Top 10 LIGO Commissioning Problems

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KAGRA Face To Face Meeting
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Outline:

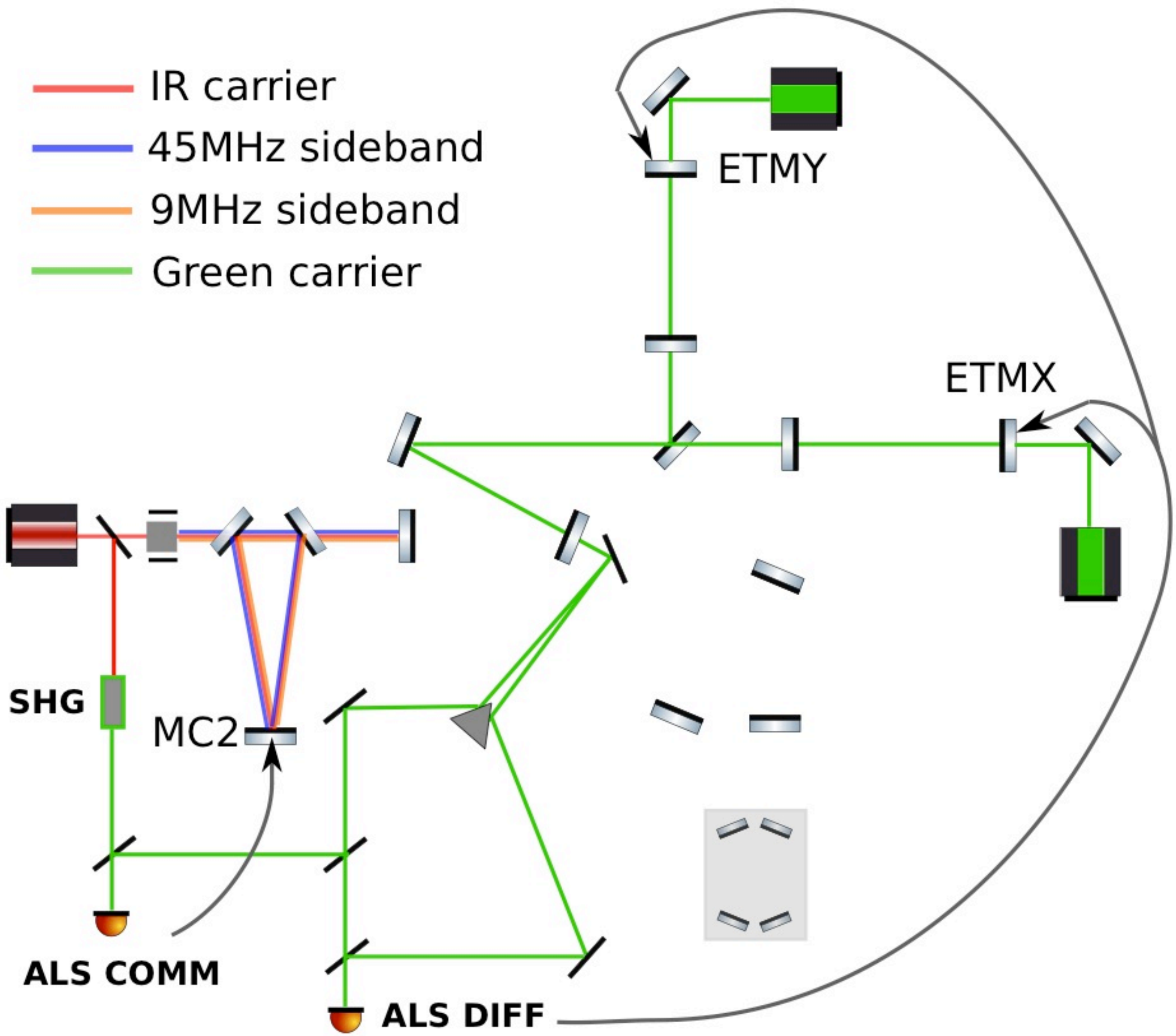
1. Arm length stabilization
2. DRMI lock acquisition
3. CARM offset reduction
4. Angular controls
5. Achieving robustness

Lock Acquisition and Control

6. Electrostatic actuators
7. Charging noise
8. Auxiliary channels
9. Glitches/whistles/PI
10. Scattering

Sensitivity

Arm length stabilization

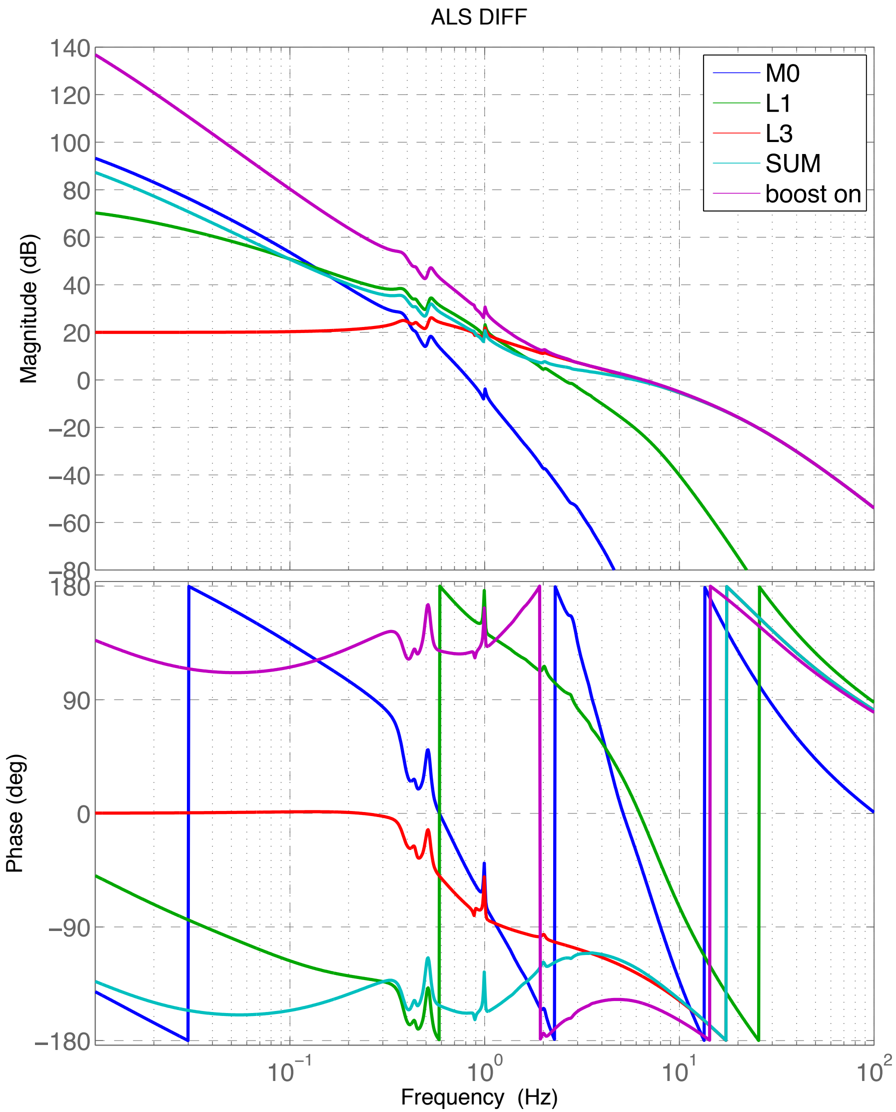


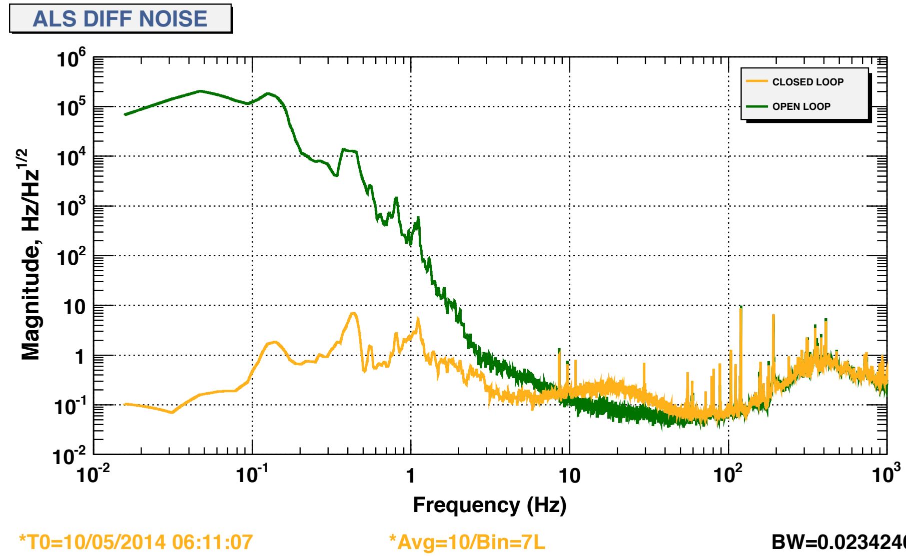
Problems:

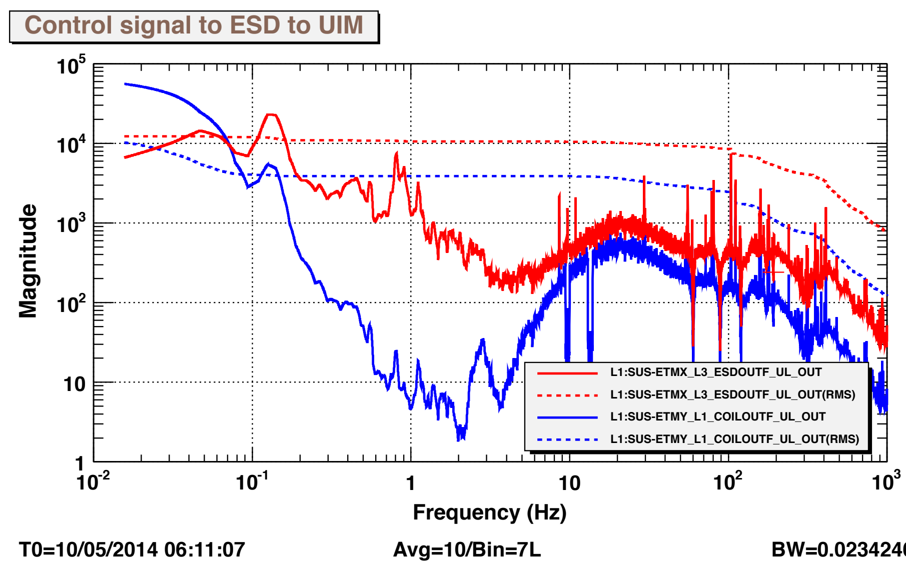
- ALS PDH signal was corrupted by HOM and locking on 00 mode was probabilistic. We clipped the beam on REFL PD to optimize PDH signal
- ALS beat signals glitches probably due to fibers. Glitches sometimes cause lock losses
- Consequences of the low finesse cavities: transmission of arms is low, cavity pole increased up to 4kHz, length noise from angular motion
- ALS noise due to optical path fluctuations is

