

LHO End of 04 PEM Coupling Measurements

Samantha Callos, Genevieve Connolly, Robert Schofield, Ryan Short, Carlos Campos

Quick Overview

- What are PEM coupling and injections?
- How are coupling functions calculated?
- Vibrational coupling results
- Magnetic coupling results
- Summary & future projects

PEM Coupling & Injections

- Coupling quantifies how environmental noise picked up by PEM sensors is likely to be seen in DARM
- Injections: make noise using a shaker, speaker, magnetic coil, etc and compare sensor response to DARM response
- We did vibrational & magnetic injections at the end of November after we ended the run
- Instrumentation changed → needed to do a full set of injections






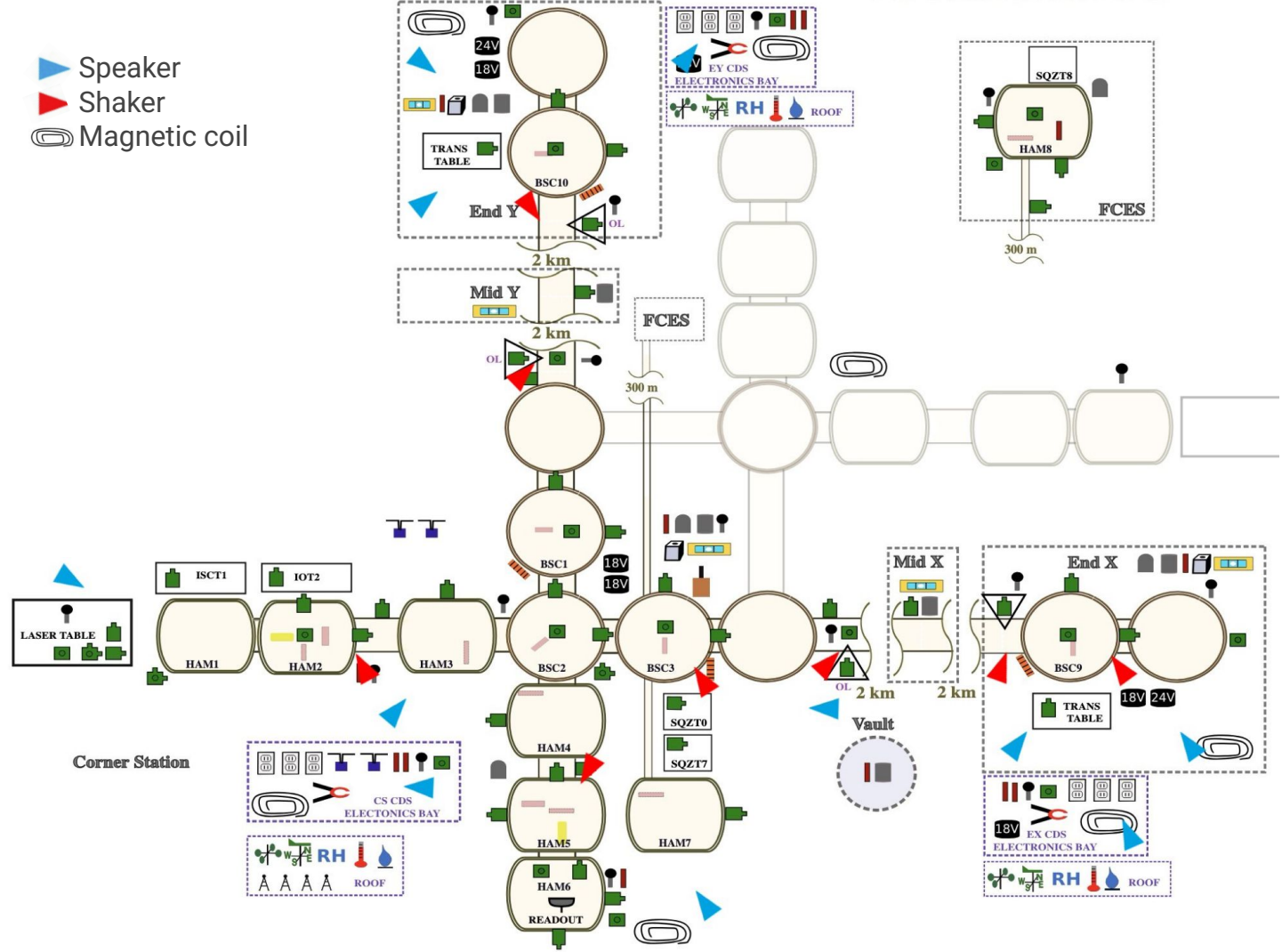
November 2025		Frequencies (Hz)	CS	EX	EY
Vibrational	Shaker	3 to 10 10 to 20 20 to 40	HAM5 X Reduction Flange BSC3 MC Tube Y Reduction Flange	BSC9 Manifold	Reduction Flange
	Acoustic	40 to 100 100 to 1000 1000 to 4000	X Manifold EBAY Far Output Input Optics PSL	EBAY Mech Door Near Door	EBAY Mech Door Near Door
Magnetic		10 to 60 60 to 100 100 to 200 200 to 600 600 to 1000 1000 to 2500 2500 to 4000	Vertex Wall Coil CER Wall Coil SQZ Bay Wall Coil	VEA Wall Coil EBAY Wall Coil	VEA Wall Coil EBAY Wall Coil

May 2023		Frequencies (Hz)	CS	EX	EY
Vibrational	Shaker	5 to 10 10 to 20 20 to 40	HAM6 X Reduction Flange BSC3 HAM2 Y Reduction Flange	BSC9 Manifold	Manifold BSC10
	Acoustic	40 to 100 100 to 1000 1000 to 4000	X Manifold EBAY Far Output Input Optics PSL**	EBAY Mech Door* Near Door*	EBAY* Mech Door* Near Door*
Magnetic		10 to 100 100 to 1000 1000 to 4000	Vertex Wall Coil CER Wall Coil SQZ Bay Wall Coil	VEA Wall Coil EBAY Wall Coil	VEA Wall Coil EBAY Wall Coil

