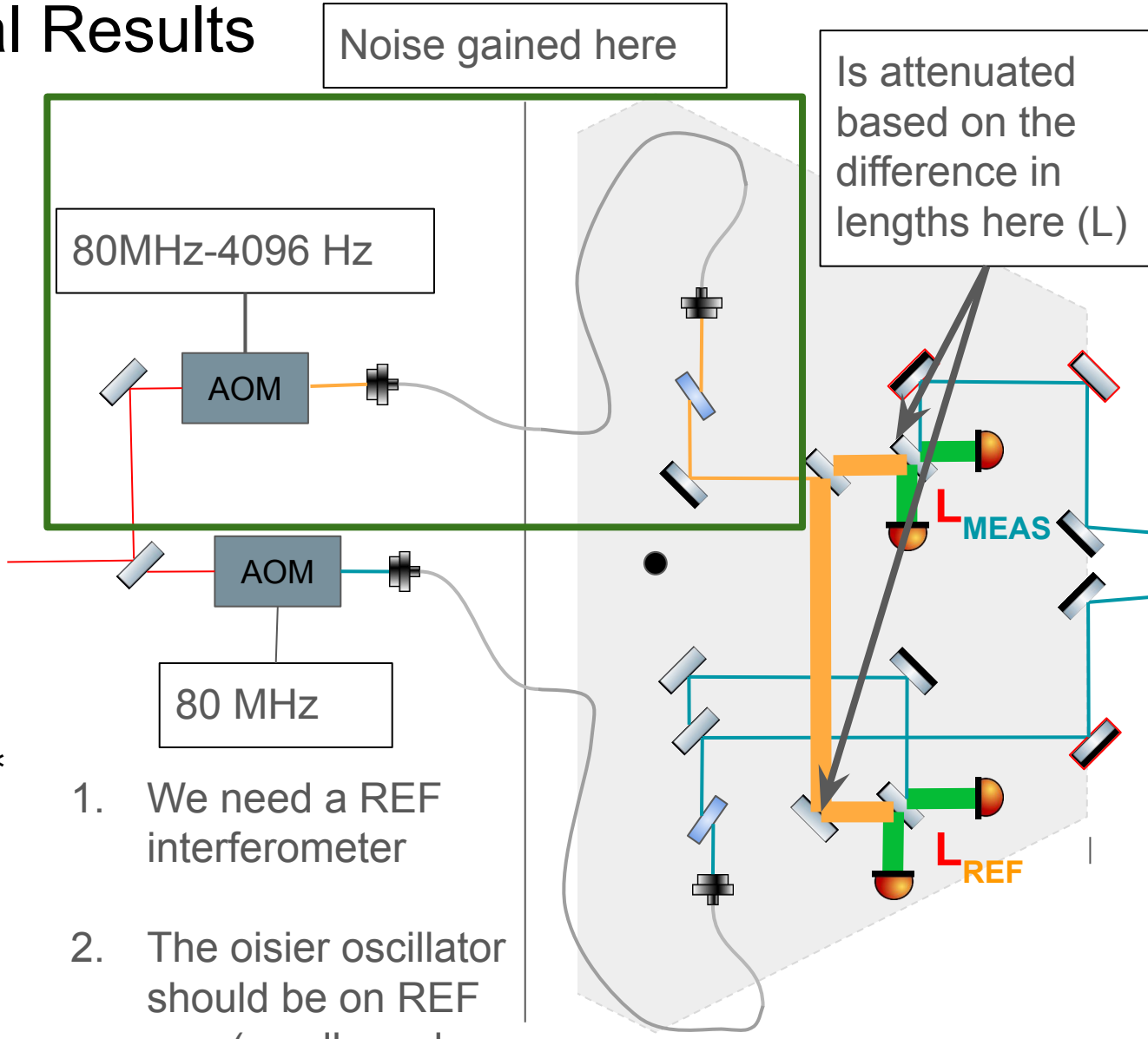
Phase Noise Final Results

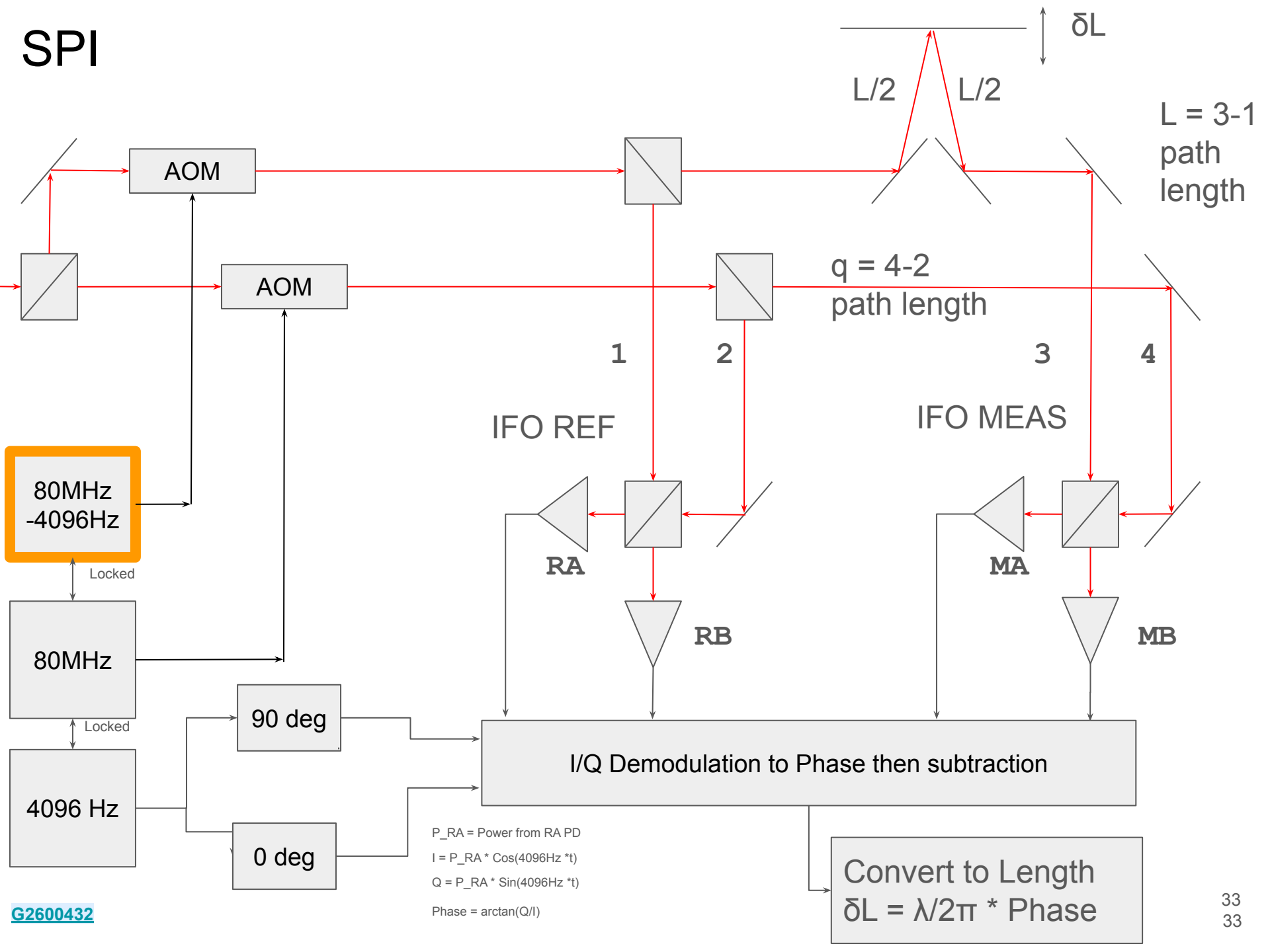
Differential Noise gained in the Meas/Ref arm is attenuated inversely proportional to the length difference light travels in Meas/Ref interferometer

Phase Noise = L/c * f * Phase Noise(w/o. Ref.)



1. We need a REF interferometer
2. The oisier oscillator should be on REF arm (smaller value for L)

SPI



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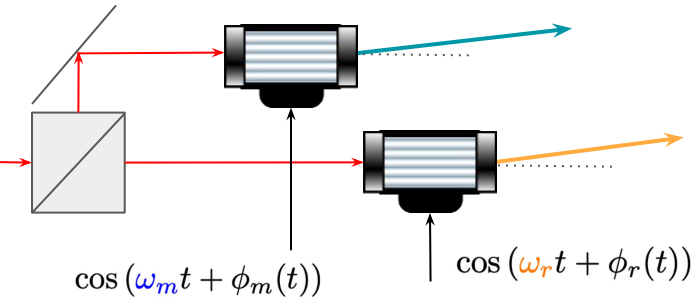
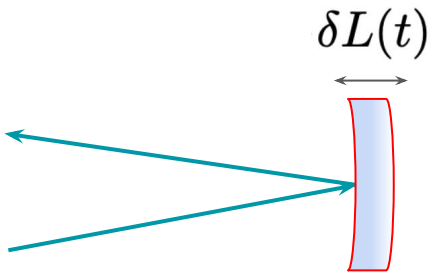
Field Equations to Power on Each PD