$$L(\Omega) = \frac{\Omega}{2FSR} l(\Omega); L_{RMS} \approx 100\, pm$$

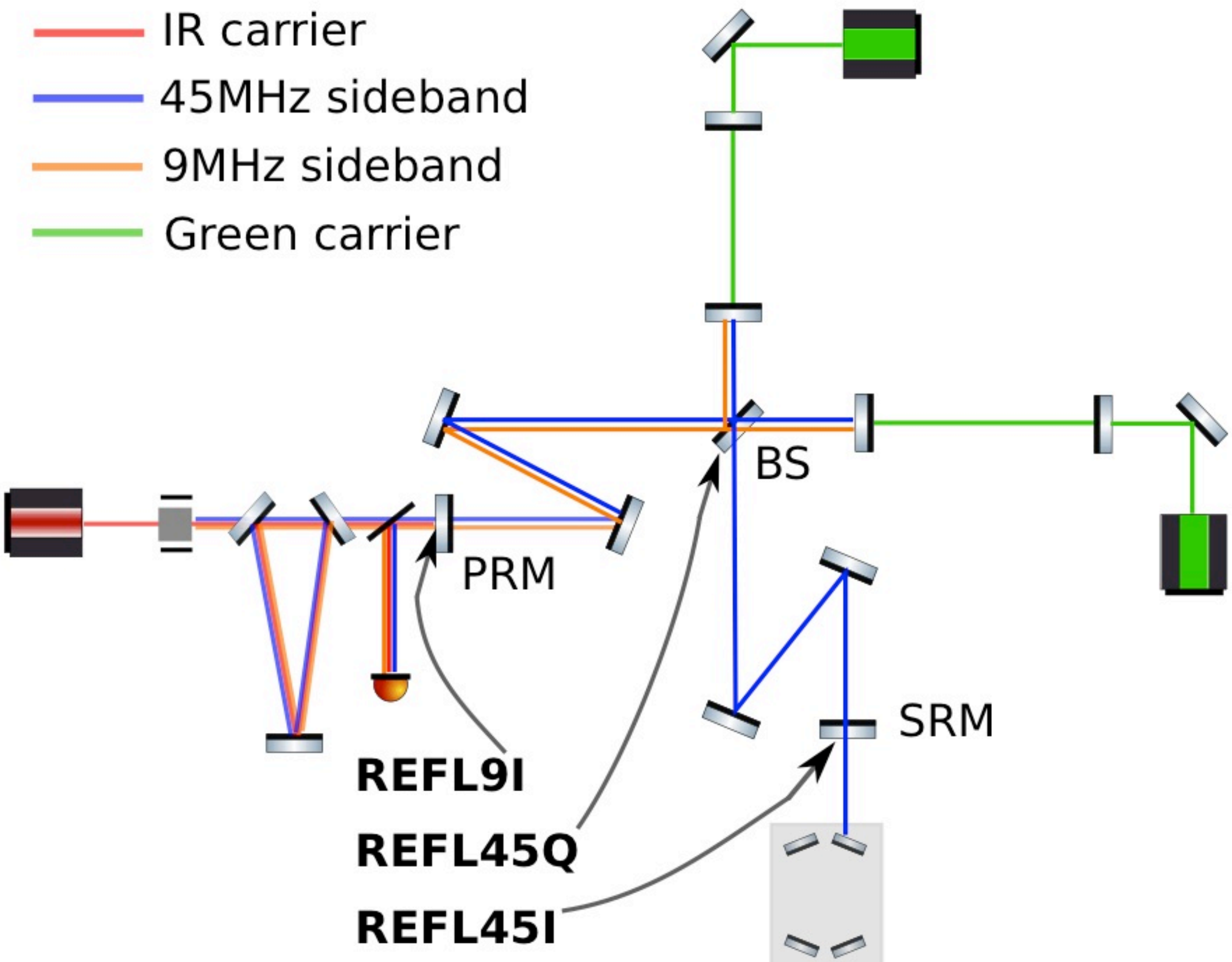
Longitudinal test mass control







DRMI locking



Problems:

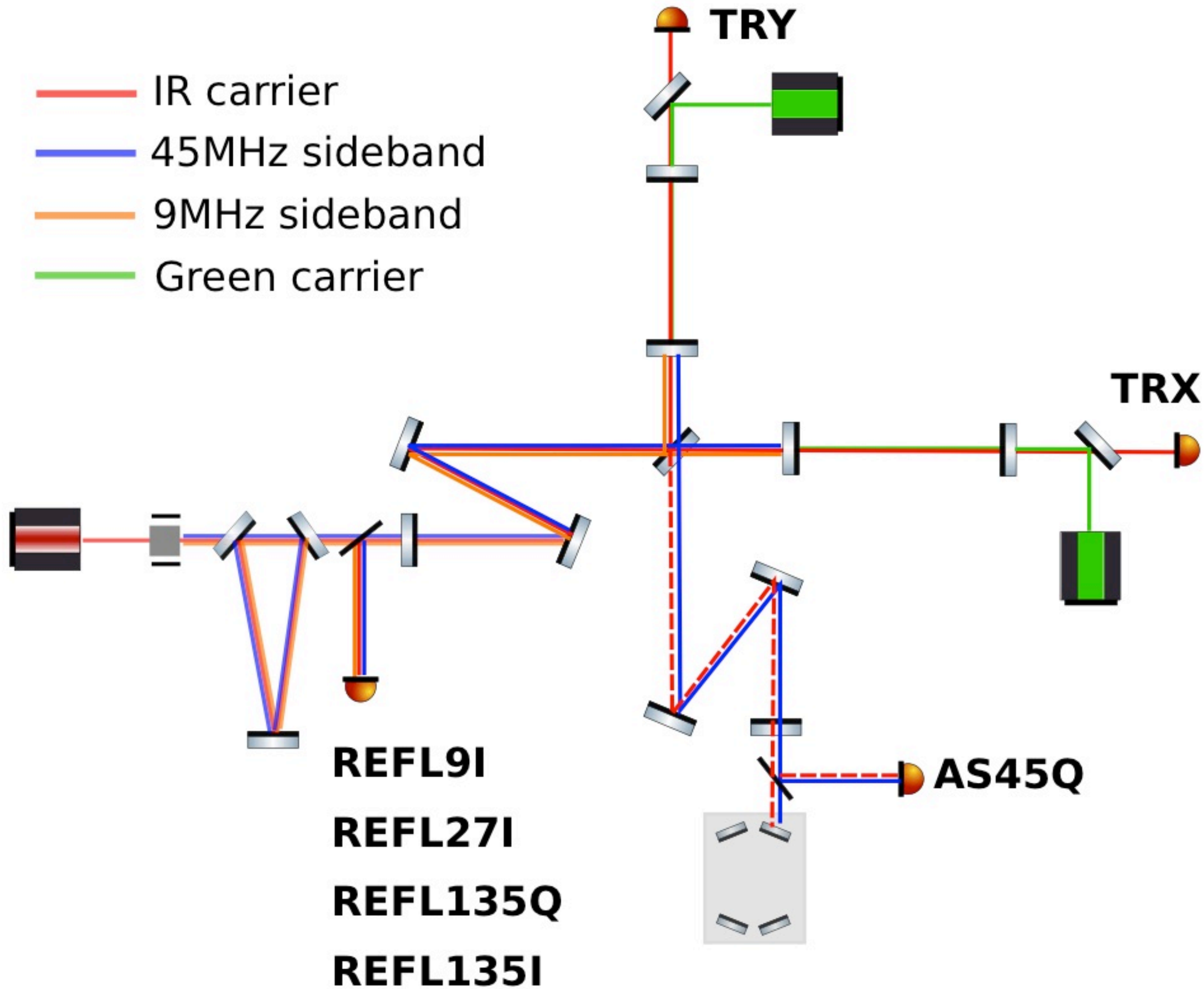
- BS longitudinal actuation creates significant angular motion. We designed F2P decoupling filters and introduced oplev servo during lock acquisition
- Could not lock if power on REFL PDs is more than 15mW (gamma = 0.3).

Input power, W	DC current, mA	# of locks in 5 mins
1.34	9.4	8
1.65	11.5	8
1.8	12.6	5
2.3	16.1	6
2.6	18.2	2
3.3	23.1	3
4.1	28.7	0

Problems:

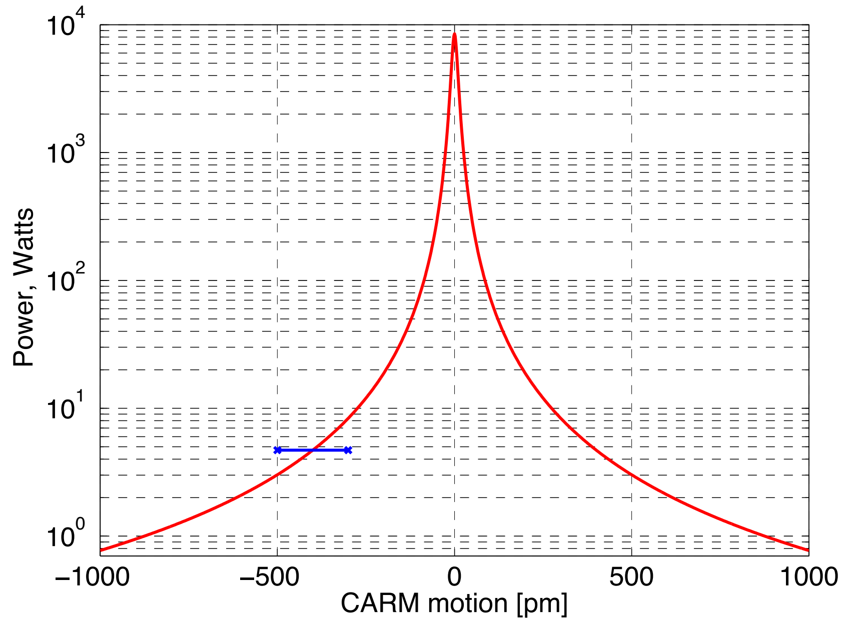
- DC optical power of more than 3mW on REFL broadband PD (3f) made PRCL/SRCL degenerate. Signal was mostly created by saturations inside PD amplifiers. Highest lines were 36MHz, 54MHz and 90MHz. Problem was solved first by reducing power on 3f detectors, then installing notch filters at 2f harmonics and then removing second PD amplifier
- BS and PR3 metal wires were heated and optics significantly drifted in pitch. For BS 10urad/800W. Problem was addressed by installing additional baffles on BS and PR3.
- DRMI lock acquisition time significantly depends on SRC alignment and BS in particular. Triggering threshold was optimized to reduce lock acquisition time.

