Advanced LIGO Commissioning Overview

GRITTS Seminar, October 15, 2014

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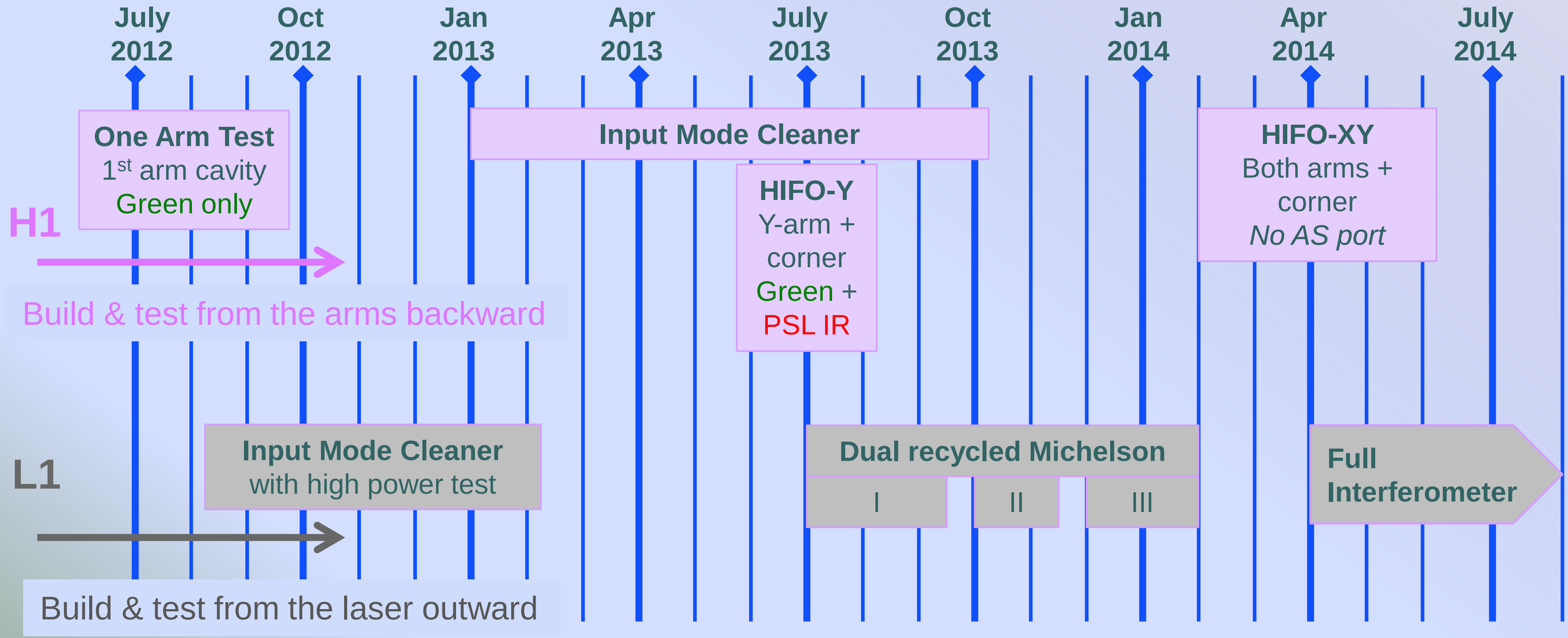
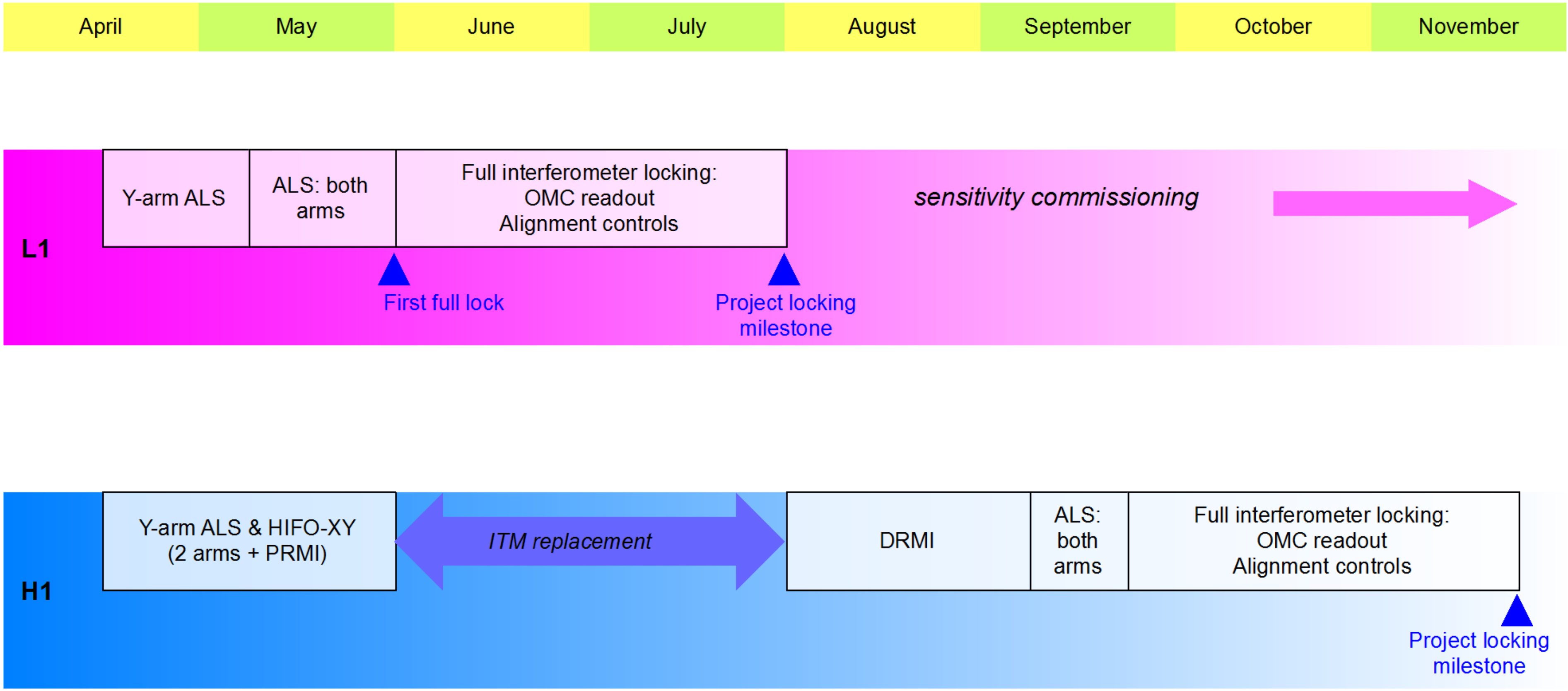
History of Integrated Testing