*40-60, 60-100, 100-1000, 1000-4000 Hz
 **40-90, 90-1000, 1000-4000 Hz



-  Speaker
-  Shaker
-  Magnetic coil

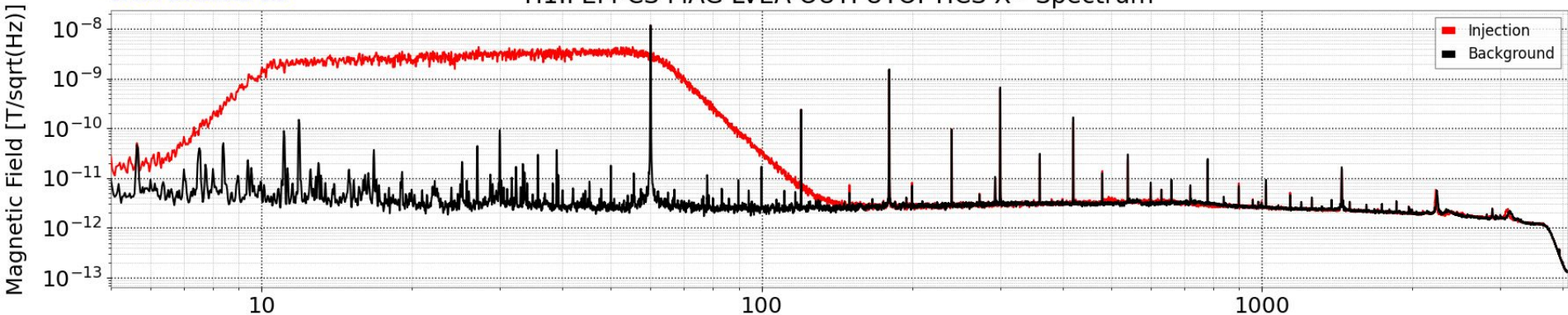


Injection name:
CS_SQZ_5m_10to60
DARM threshold: 1.3

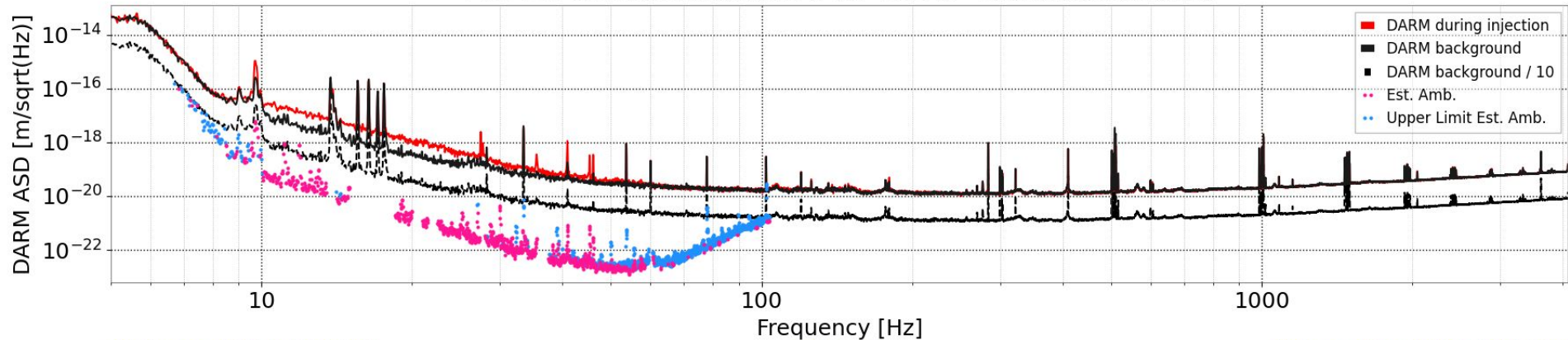
2026-03-07 02:55:18

Measured coupling factors: 1016
Upper limit coupling factors: 1815

H1:PEM-CS MAG LVEA OUTPUTOPTICS X - Spectrum



H1:PEM-CS MAG LVEA OUTPUTOPTICS X - Estimated Ambient



Injection Time: 2025-11-25 04:26:03
(1448079981)

Averages: 17
Bin width: 0.030 Hz

Background Time: 2025-11-25 03:05:58
(1448075176)

What are coupling functions?

- Y_{inj} is DARM ASD during injection
- Y_{bkg} is DARM ASD during background
- X_{inj} is sensor ASD during injection
- X_{bkg} is sensor ASD during background
- Estimated ambient: $CF(f) * X_{bkg}(f)$

Measured value: if $X_{inj}/X_{bkg} >$ sensor threshold
AND $Y_{inj}/Y_{bkg} >$ DARM threshold

$$CF(f) = \sqrt{\frac{Y_{inj}^2(f) - Y_{bkg}^2(f)}{X_{inj}^2(f) - X_{bkg}^2(f)}}$$

- Composite: take CF value for the loudest injection in the sensor at each frequency bin
- Sitewide: take the highest CF value at each frequency bin across all channels (measured values take precedence over upper limits)

Upper limit value: if $X_{inj}/X_{bkg} >$ sensor threshold
BUT $Y_{inj}/Y_{bkg} <$ DARM threshold

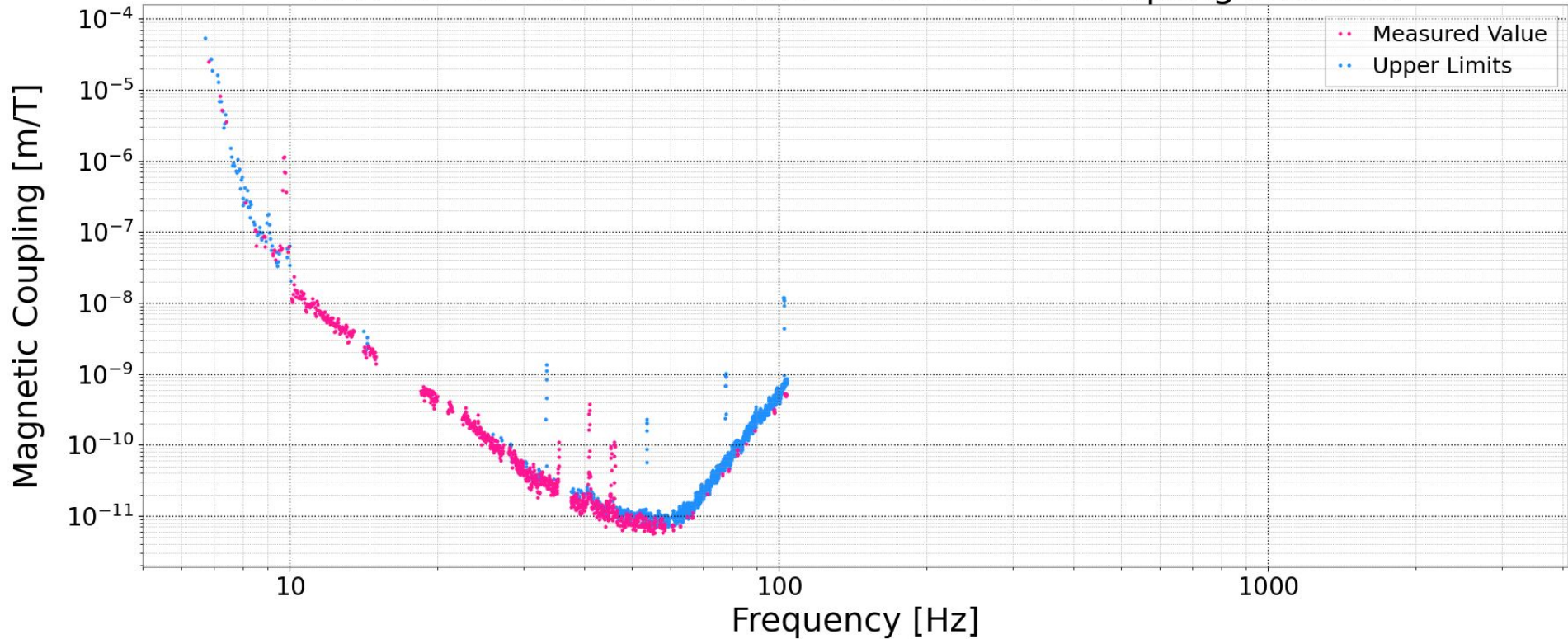
$$CF(f) = \frac{Y_{bkg}(f)}{\sqrt{X_{inj}^2(f) - X_{bkg}^2(f)}}$$