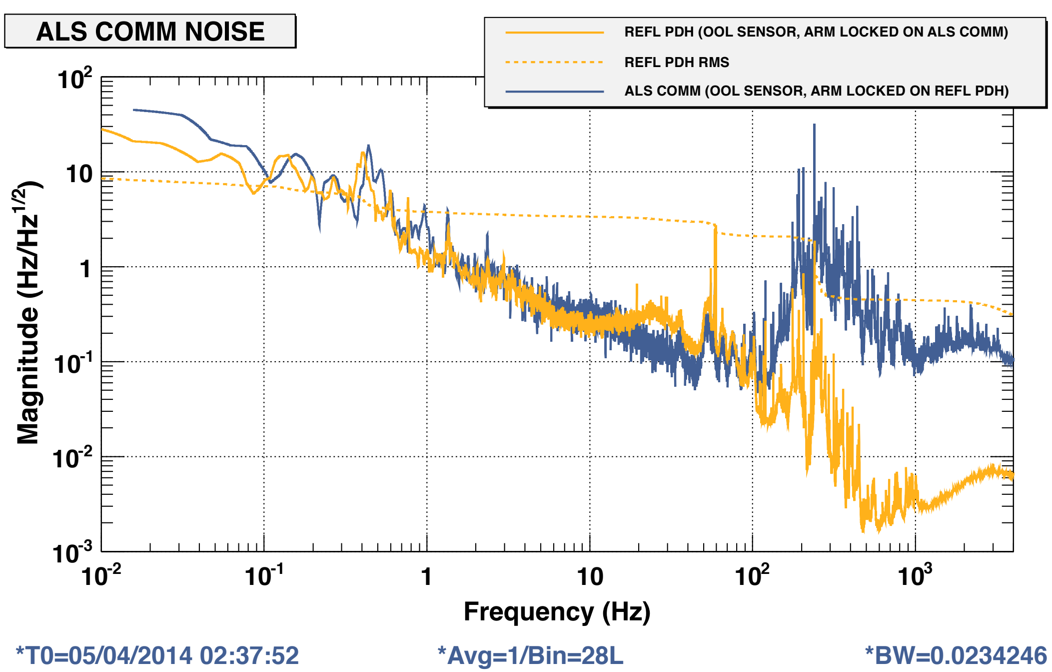
CARM offset reduction

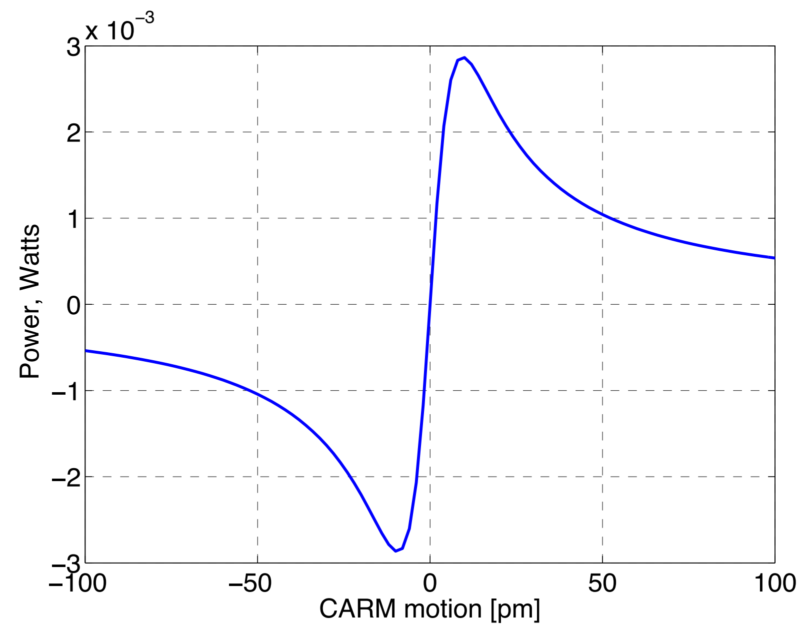


CARM Sensing Signals

CARM offset	Error signal	Actuation
10nm - 400pm	ALS COMM	MC2 length
400pm - 10pm	$\sqrt{\text{TRX+TRY}}$	MC2 length
10pm - 0pm	REFL_9_I	MC2 length
0pm	REFL_9_I	MC2 + AO



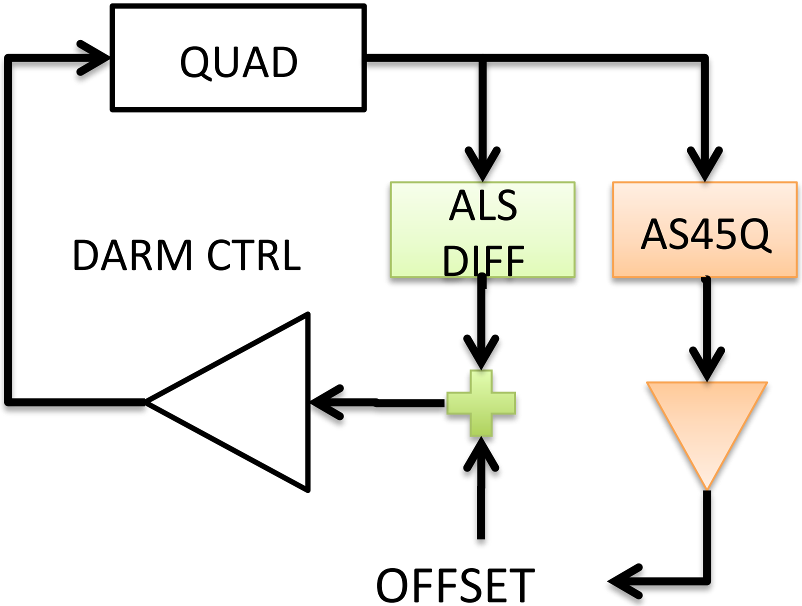


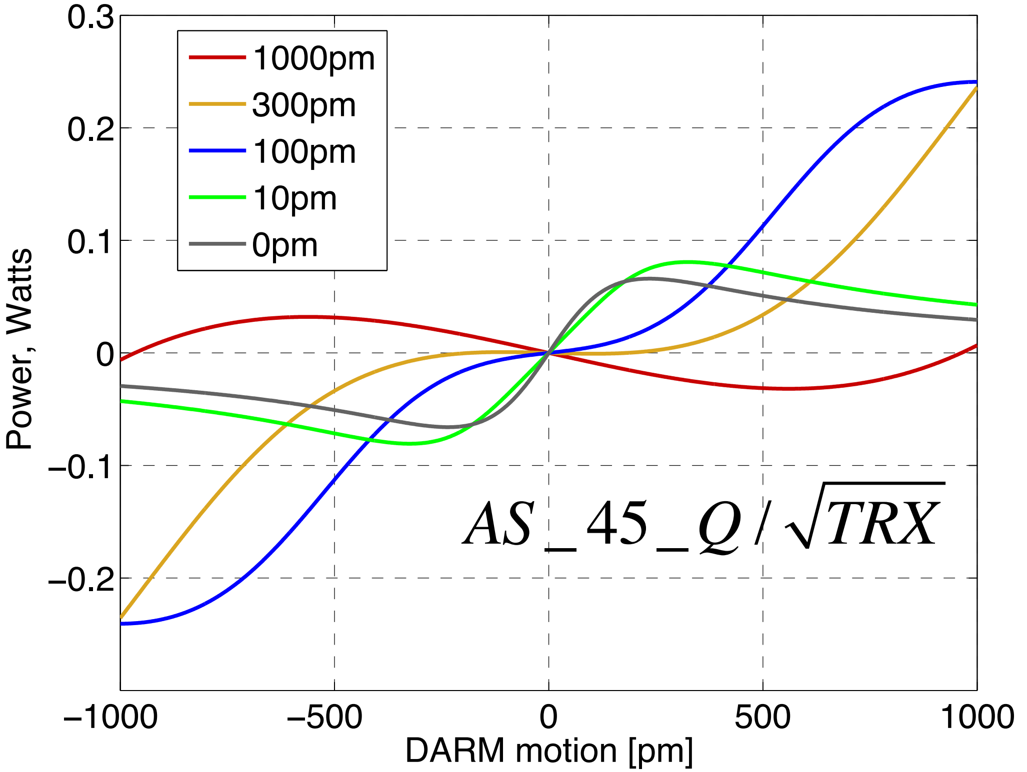


DARM Sensing Signals

CARM offset	Error signal	Actuation
10nm - 250pm	ALS DIFF	ETMX - ETMY
250pm - 100pm	ALS DIFF; AS45Q	ETMX – ETMY; ALS DIFF OFFSET
100pm - 0pm	AS45Q	ETMX - ETMY