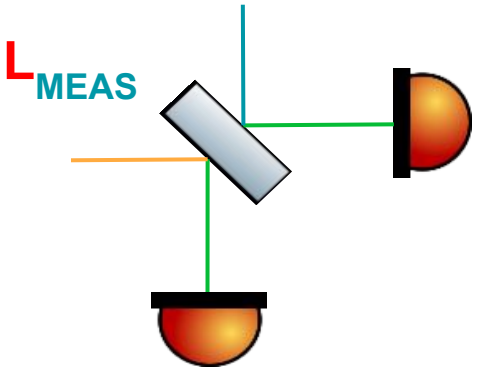
(Fiber) AOMs frequency shift the light at a slight difference in frequency plus noise from the RF sources.



Mirror motion on HAM 2 adds phase to one of the beams

$$\phi_{\delta L}(t) = \frac{2\pi}{\lambda}\delta L(t)$$

The beams recombine on the measured output producing a beat note, $\omega_m - \omega_r = \omega_h$ plus phase noise and our signal



$$A_{meas}\cos(\omega_h t + \phi_{meas}(t)) + \text{DC Terms}$$

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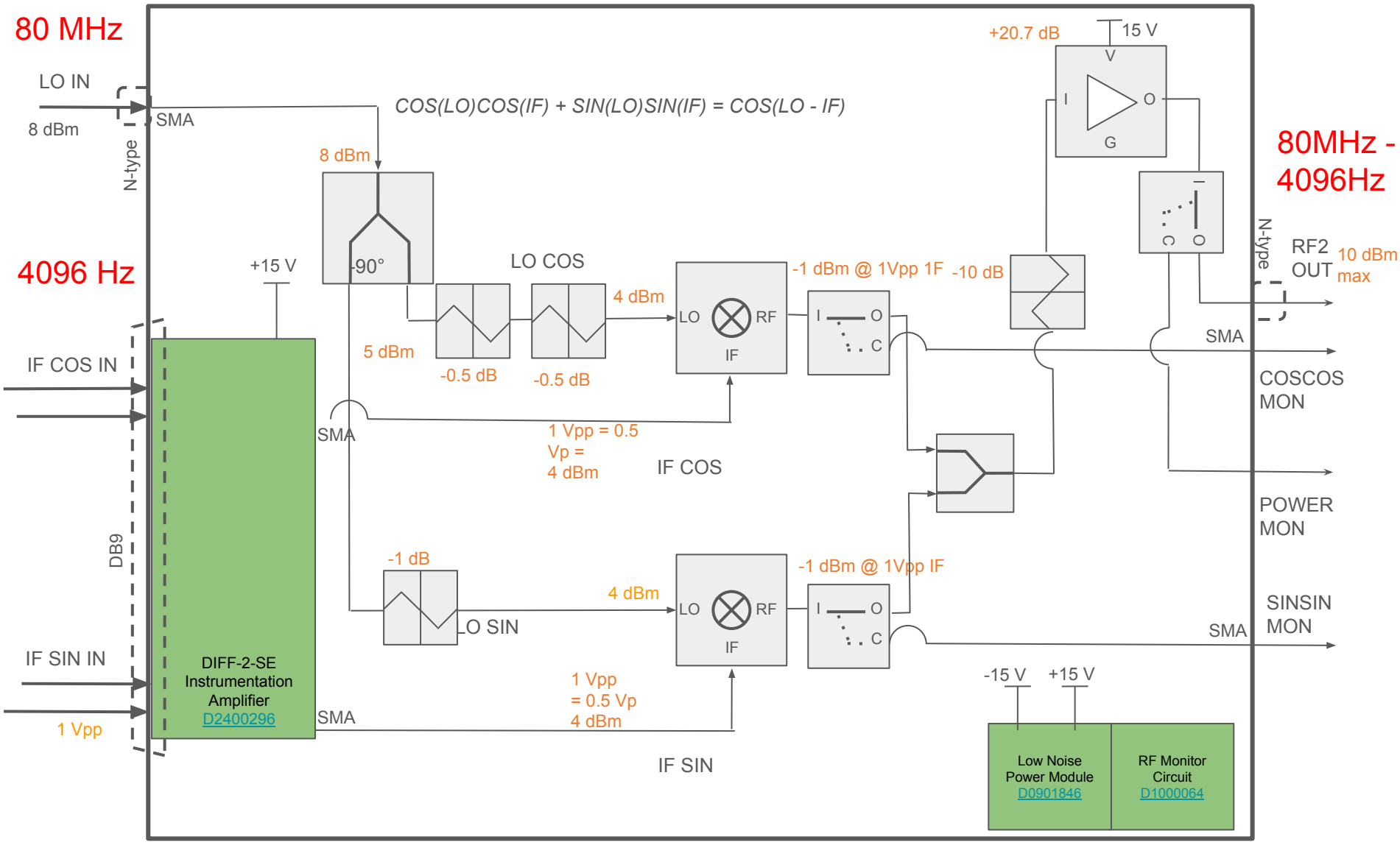
Prototype Design
D2400315-v2