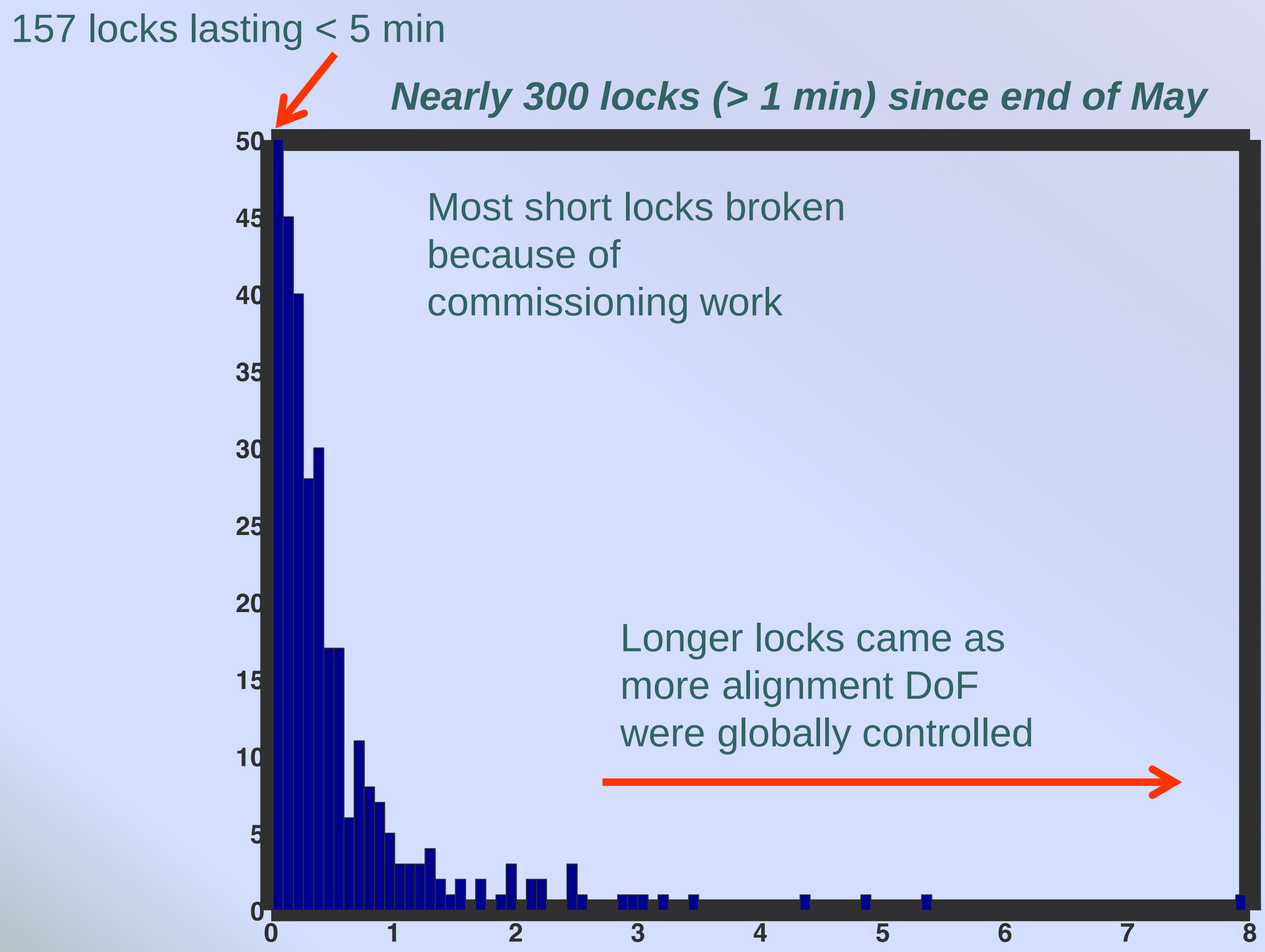
- Integrated testing phases interleaved with installation
- Complementary division between LHO and LLO
  - Designed to address biggest areas of risk as soon as possible
  - H1 focused on long arm cavities; L1 worked outward from the vertex