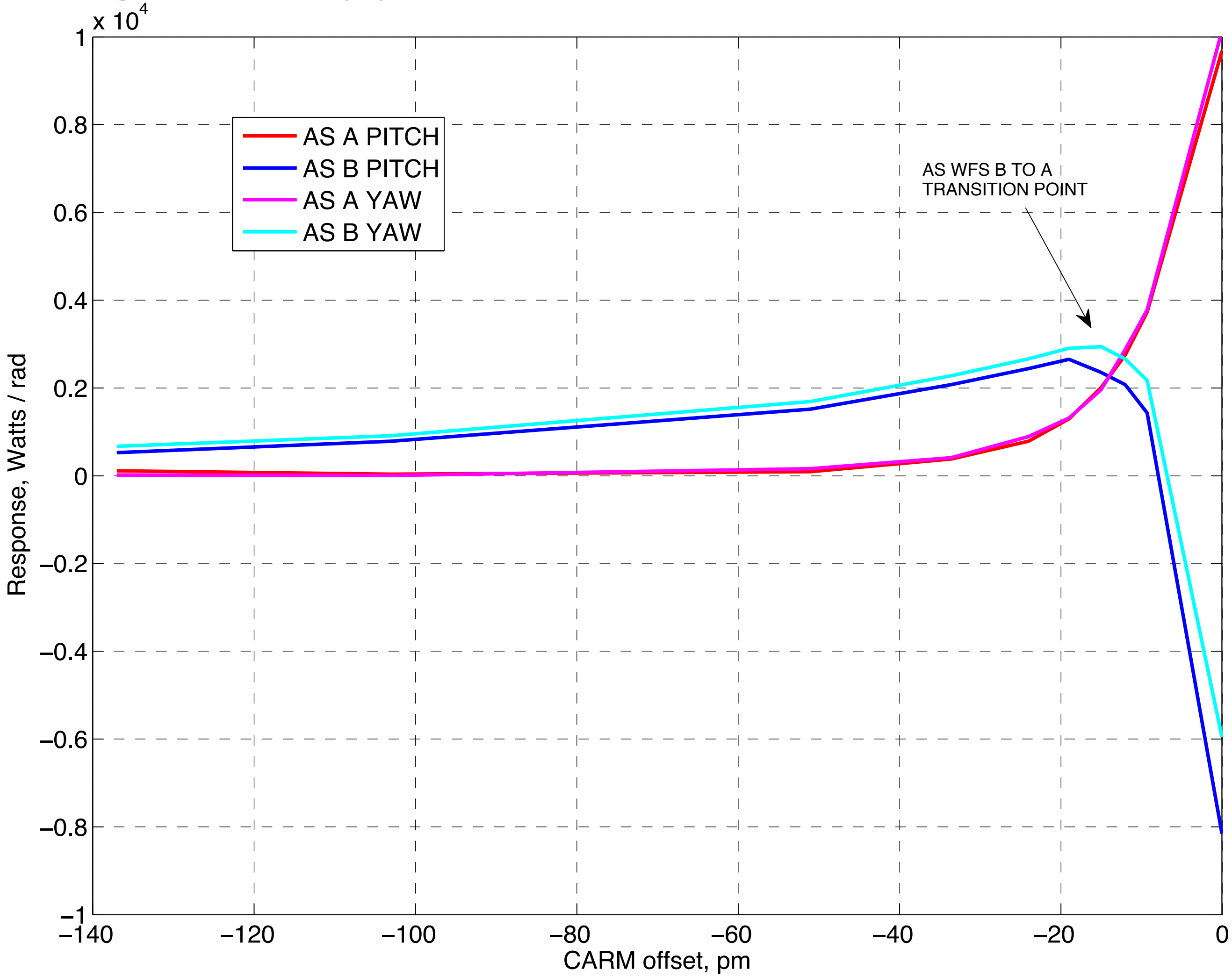
Arm misalignment causes DARM offset



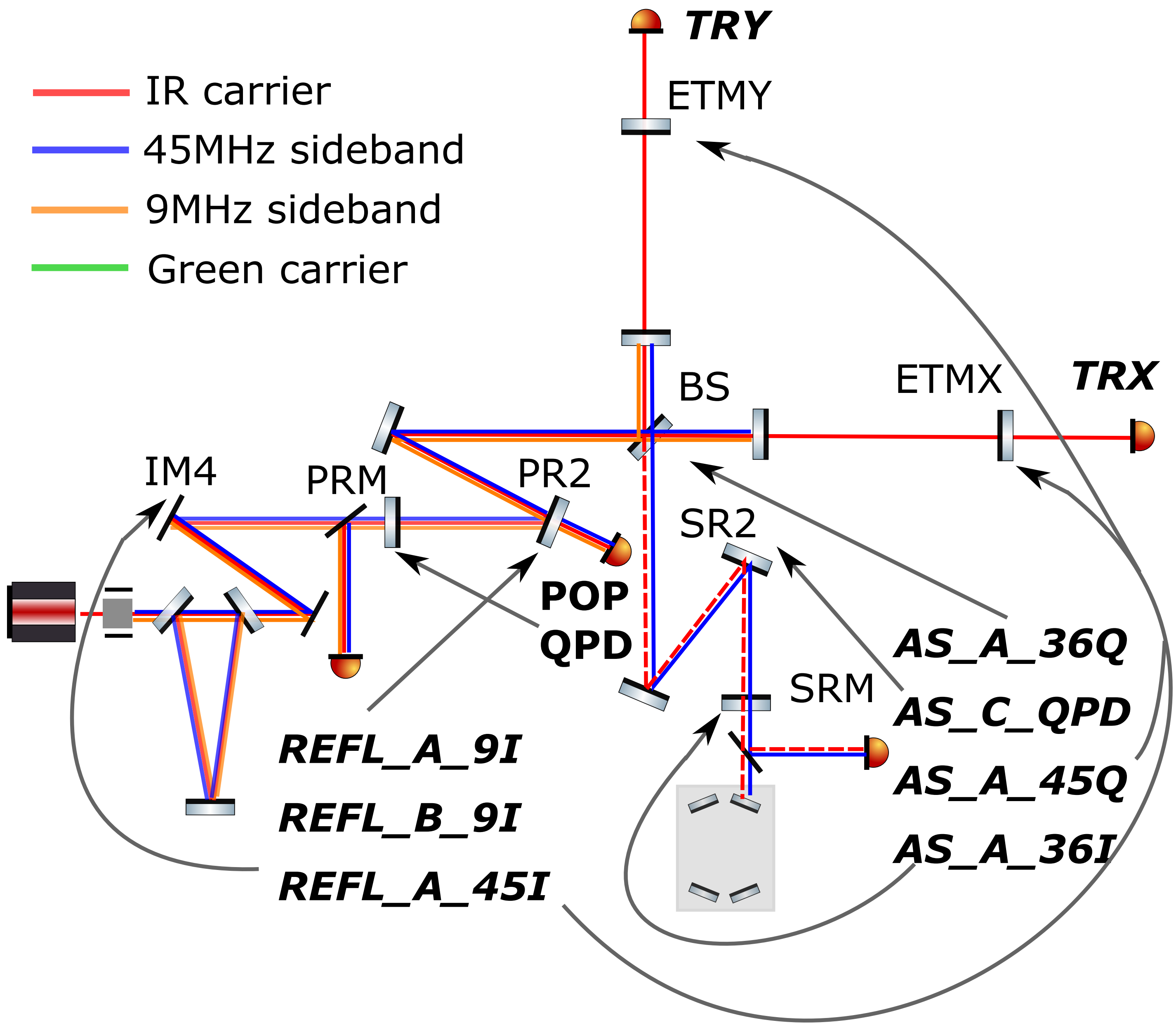


Top problem: Relative arm alignment

Relative arm misalignment is clearly seen on the camera at AS port. Light leaks out from IFO and corrupts most of the servos. Solution is to use two AS WFS in orthogonal Gouy phases.



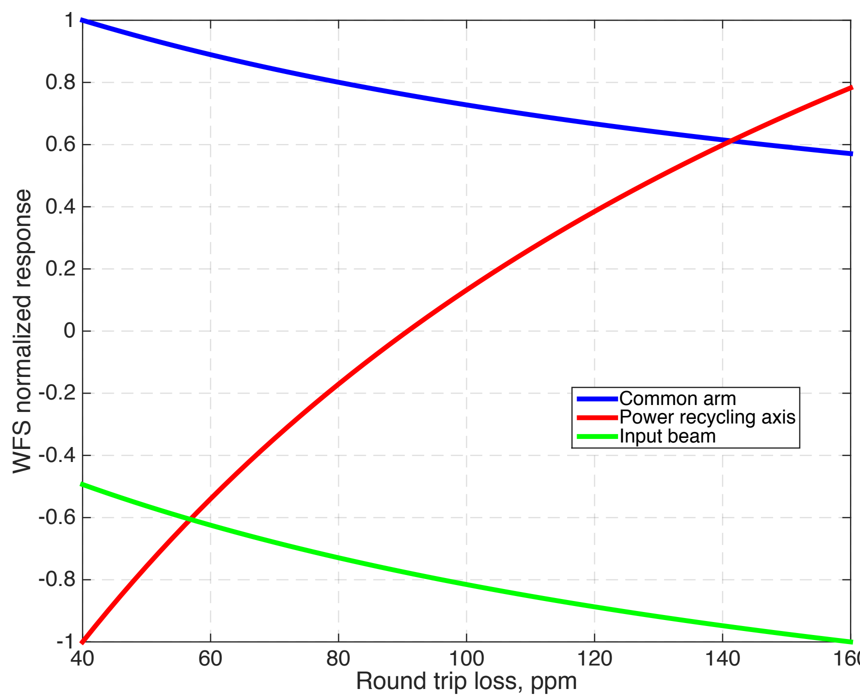
Angular controls



Problems:

- Sensing matrix significantly depends on the contrast defect. We tuned power of CO2 lasers to balance ITMX and ITMY lenses

- Sensing matrix depends on the losses in the arm cavities. Losses depend on the beam position on test masses.

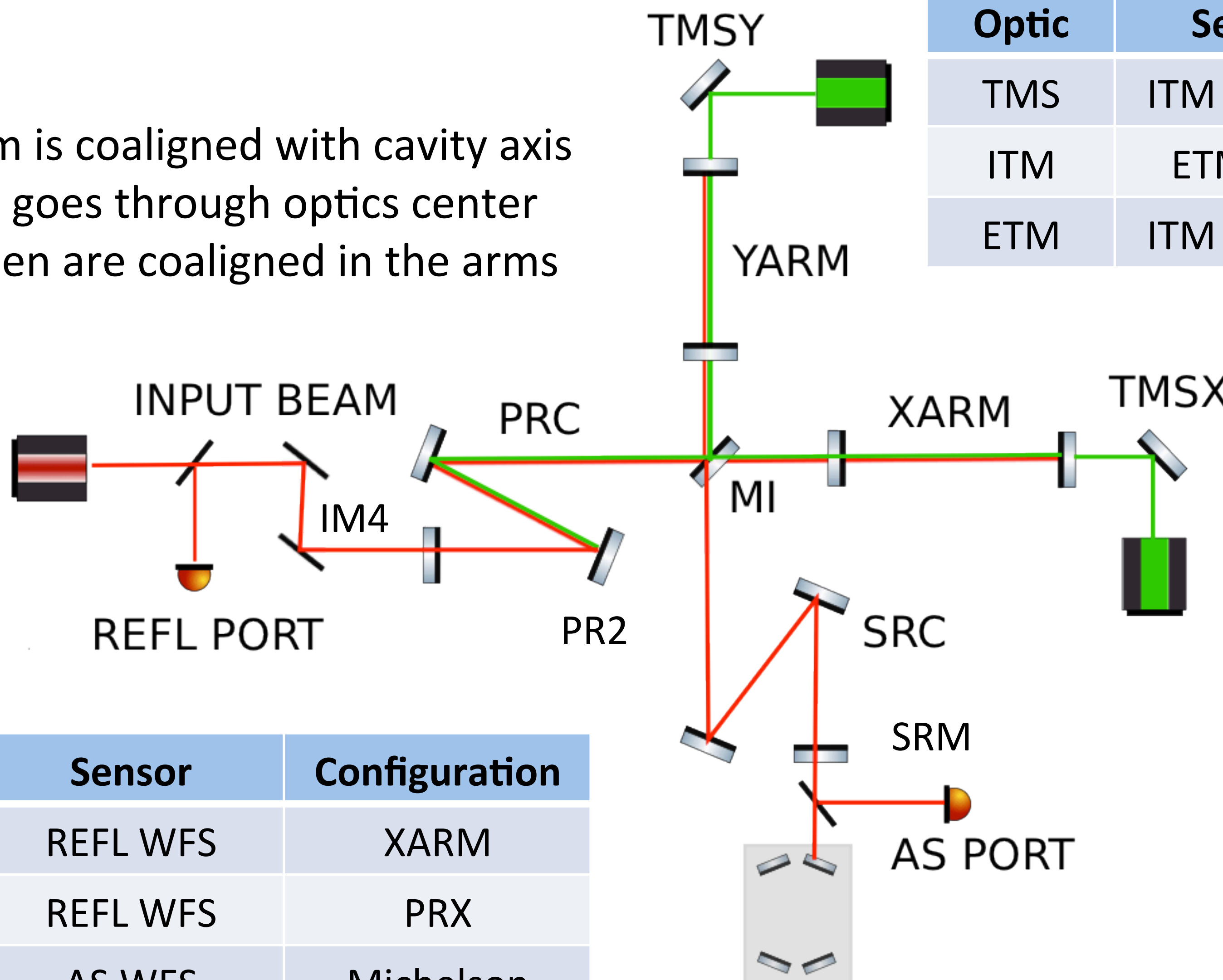


- It is good to check optical losses in the arm cavities before locking starts

Robustness: initial alignment

Goals:
- Input beam is coaligned with cavity axis
- Cavity axis goes through optics center
- IR and Green are coaligned in the arms

Optic	Sensor
TMS	ITM camera
ITM	ETM BPD
ETM	ITM camera



Optic	Sensor	Configuration
PR2, IM4	REFL WFS	XARM
PRM	REFL WFS	PRX
BS	AS WFS	Michelson
SRM	REFL WFS	SRY

Robustness: bounce/roll/violin modes

- Use DARM and AS WFS as sensing signals for bounce and roll damping
- Use L2 pitch and M0 vertical to damp bounce and roll modes
- Most significant problem is that phase of the servo depends on the beam position in the arm cavities
- DARM error and L2 actuators are used for violin mode damping. Some of the modes are close and should be damped in series.

Robustness: bounce/roll modes

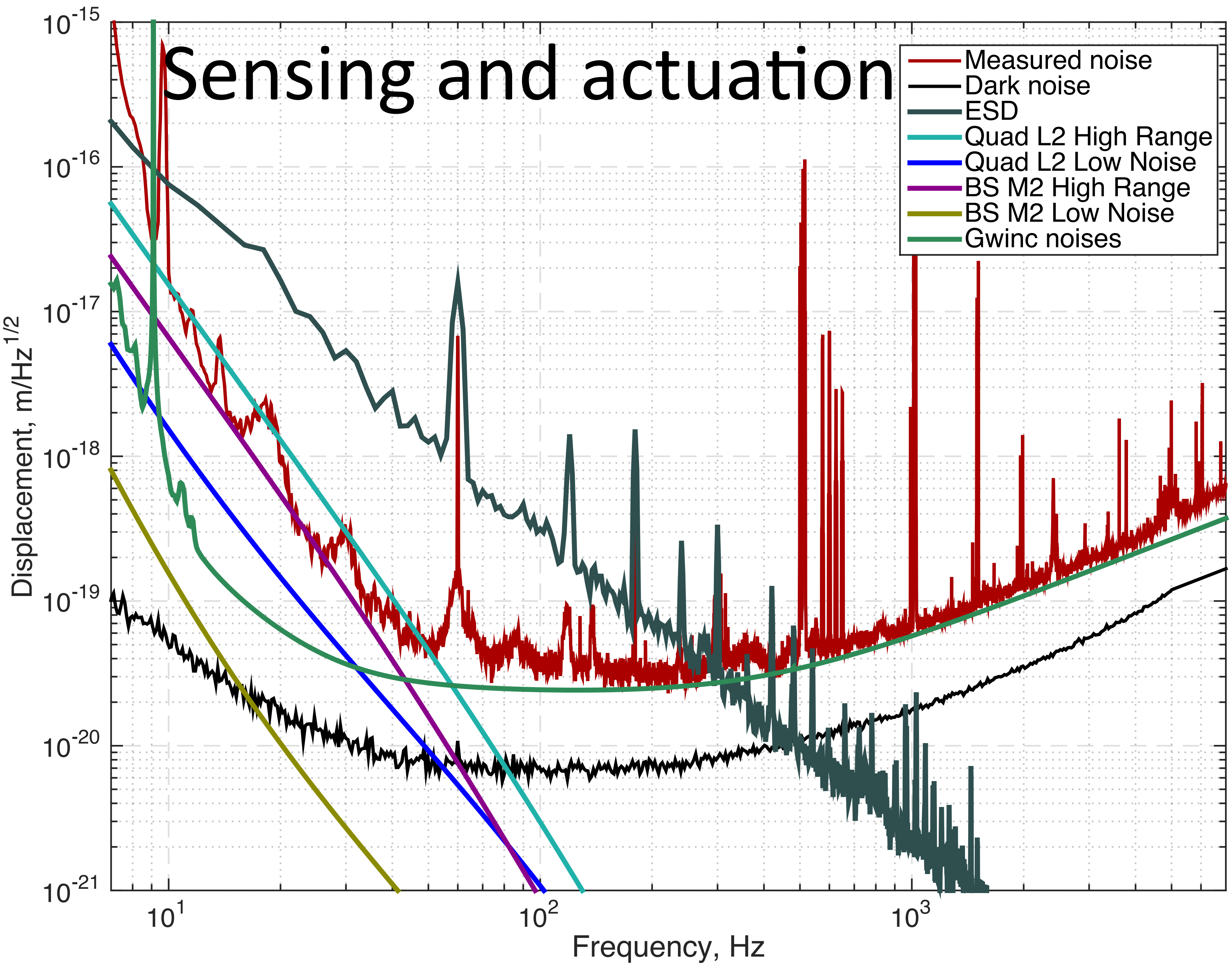
Mode	Test mass	f_0, Hz	Error signal	Servo	Actuator
bounce	ETMX	9.59	DARM ERR	$+BP_{f_0} \cdot G_{+60^\circ}$	M0 VERT
bounce	ETMY	9.71	DARM ERR	$-BP_{f_0} \cdot G_{+60^\circ}$	M0 VERT
bounce	ITMX	9.62	DARM ERR	$+BP_{f_0}$	M0 VERT
bounce	ITMY	9.68	DARM ERR	$-BP_{f_0} \cdot G_{+60^\circ}$	M0 VERT
roll	ETMX	13.59	WFS AS45Q PIT	$-BP_{f_0} \cdot G_{-60^\circ}$	L2 PIT
roll	ETMY	13.78	WFS AS45Q PIT	$+BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
roll	ITMX	13.65	DARM ERR	$+BP_{f_0}$	M0 ROLL
roll	ITMY	13.75	DARM ERR	$-BP_{f_0}$	M0 ROLL