Injection name:
CS_SQZ_5m_10to60
DARM threshold: 1.3

2026-03-07 02:55:18

Measured coupling factors: 1016
Upper limit coupling factors: 1815

H1:PEM-CS MAG LVEA OUTPUTOPTICS X - Coupling Function

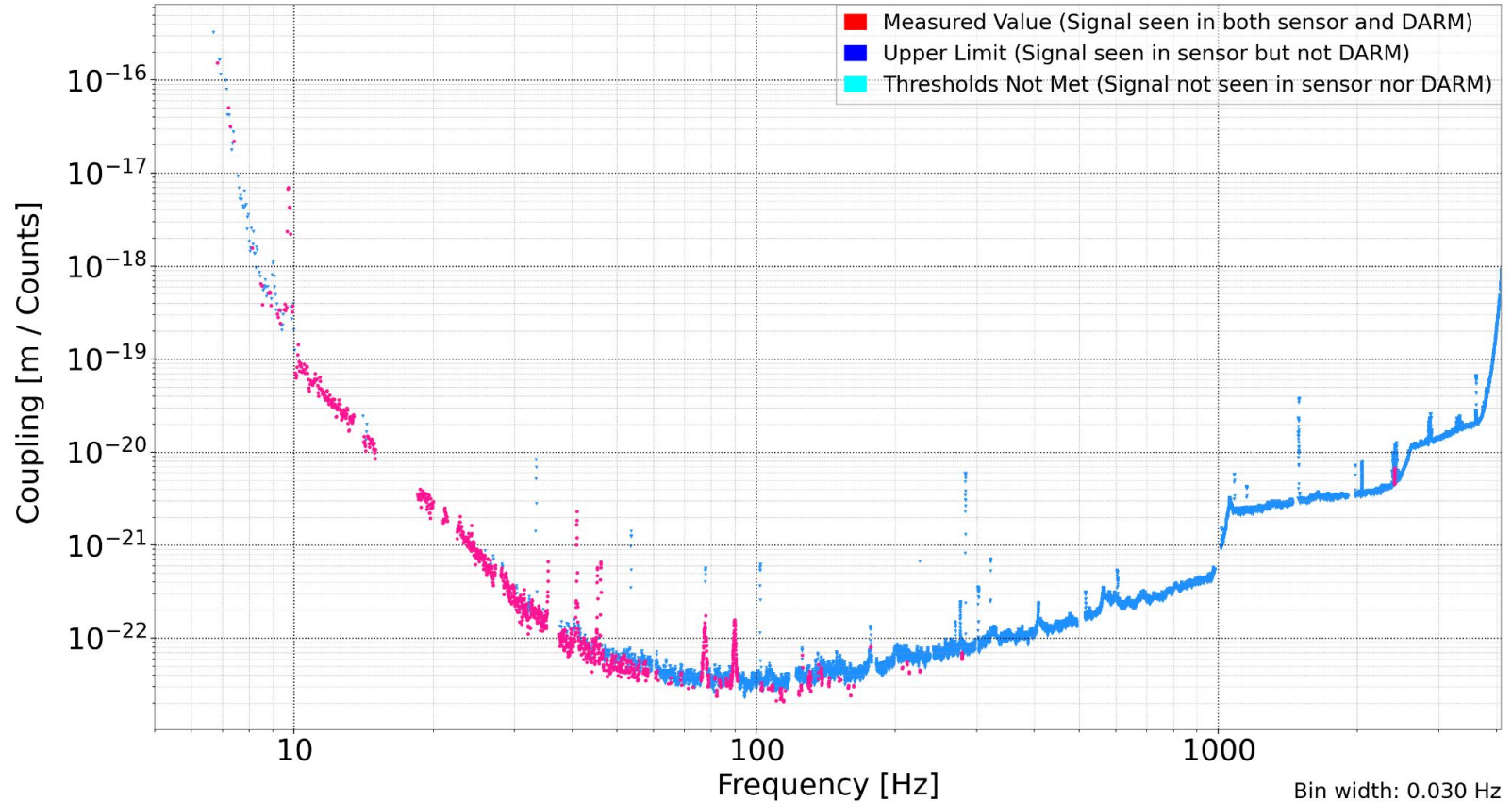


Injection Time: 2025-11-25 04:26:03
(1448079981)

Averages: 17
Bin width: 0.030 Hz

Background Time: 2025-11-25 03:05:58
(1448075176)

H1:PEM-CS MAG LVEA OUTPUTOPTICS X - Composite Coupling Function (based on loudest injection at each frequency)

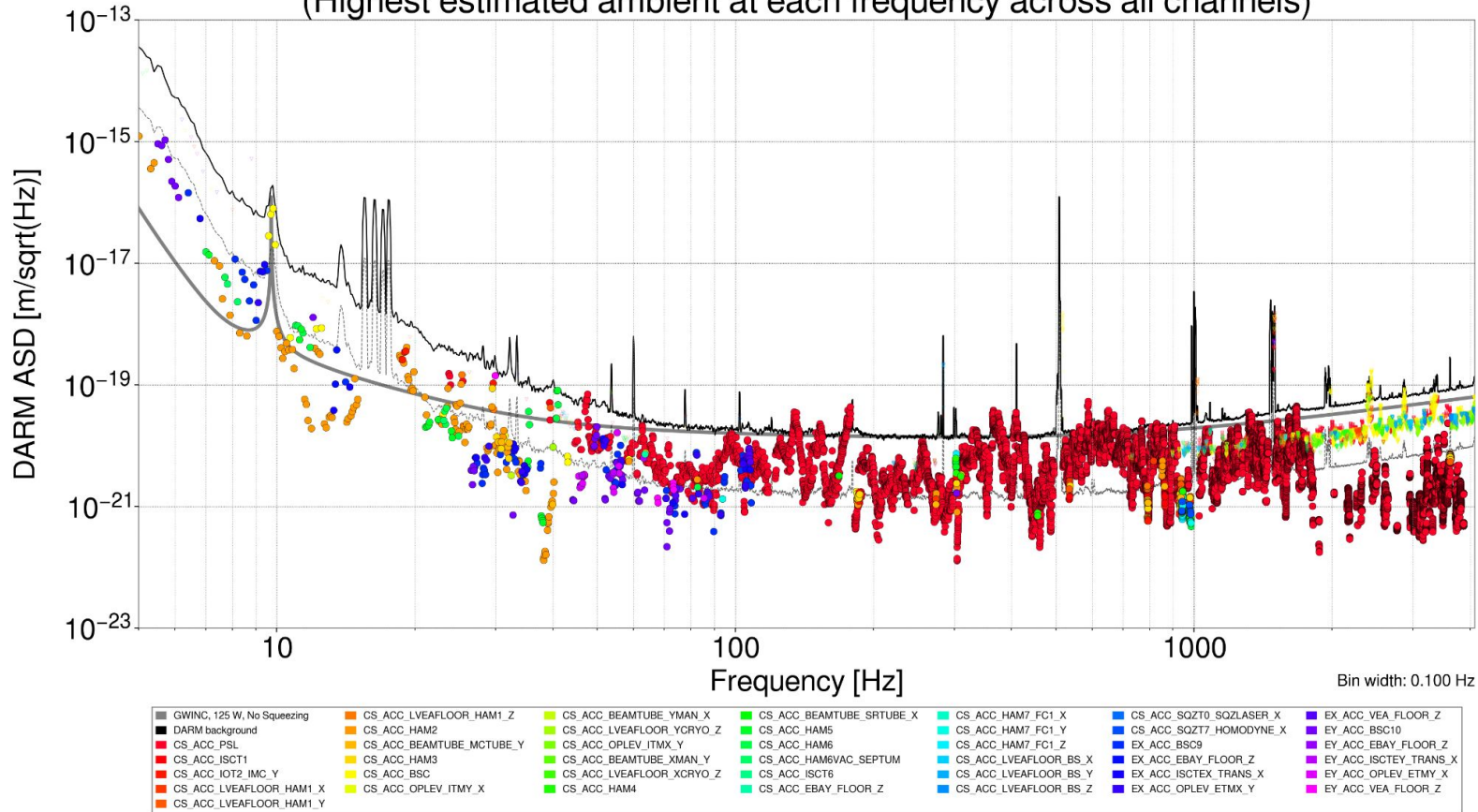


Vibrational Injections

H1 Vibrational - Estimated Ambient

(Highest estimated ambient at each frequency across all channels)