Current Timeline

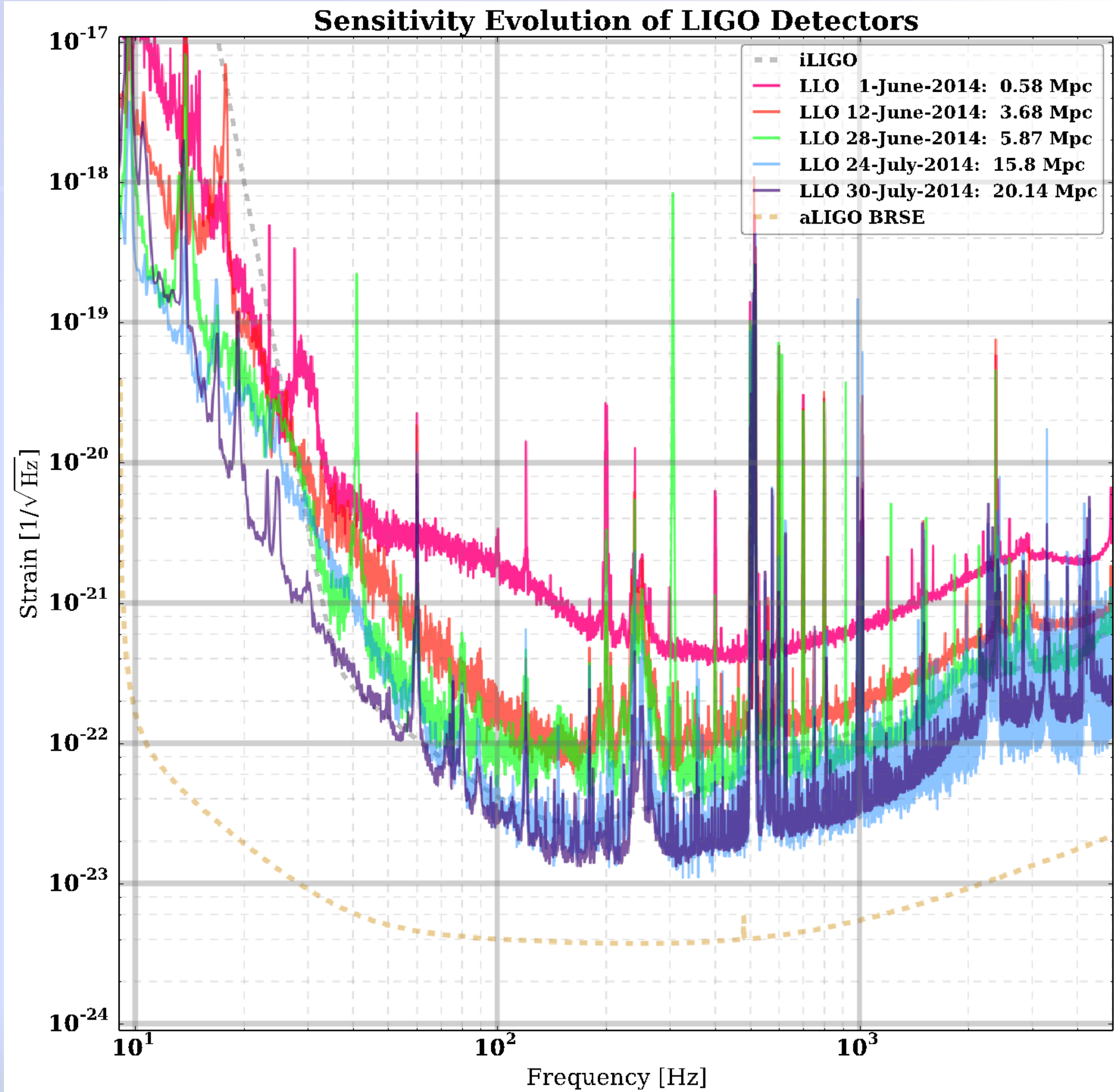


L1 Locking Statistics

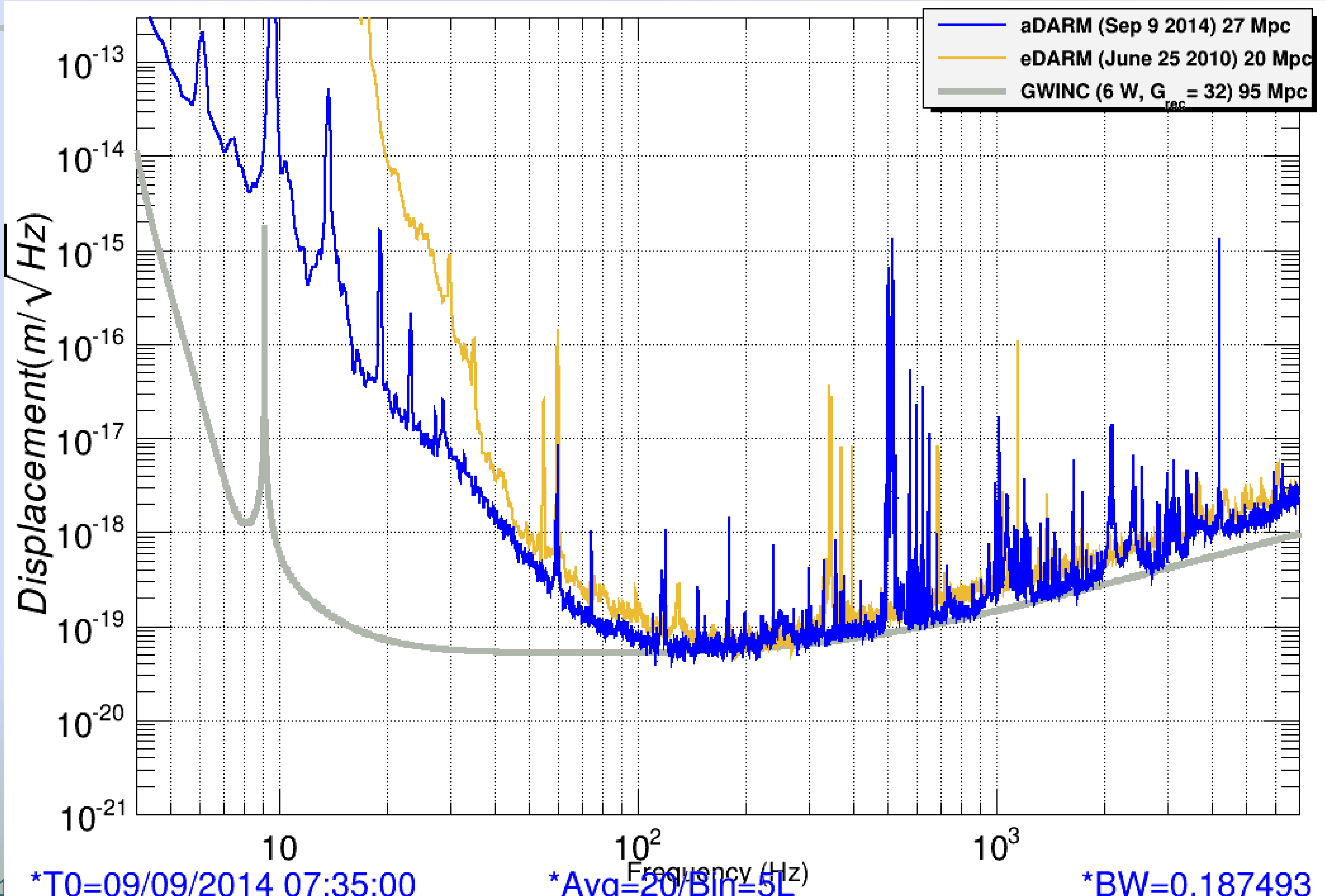


LIGO

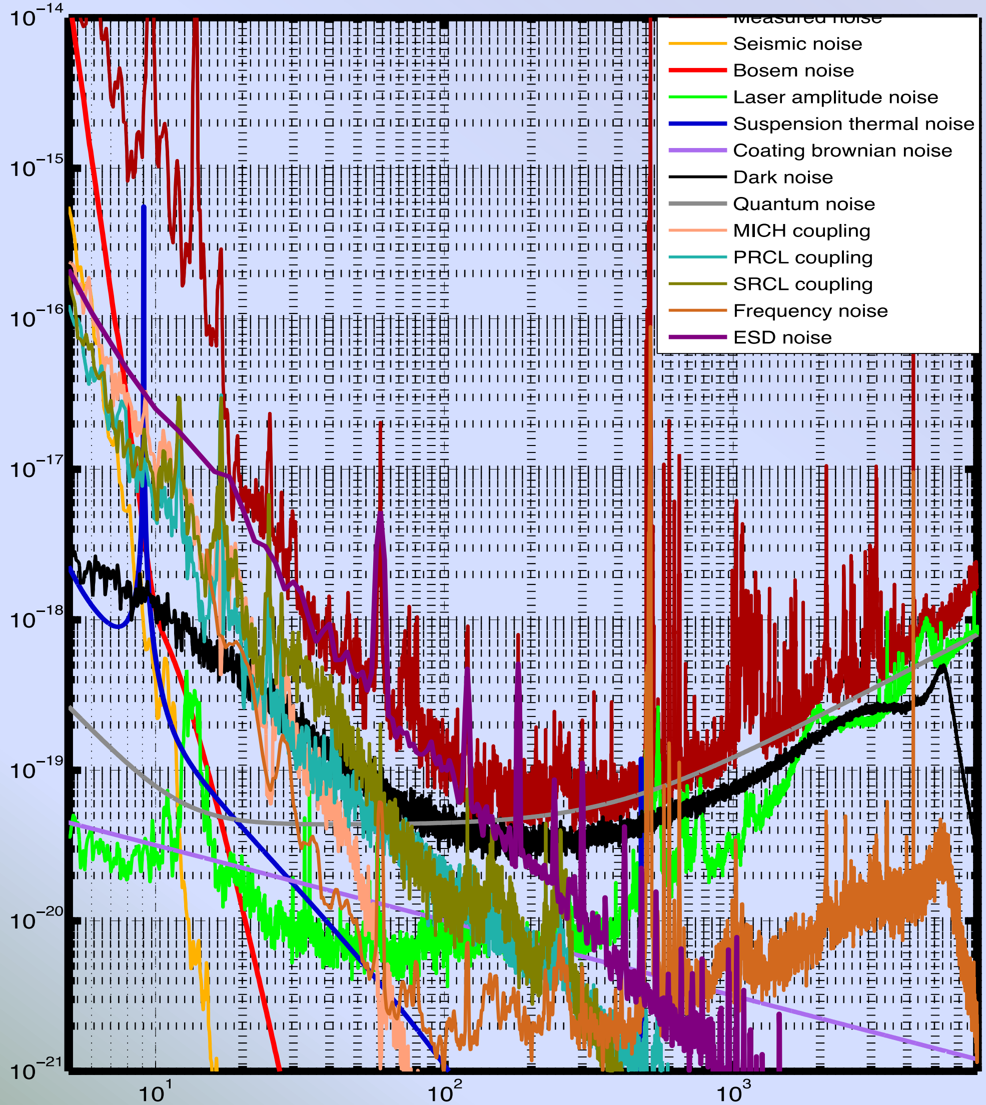
Sensitivity Improvements

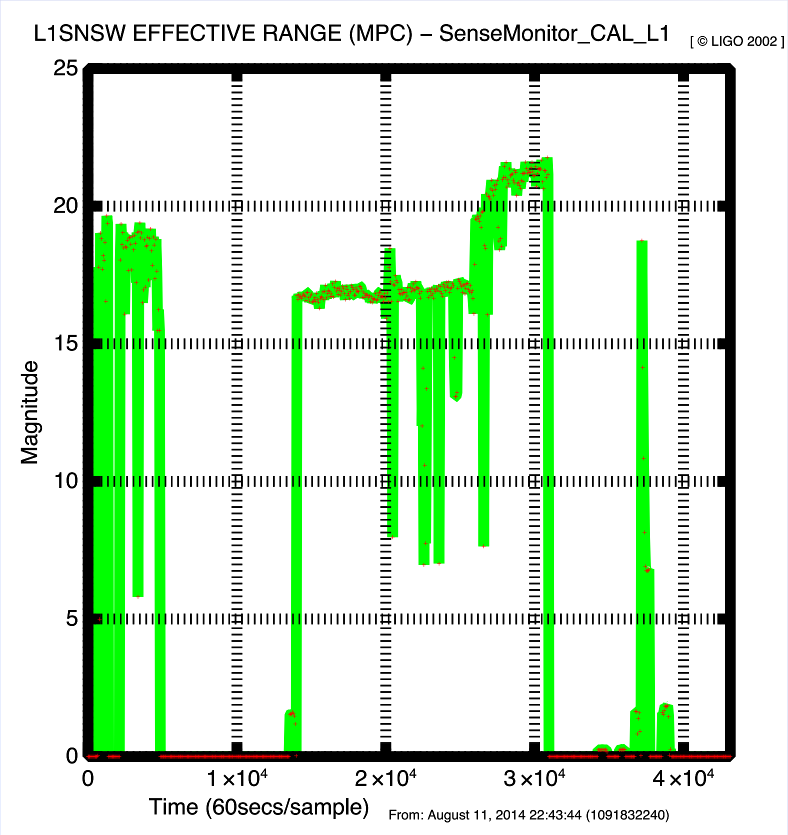