Robustness: violin modes

Test mass	f_0, Hz	Servo	Actuator
ETMX	513.15	$+BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
ETMX	513.27	$+BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
ETMX	515.55	BP_{f_0}	L2 LONG
ETMX	516.9	$+BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
ETMY	499.6	$-BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
ETMY	503.1	$+BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
ETMY	515.34	BP_{f_0}	L2 LONG
ETMY	515.37	BP_{f_0}	L2 LONG
ITMX	509.0	$+BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
ITMX	510.9	$+BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
ITMX	515.8	BP_{f_0}	L2 LONG
ITMX	516.0	BP_{f_0}	L2 LONG
ITMY	508.4	$-BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
ITMY	509.4	$-BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
ITMY	510.2	$-BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT
ITMY	511.5	$-BP_{f_0} \cdot G_{+60^\circ}$	L2 PIT

Electrostatic actuator

- AI filter could not drive 15m long cable to HV amplifier. This noise was seen at the level of 10^{-16} m/sqHz @ 100Hz in DARM.
- DAC noise was not filtered and dominated DARM noise in the frequency range 10Hz – 200Hz. First we used L2 actuator for high frequency DARM control, then filtered ITMX actuator and then low noise ETMX actuator.
- Bias could not be reduced due to static charge accumulated on the test mass surface



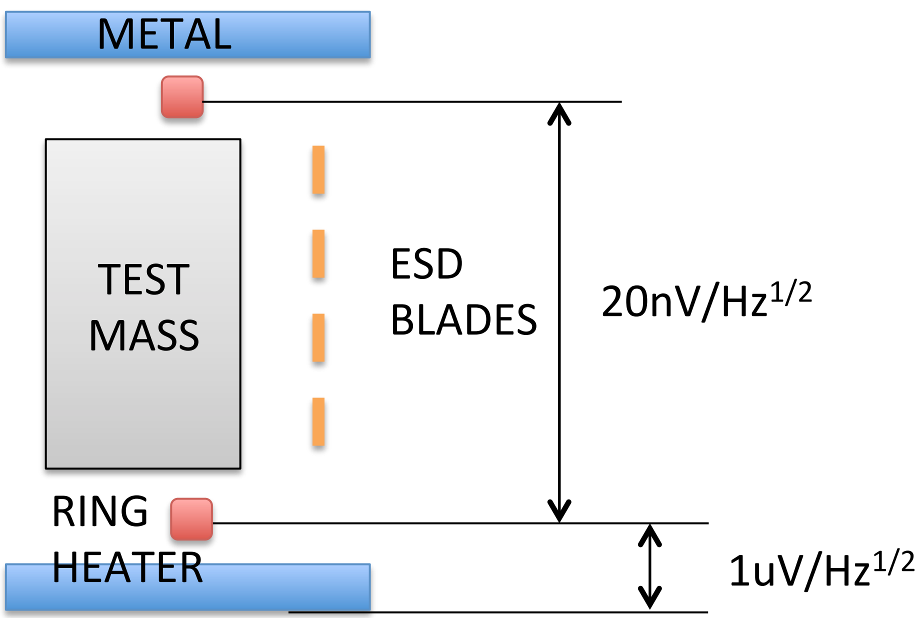
Sensing and actuation
Measured noise
Dark noise
ESD
Quad L2 High Range
Quad L2 Low Noise
BS M2 High Range
BS M2 Low Noise
Gwinc noises
Displacement, m/Hz^1/2
Frequency, Hz
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^1
10^2
10^3

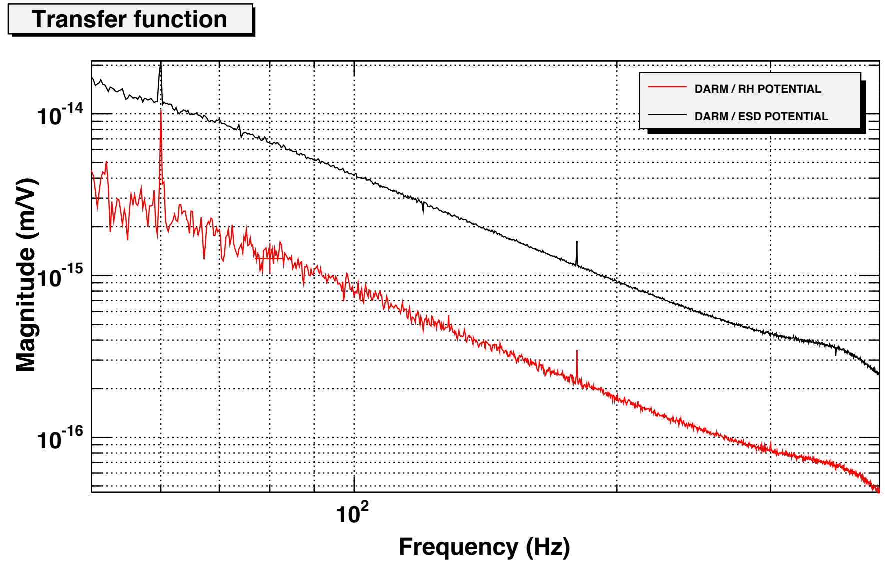
Noises: charge on test masses

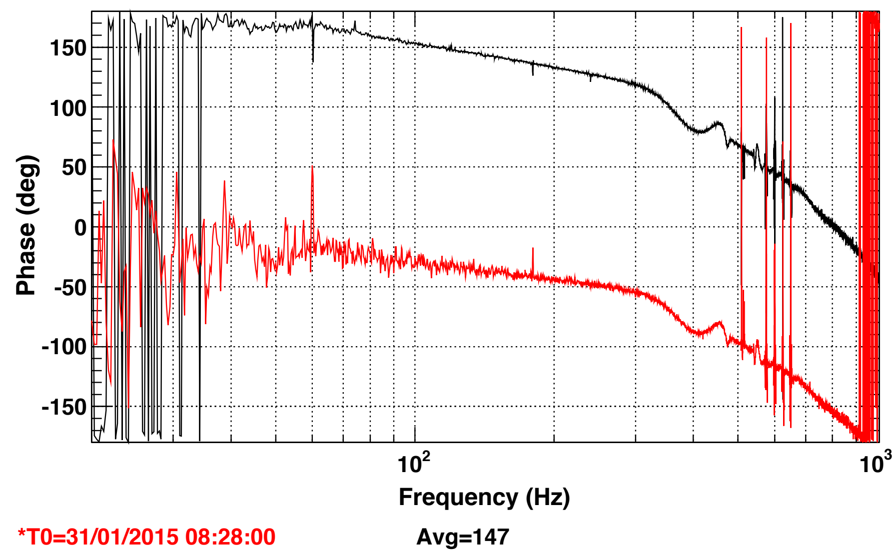
$F = a(V_{bias}-V_{ctrl})^2+b(V_{bias}+V_{ctrl})+c(V_{bias}+V_{ctrl})^2$

Measured:

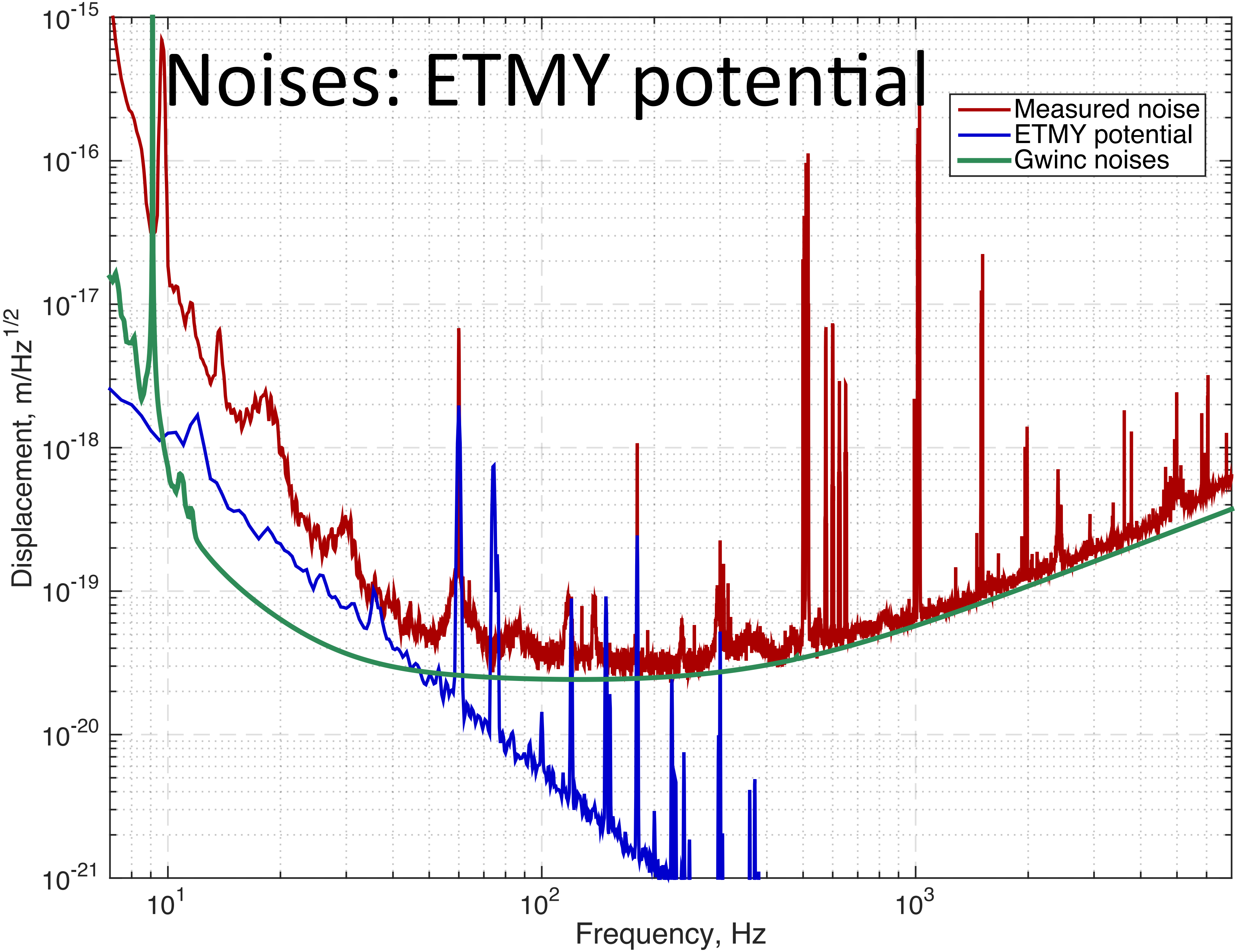
- TF from RH and ESD to DARM with no ESD bias – coupling through charge
- voltage between floating ring heaters
- voltage between one floating ring heater and metal