2023
ACC
PEM
Injs

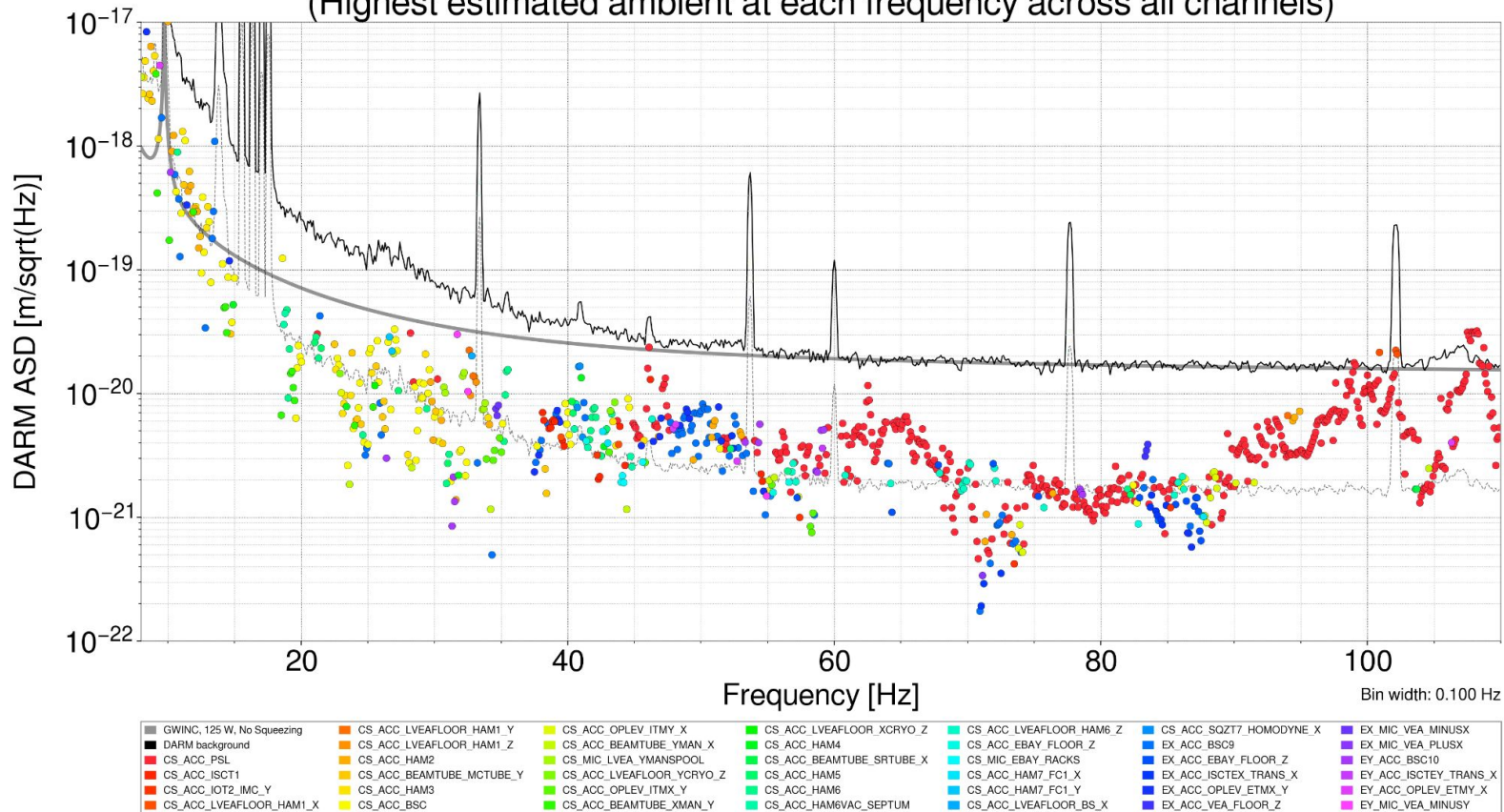


Ambient estimates are made by multiplying coupling factors by injection-free sensor levels. CIRCLES indicate estimates from measured coupling factors, i.e. where the injection signal was seen in the sensor and in DARM. TRIANGLES represent upper limit coupling factors, i.e. where a signal was seen in the sensor but not in DARM. For some channels, at certain frequencies the ambient estimates are upper limits because the ambient level is below the sensor noise floor.

H1 Vibrational - Estimated Ambient

(Highest estimated ambient at each frequency across all channels)

2025
(8 - 110 Hz)

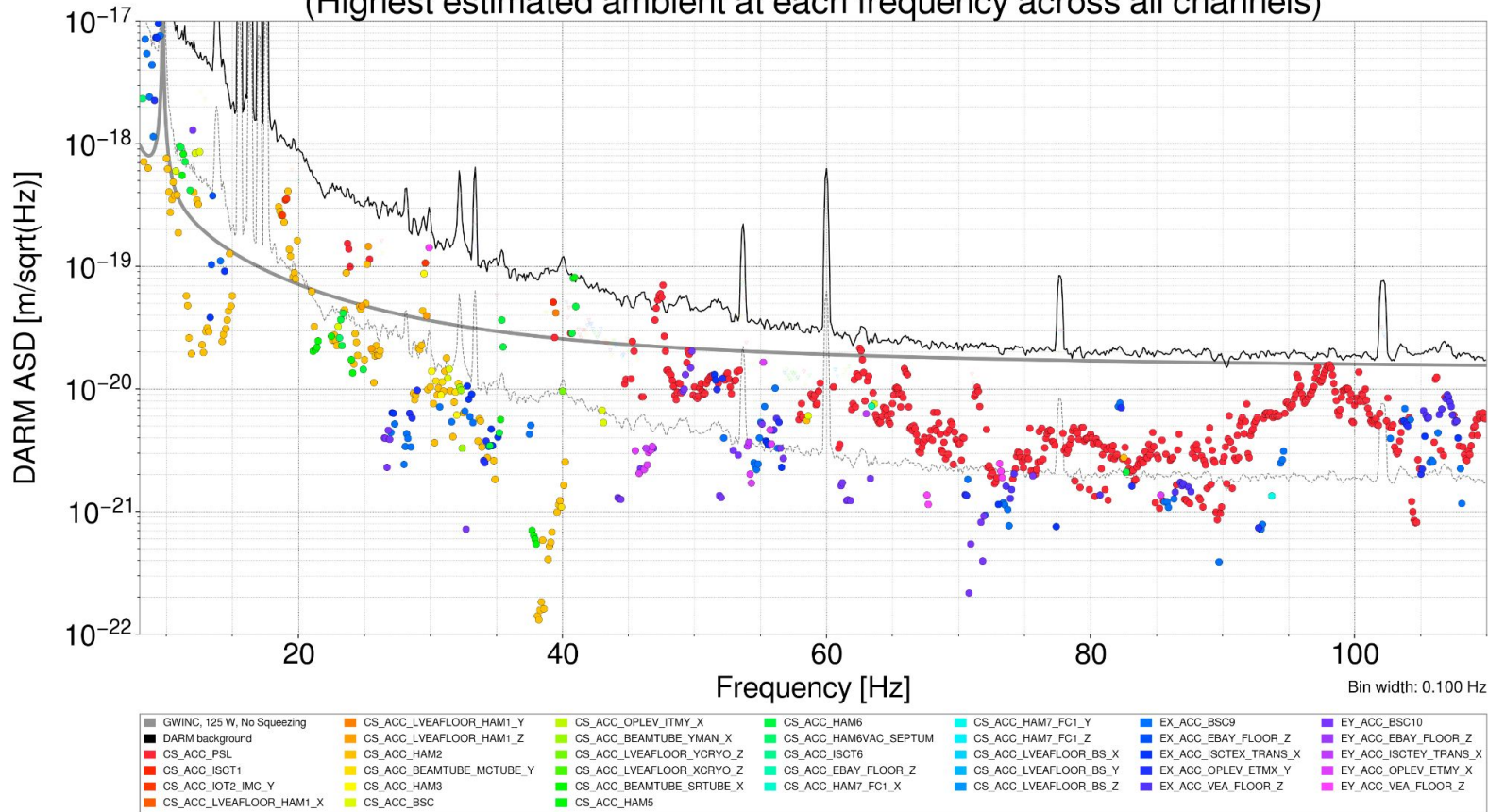


Ambient estimates are made by multiplying coupling factors by injection-free sensor levels. CIRCLES indicate estimates from measured coupling factors, i.e. where the injection signal was seen in the sensor and in DARM. TRIANGLES represent upper limit coupling factors, i.e. where a signal was seen in the sensor but not in DARM. For some channels, at certain frequencies the ambient estimates are upper limits because the ambient level is below the sensor noise floor.