Compare with Enhanced LIGO



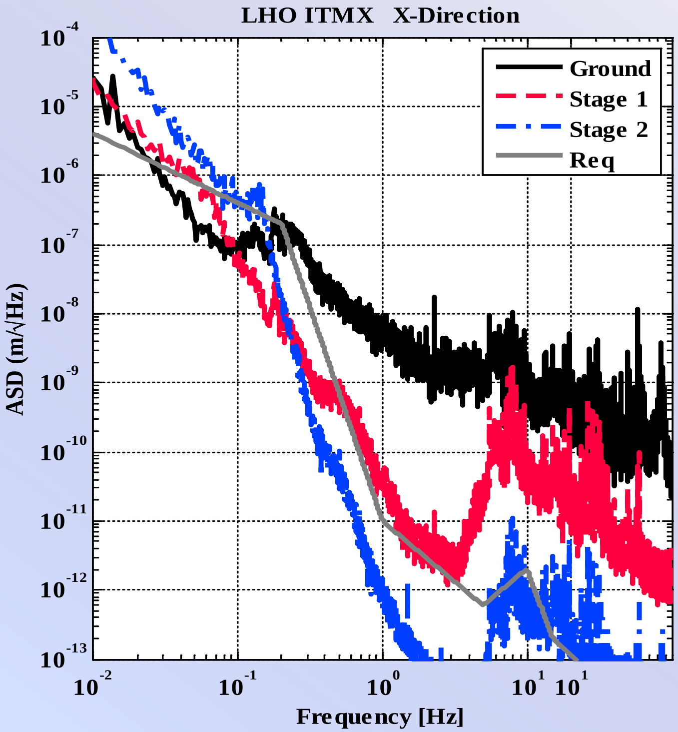
L1 Noise Budget & Range

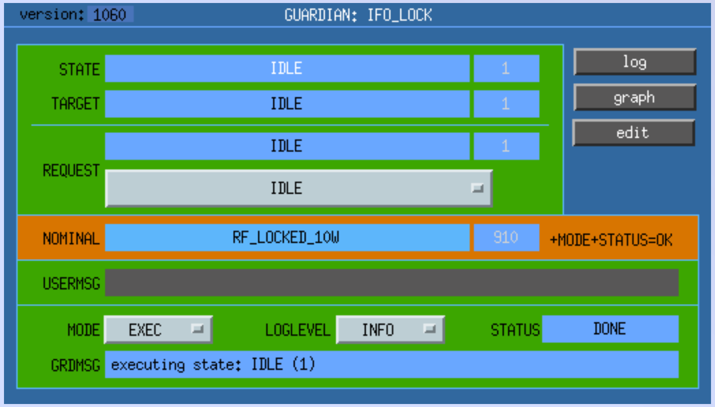




Subsystem highlights

- Pre-Stabilized Laser (PSL) commissioned