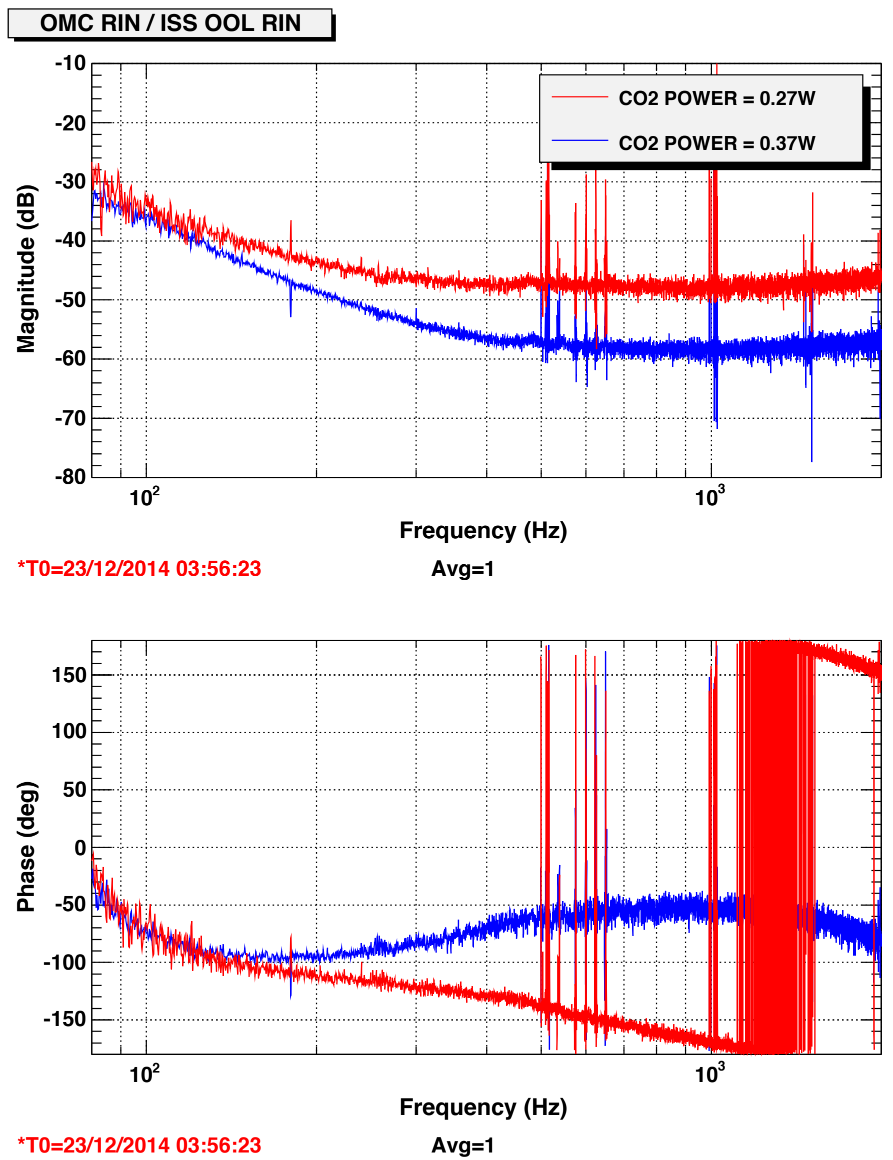


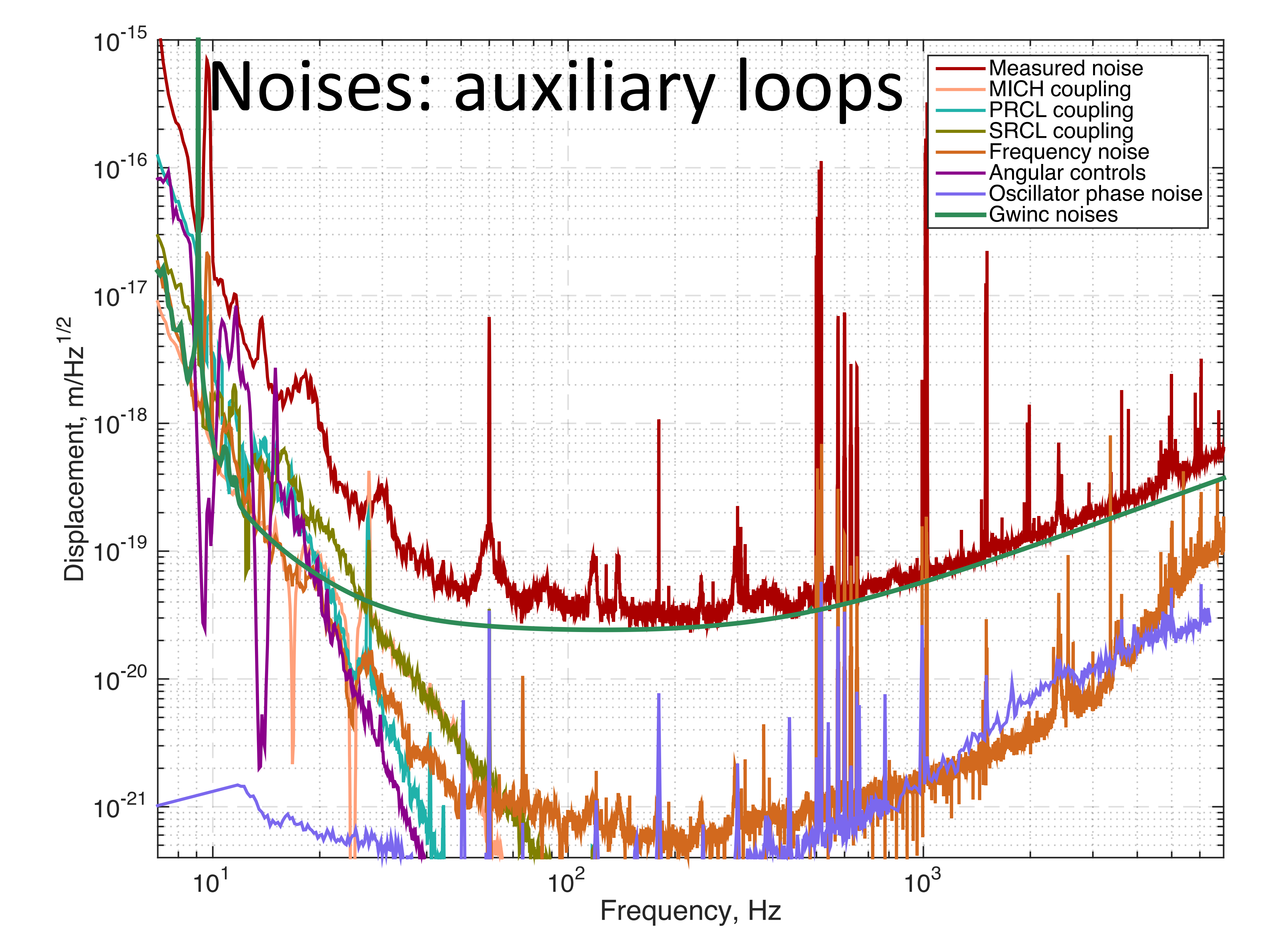
Noises: ETMY potential

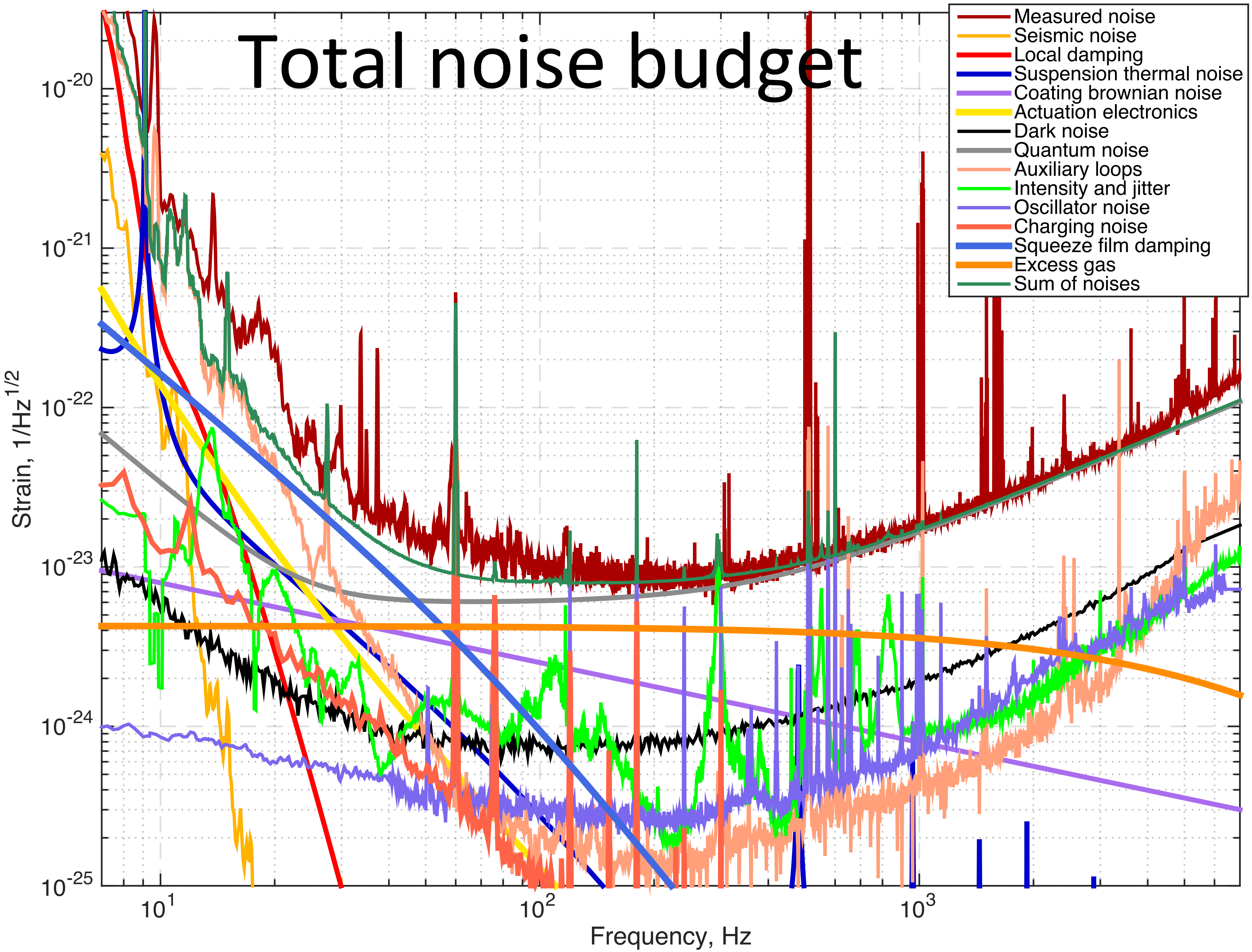


Auxiliary channels

- We run MICH, SRCL FF to reduce noise coupling to DARM. SRCL linear coupling depends on DARM offset and angular fluctuations
- Coupling of intensity noise significantly depends on the contrast defect
- Broadband amplitude noise of Marconi RF oscillator was only a factor of 3 below DARM noise
- Resonance of the input PZT mirror mount was seen in DARM. We run feedback servo to suppress it.