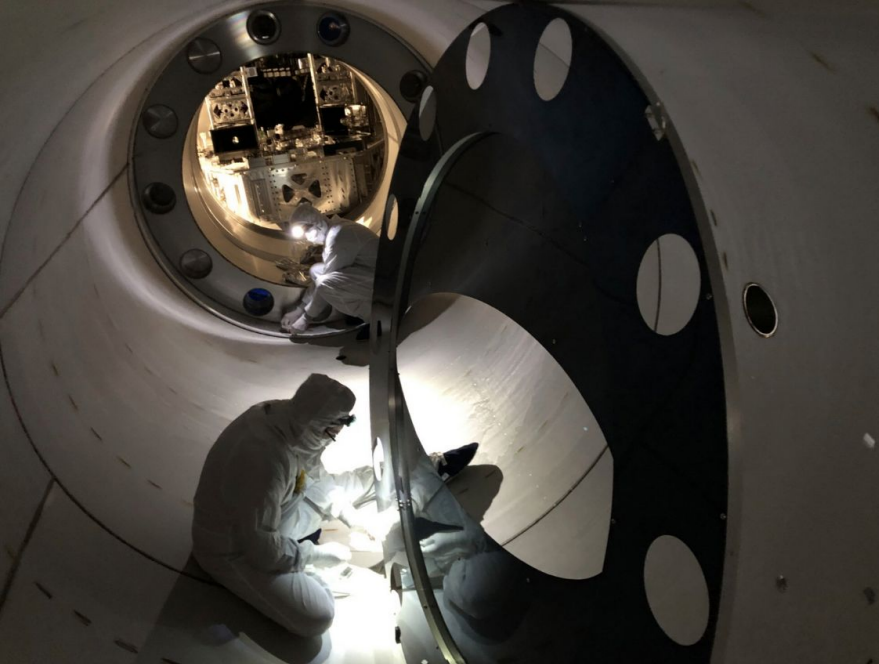
H1 Vibrational - Estimated Ambient

(Highest estimated ambient at each frequency across all channels)

2023
(8 - 110 Hz)



Ambient estimates are made by multiplying coupling factors by injection-free sensor levels. CIRCLES indicate estimates from measured coupling factors, i.e. where the injection signal was seen in the sensor and in DARM. TRIANGLES represent upper limit coupling factors, i.e. where a signal was seen in the sensor but not in DARM. For some channels, at certain frequencies the ambient estimates are upper limits because the ambient level is below the sensor noise floor.



Vibration Summary

- Low frequency coupling improved by damping at EX cryo baffle and CS MC baffle adjustments
- Upper limits improved due to more background sampling
- Jitter looks a little worse but some of it is subtracted out. In IR1 we will have a jitter attenuation cavity.
- Overall as we get more sensitive and mitigate linear noise, we find more nonlinear noise.

Alogs:

76969: EX cryo baffle

75654: MC tube

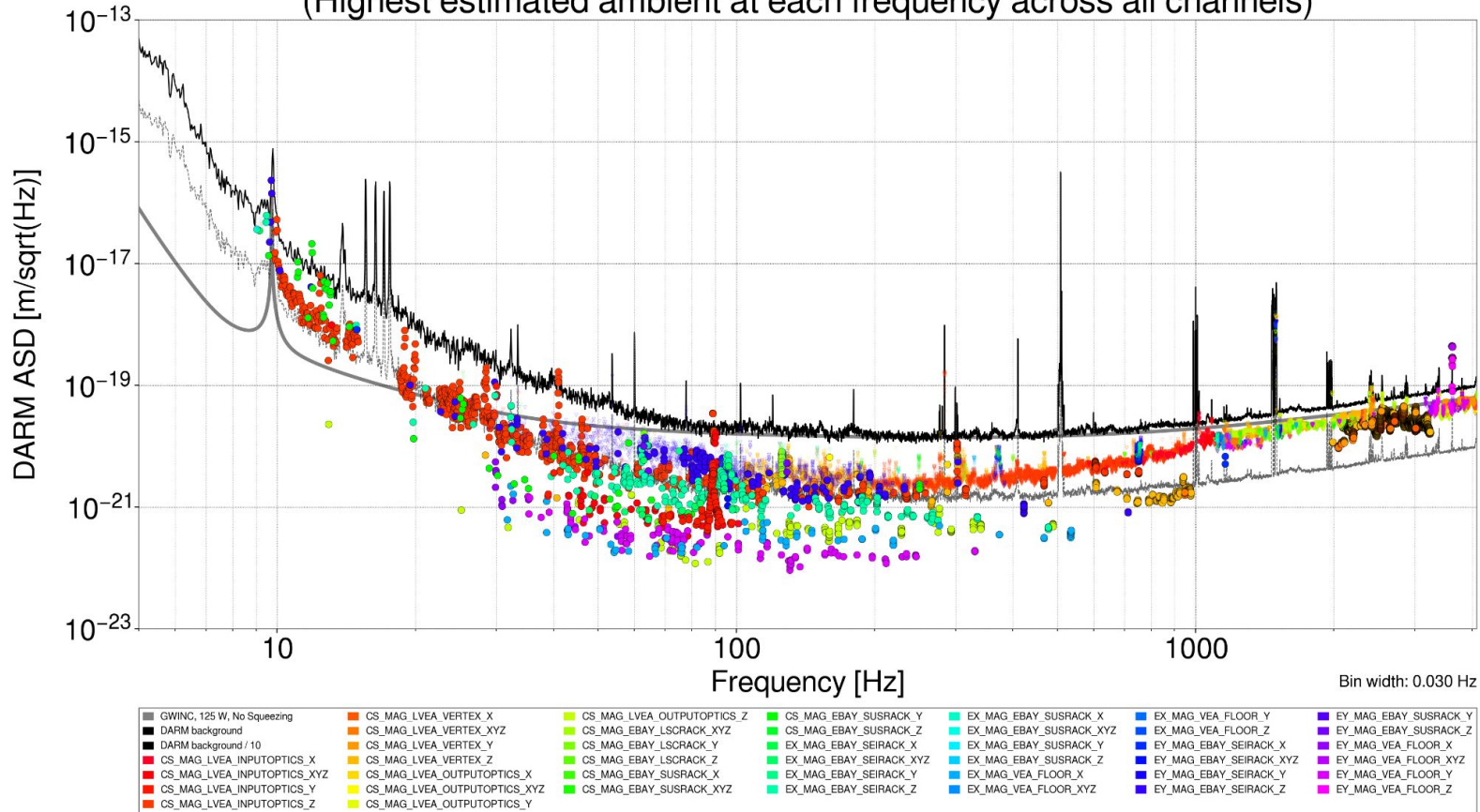
75637: MC tube

Magnetic Injections

H1 Magnetic - Estimated Ambient

(Highest estimated ambient at each frequency across all channels)