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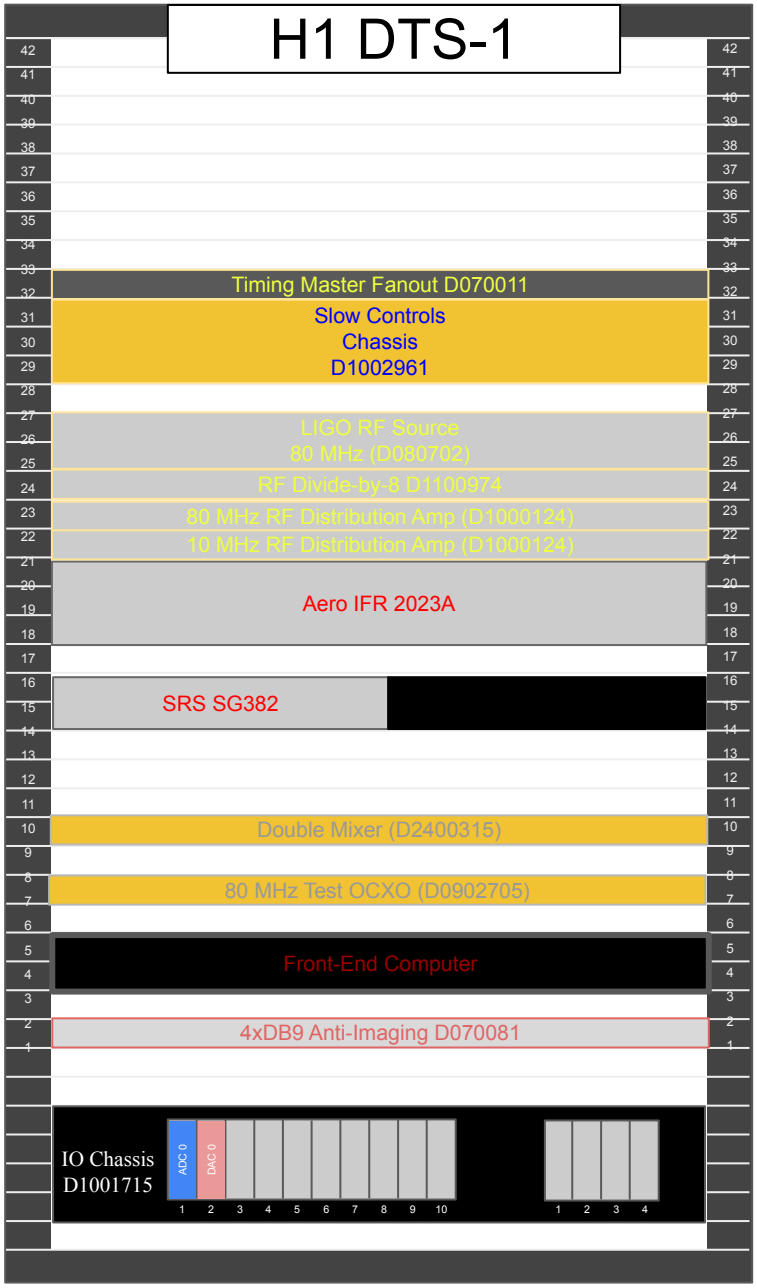
See Slide 31 of G2400903 for how this fits in the greater context of the SPI RF system

SPI Phase Noise Trade Study LHO DAQ Test Stand Rack Layout D2400283



Picture of the Double Mixer Prototype