Noises: auxiliary loops
Measured noise
MICH coupling
PRCL coupling
SRCL coupling
Frequency noise
Angular controls
Oscillator phase noise
Gwinc noises
Displacement, m/Hz$^{1/2}$
Frequency, Hz
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{1}
10^{2}
10^{3}

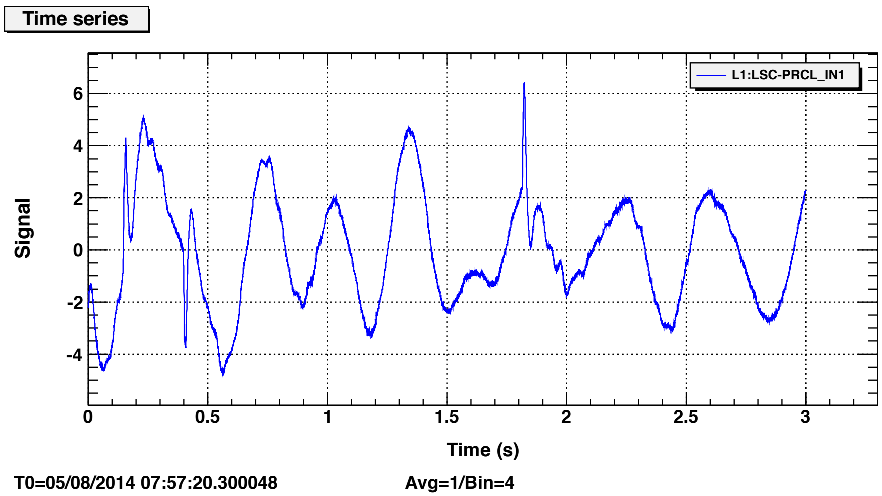


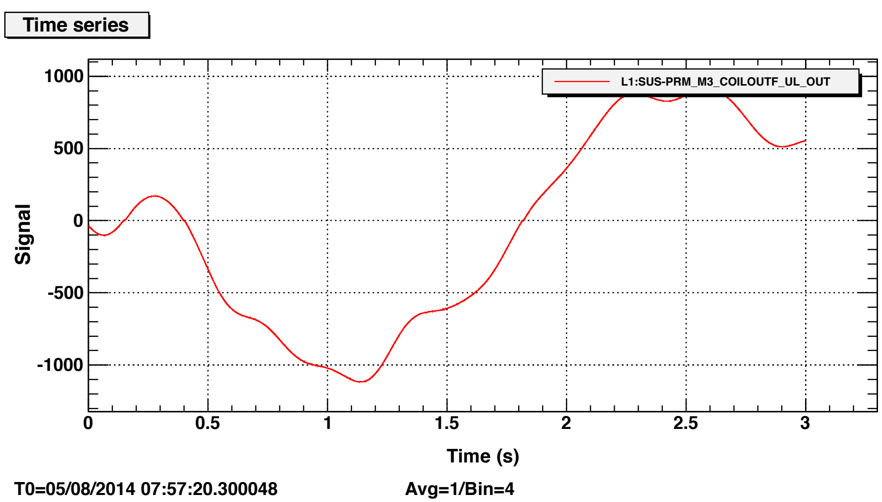
Total noise budget
Measured noise
Seismic noise
Local damping
Suspension thermal noise
Coating brownian noise
Actuation electronics
Dark noise
Quantum noise
Auxiliary loops
Intensity and jitter
Oscillator noise
Charging noise
Squeeze film damping
Excess gas
Sum of noises
Strain, 1/Hz^1/2
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
10^1
10^2
10^3
Frequency, Hz

Glitches/whistles/PI

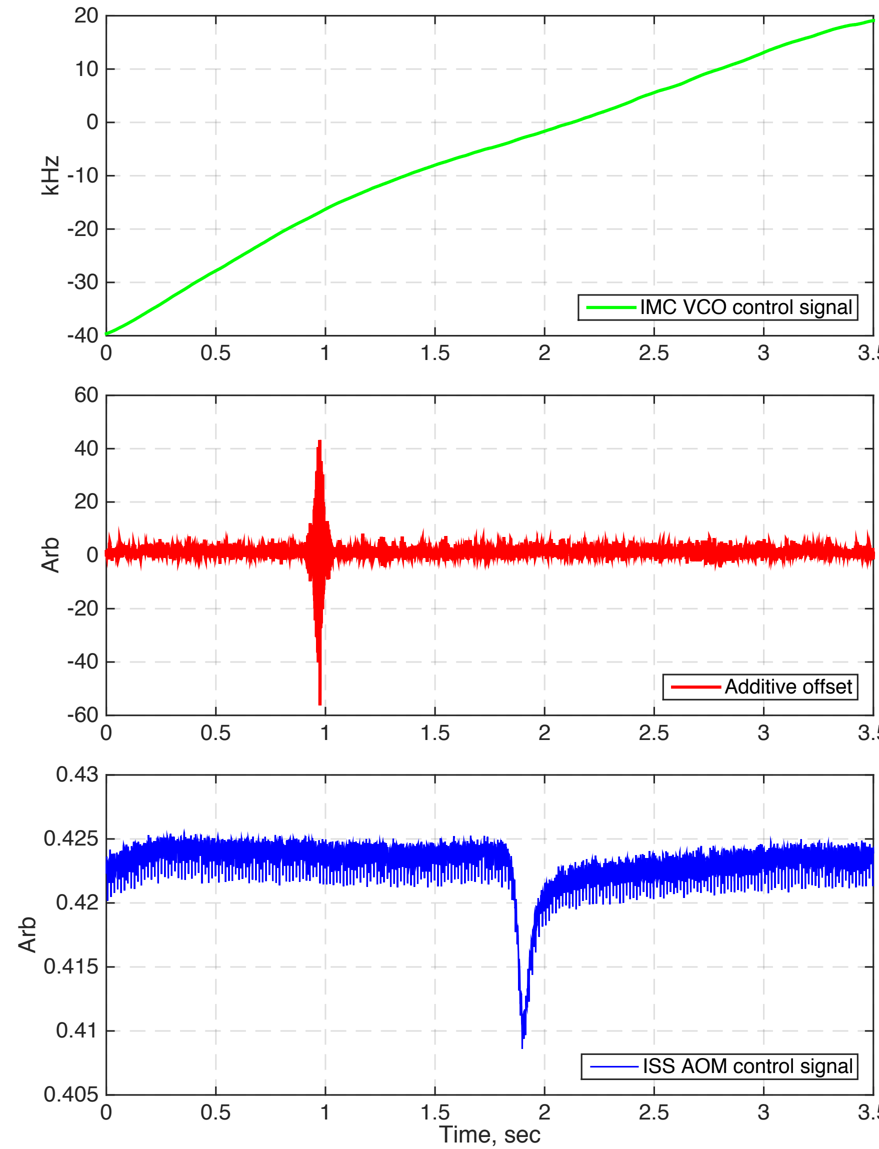
- First glitches we saw came from 18bit DAC zero crossing. We need to run routing that matches two DAC circuits. In the long run we plan to replace these DACs
- Whistle in the frequency and intensity servos are present due to RF crosstalk in the electronics rack. Whistles happen when IMC VCO control signal crosses particular values.
- Parametric instabilities are main sources of lock losses at this point. We can reduce power or actively damp body modes. Design of passive dampers is now discussed.

DAC zero crossing





Frequency and intensity glitches

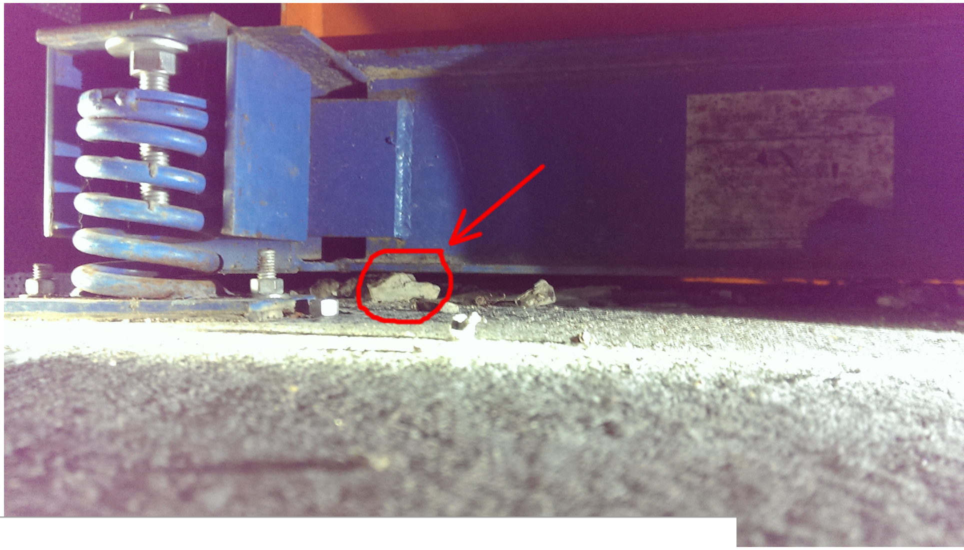


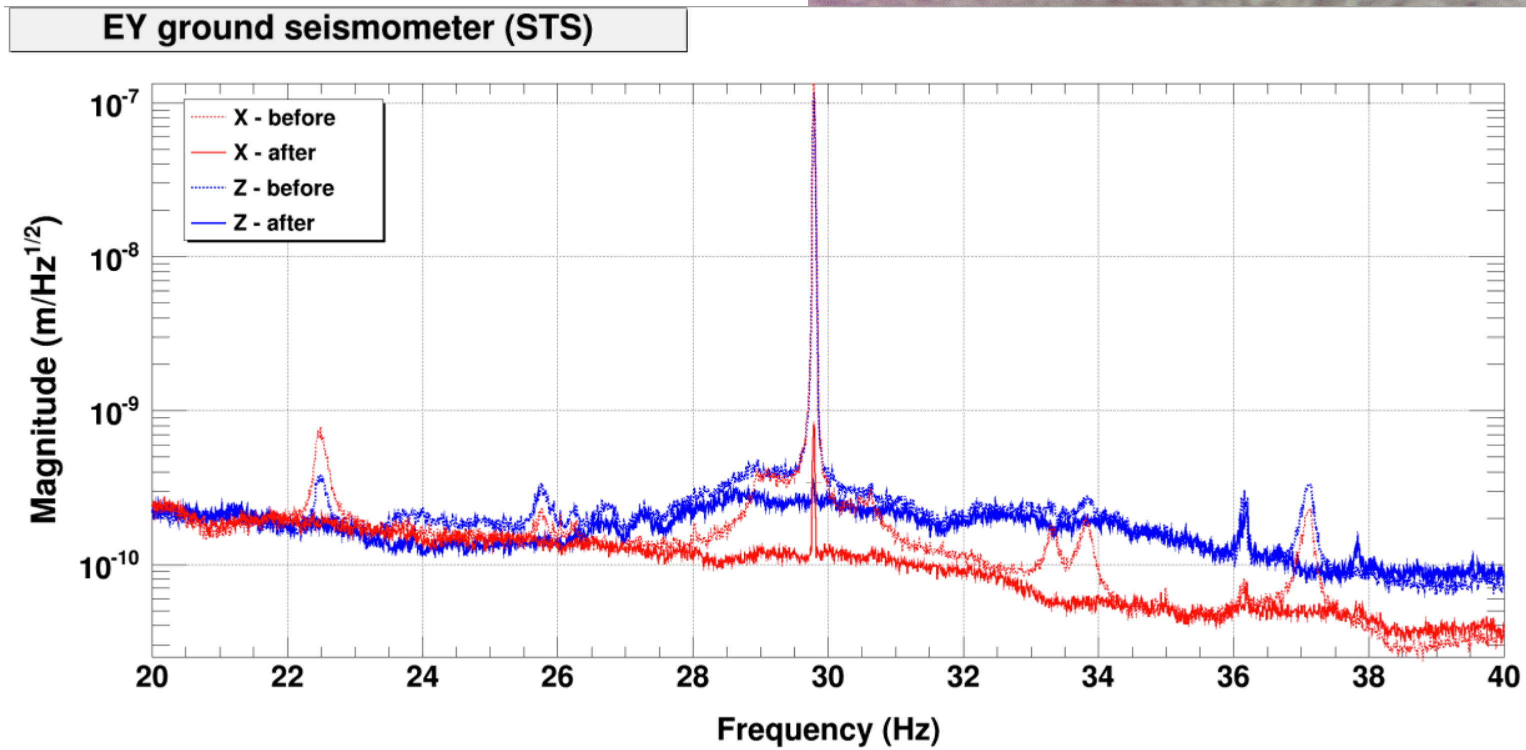
Scattering

- Most significant scattering comes from the output port. We see scattering shelves and broadband couplings.
- Scattering at the input port couples to DARM through intensity and frequency servo
- Scattering in the arm cavities is below current sensitivity curve but might be a problem around 14Hz in the future
- 30Hz line from HVAC might couple through scattering at the end stations
- Scattering at the output port is now being studied