2023
MAG
PEM
Injs

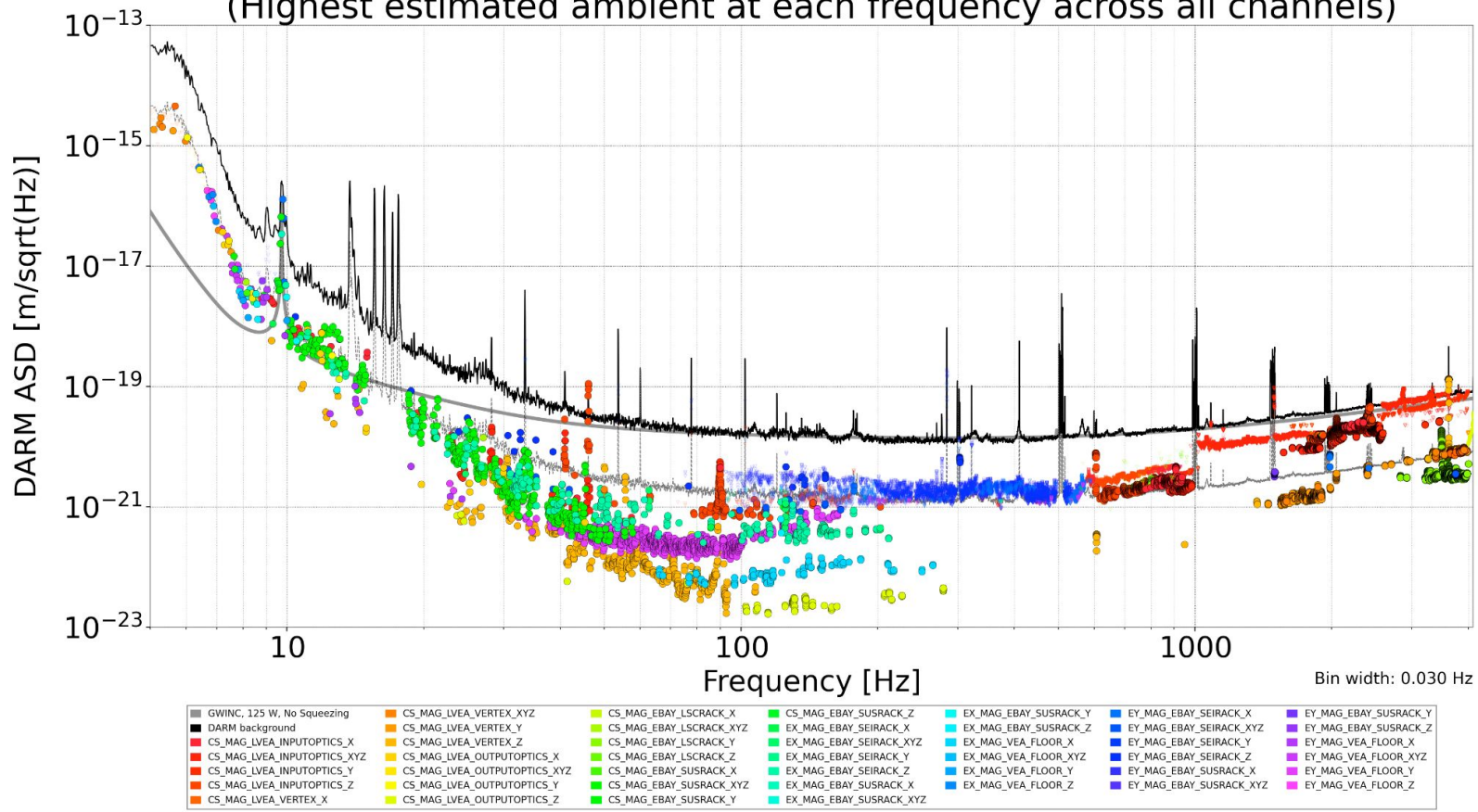


Ambient estimates are made by multiplying coupling factors by injection-free sensor levels. CIRCLES indicate estimates from measured coupling factors, i.e. where the injection signal was seen in the sensor and in DARM. TRIANGLES represent upper limit coupling factors, i.e. where a signal was seen in the sensor but not in DARM. For some channels, at certain frequencies the ambient estimates are upper limits because the ambient level is below the sensor noise floor.

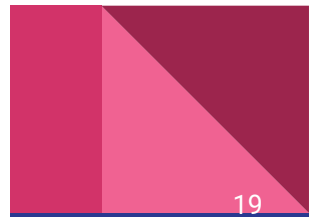
H1 Magnetic - Estimated Ambient

(Highest estimated ambient at each frequency across all channels)

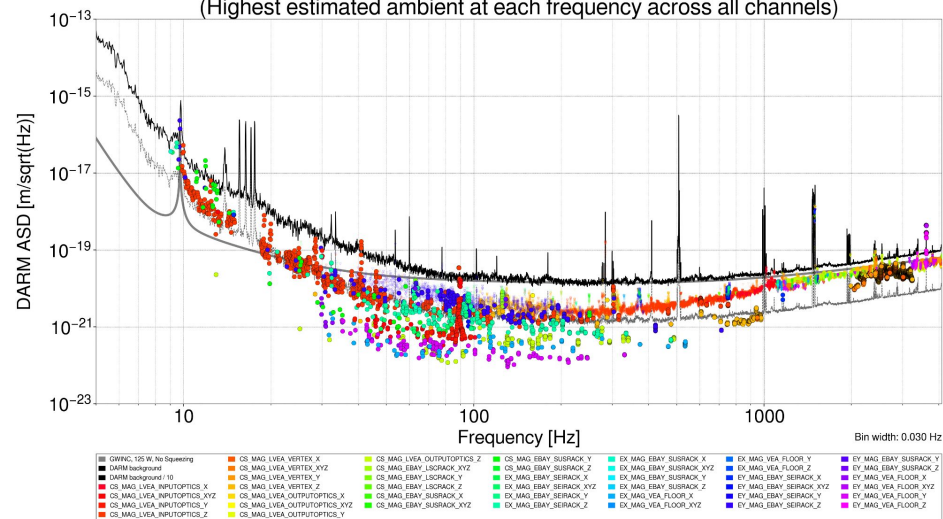
2025
MAG
PEM
Injs



Ambient estimates are made by multiplying coupling factors by injection-free sensor levels. CIRCLES indicate estimates from measured coupling factors, i.e. where the injection signal was seen in the sensor and in DARM. TRIANGLES represent upper limit coupling factors, i.e. where a signal was seen in the sensor but not in DARM. For some channels, at certain frequencies the ambient estimates are upper limits because the ambient level is below the sensor noise floor.



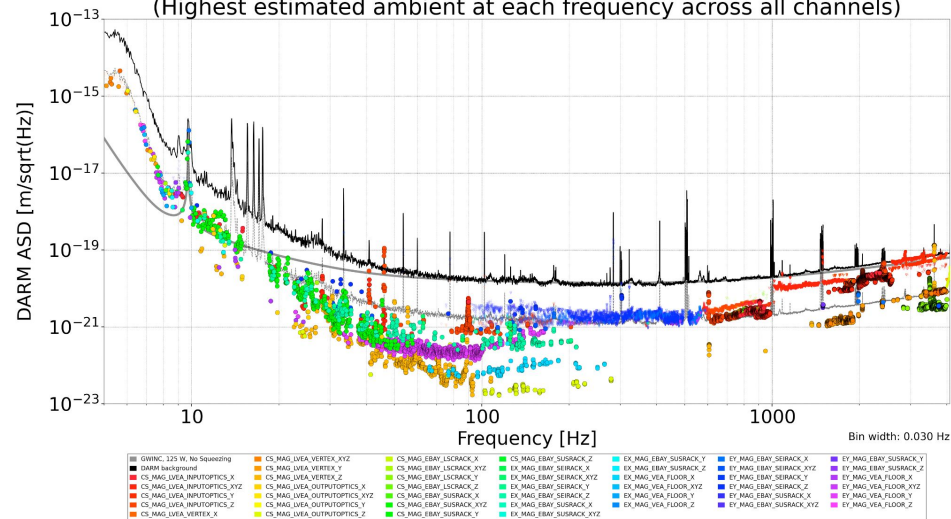
H1 Magnetic - Estimated Ambient
(Highest estimated ambient at each frequency across all channels)



Ambient estimates are made by multiplying coupling factors by injection-free sensor levels. CIRCLES indicate estimates from measured coupling factors, i.e. where the injection signal was seen in the sensor and in DARM. TRIANGLES represent upper limit coupling factors, i.e. where a signal was seen in the sensor but not in DARM. For some channels, at certain frequencies the ambient estimates are upper limits because the ambient level is below the sensor noise floor.