Sources: Y-end scatter

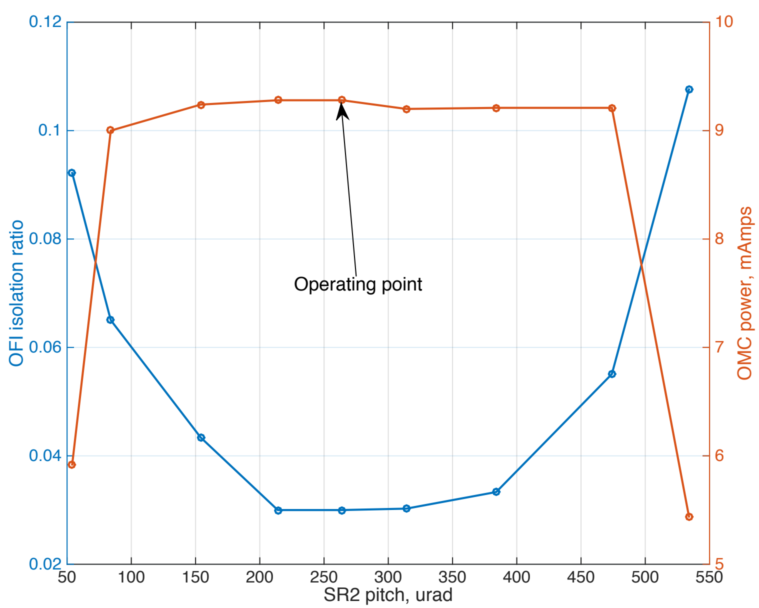
30Hz line coming from Y-end HVAC was successfully eliminated

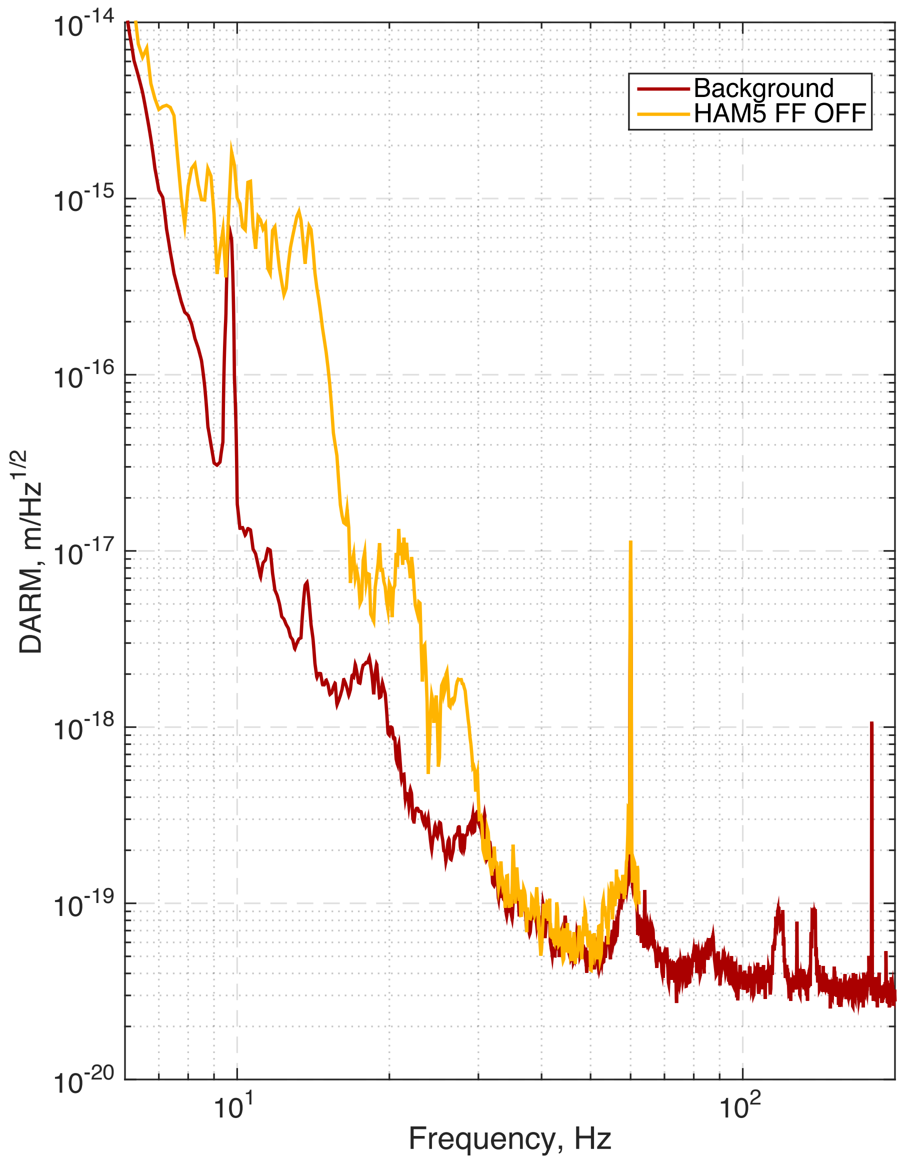




OMC shelves

- Fringe wrapping is seen during winter time when seismic noise is high.
- Field reflectivity measured in full lock is $r = 10^{-4}$ (LLO), $r=10^{-5}$ (LHO).
- Measured OFI isolation ratio at LLO is 3% in power.

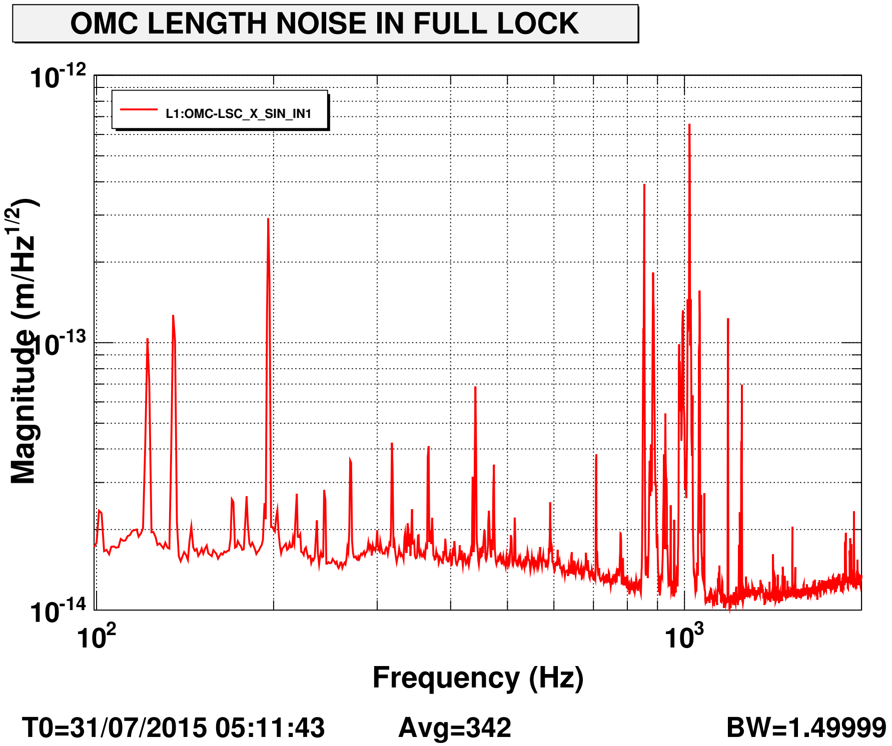


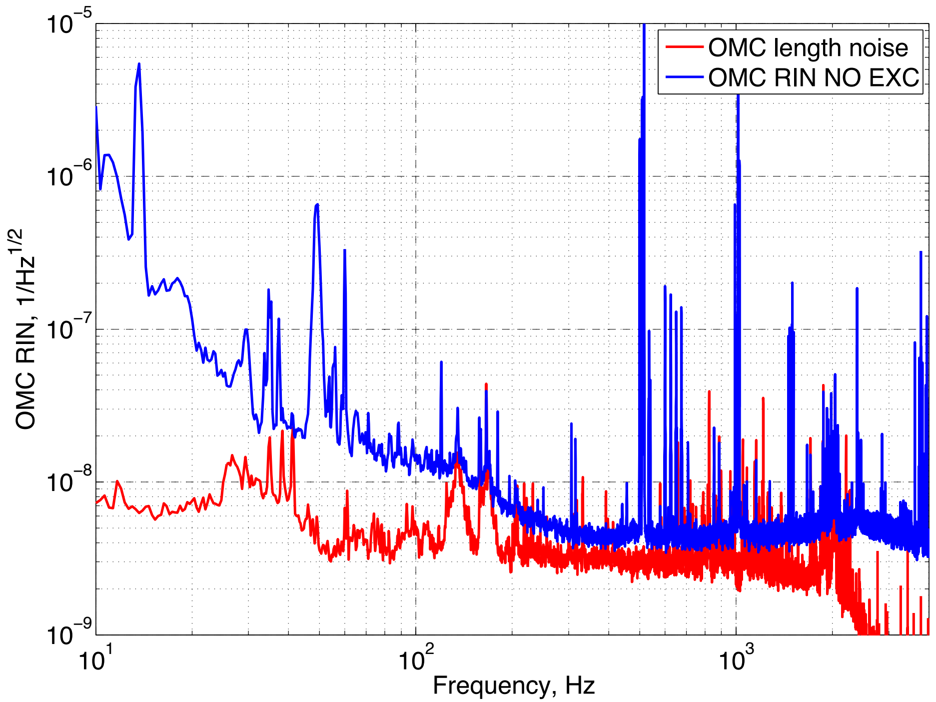


Coupling through OMC length

We see down conversion noise from 1kHz lines down to 100Hz when pumps are engaged near the output port of interferometer

$$RIN(t) \approx \frac{x^2(t)}{a_0^2}$$





Conclusions

- Most significant problems of lock acquisition and noise hunting were discusses in this talk
    1. Arm length stabilization
    2. DRMI lock acquisition
    3. CARM offset reduction
    4. Angular controls
    5. Achieving robustness
    6. Electrostatic actuators
    7. Charging noise
    8. Auxiliary channels
    9. Glitches/whistles/PI
    10. Scattering
- First aLIGO science run will start in Sep 2015
- GO KAGRA!