2023

H1 Magnetic - Estimated Ambient
(Highest estimated ambient at each frequency across all channels)



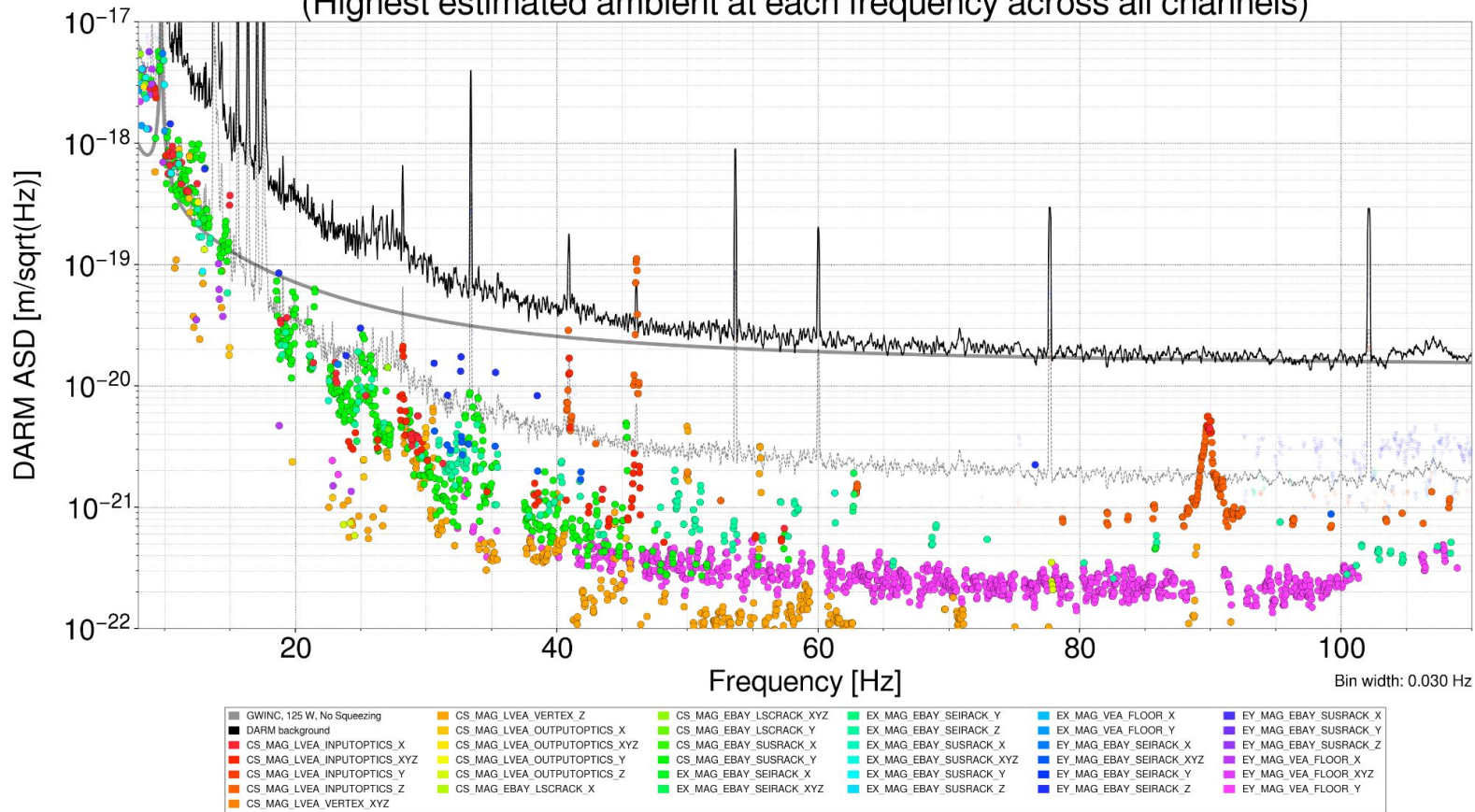
Ambient estimates are made by multiplying coupling factors by injection-free sensor levels. CIRCLES indicate estimates from measured coupling factors, i.e. where the injection signal was seen in the sensor and in DARM. TRIANGLES represent upper limit coupling factors, i.e. where a signal was seen in the sensor but not in DARM. For some channels, at certain frequencies the ambient estimates are upper limits because the ambient level is below the sensor noise floor.

2025

H1 Magnetic - Estimated Ambient

(Highest estimated ambient at each frequency across all channels)

2025
(8 - 110 Hz)

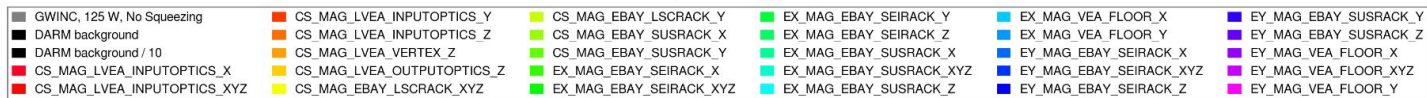
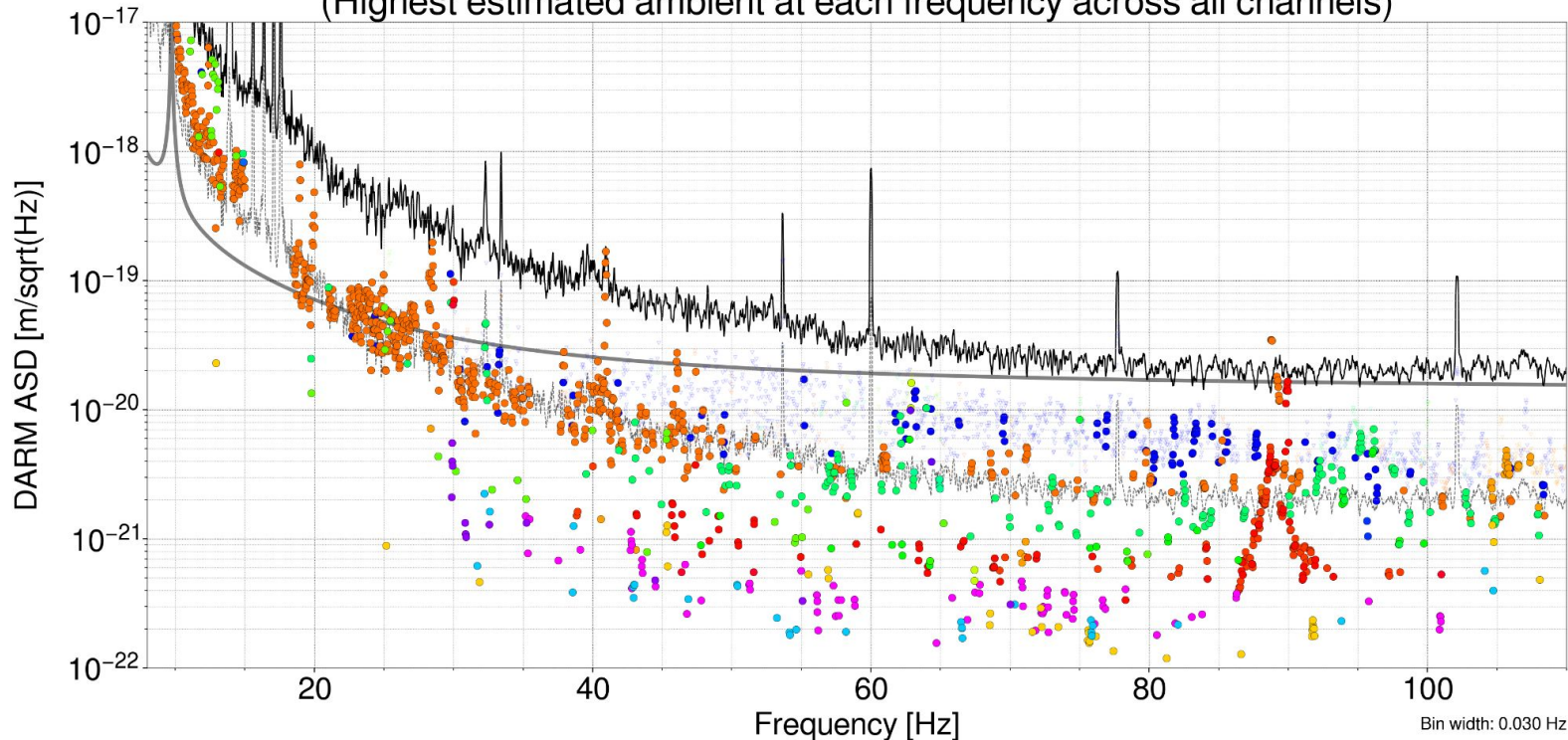


Ambient estimates are made by multiplying coupling factors by injection-free sensor levels. CIRCLES indicate estimates from measured coupling factors, i.e. where the injection signal was seen in the sensor and in DARM. TRIANGLES represent upper limit coupling factors, i.e. where a signal was seen in the sensor but not in DARM. For some channels, at certain frequencies the ambient estimates are upper limits because the ambient level is below the sensor noise floor.

H1 Magnetic - Estimated Ambient

(Highest estimated ambient at each frequency across all channels)

2023
(8 - 110 Hz)



Ambient estimates are made by multiplying coupling factors by injection-free sensor levels. CIRCLES indicate estimates from measured coupling factors, i.e. where the injection signal was seen in the sensor and in DARM. TRIANGLES represent upper limit coupling factors, i.e. where a signal was seen in the sensor but not in DARM. For some channels, at certain frequencies the ambient estimates are upper limits because the ambient level is below the sensor noise floor.

Magnetic Summary

- Testing new automated magnetic injection system
- Injected at more frequency bands
 - broader bands results in more upper limits because the threshold for hitting an upper limit is lower
- Injected closer to saturation to lower the upper limits
- The amount of coupling remains roughly the same
- Future MAG injections: Bring back single line and comb injections to look deeper/beyond upper limits

PEMCheck

H1

omegascan

stationarity

glitchfind

rangecheck

gspynettree

lockcheck

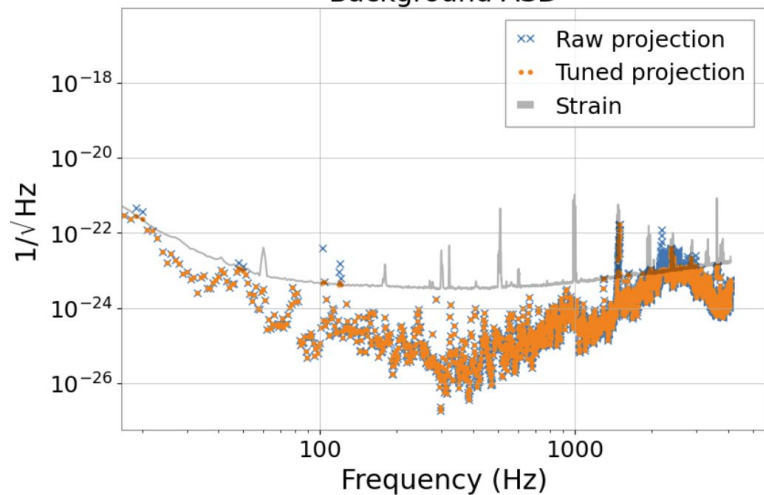
omega_overlap

hveto

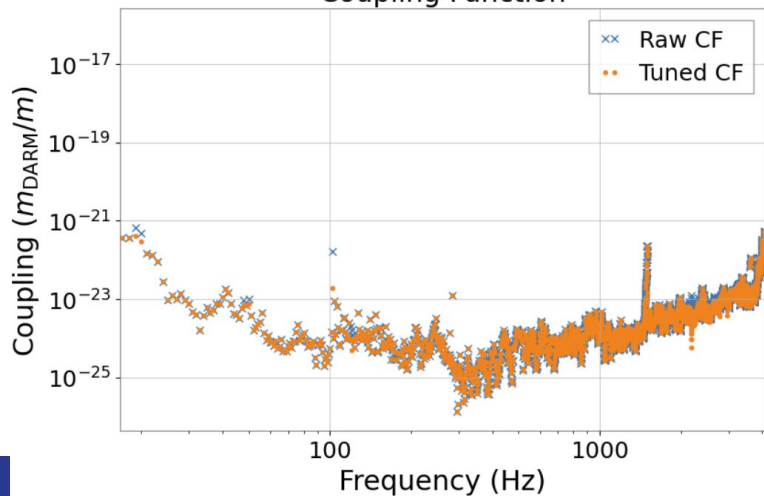
pemcheck

- DQR app
- PEMCheck uses coupling functions to evaluate the probability of noise contributing to GraceDB events
- “Raw” coupling function: what we just talked about
- “Tuned” coupling function: recalculated from sensor and DARM ASDs at the time of the event
- Raw & tuned CFs should be aligned. If not, there may have been noise at the time of the event.

Background ASD



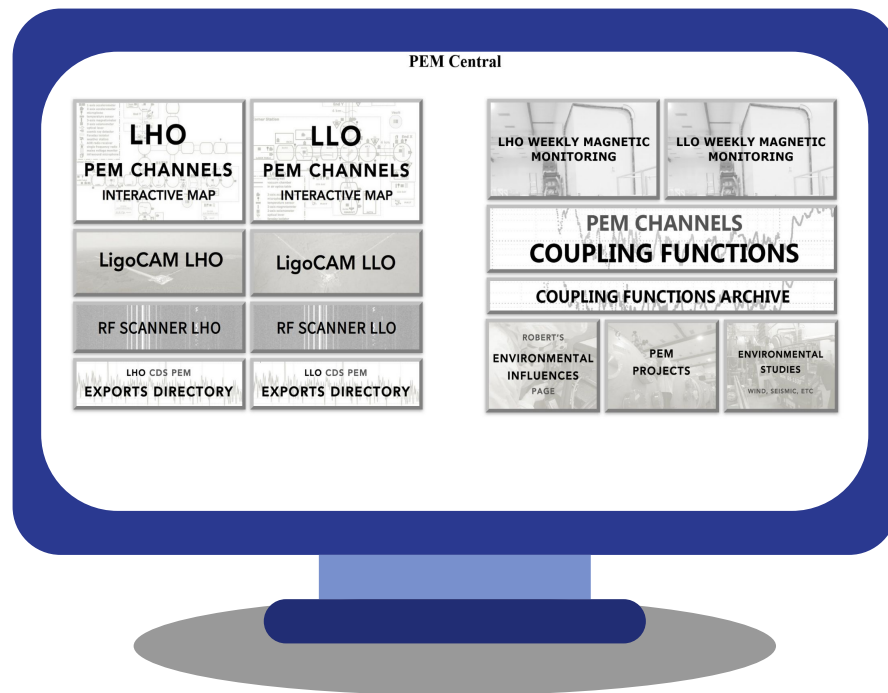
Coupling Function






Where can I find the injection data?










The PEM website!
pem.ligo.org



PEM Central

 <p>LHO PEM CHANNELS INTERACTIVE MAP</p>	 <p>LLO PEM CHANNELS INTERACTIVE MAP</p>
 <p>LigoCAM LHO</p>	 <p>LigoCAM LLO</p>
 <p>RF SCANNER LHO</p>	 <p>RF SCANNER LLO</p>
 <p>LHO CDS PEM EXPORTS DIRECTORY</p>	 <p>LLO CDS PEM EXPORTS DIRECTORY</p>

 <p>LHO WEEKLY MAGNETIC MONITORING</p>	 <p>LLO WEEKLY MAGNETIC MONITORING</p>	
 <p>PEM CHANNELS COUPLING FUNCTIONS</p>		
 <p>COUPLING FUNCTIONS ARCHIVE</p>		
 <p>ROBERT'S ENVIRONMENTAL INFLUENCES PAGE</p>	 <p>PEM PROJECTS</p>	 <p>ENVIRONMENTAL STUDIES WIND, SEISMIC, ETC</p>

Exports directory → 2025Endof04PEMinjections

Coupling Functions → Additional resources → 04 git repo

Overall Summary

- Hardware improvements → improvement in coupling (i.e. there is less coupling)
- Upper limits improved by injecting closer to saturation
- Compared to 2023, we have roughly the same amount (magnetic) or less (vibrational) coupling
- Additionally
 - Livingston also did an injection set, analysis ongoing