- Input Mode Cleaner (IMC) has been fully commissioned
- All seismic isolators (SEI) work as designed and are fully automated
- All suspensions (SUS) work as designed and are fully automated
- Interferometer locking
  - Routine at LLO
  - Immanent at LHO
- Interferometer Automation
  - Significant progress

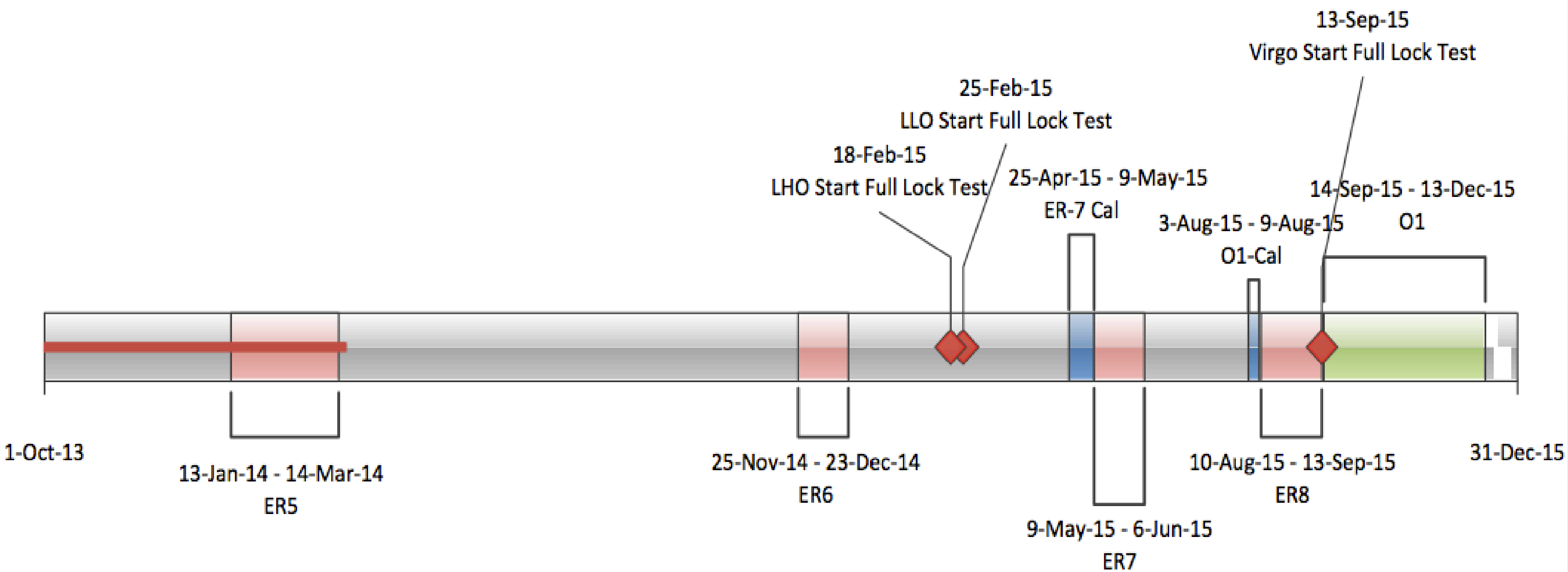




Commissioning Focus on the First Observational Run

- Target sensitivity
  - Binary neutron star coalescence range of 40–80 Mpc, each detector
  - Important frequency band: 20–300 Hz
  - Input laser power: 25 W
- Nominal duration
  - 3 months
- Run start
  - Some time in 2015, perhaps mid 2015

Run Planning

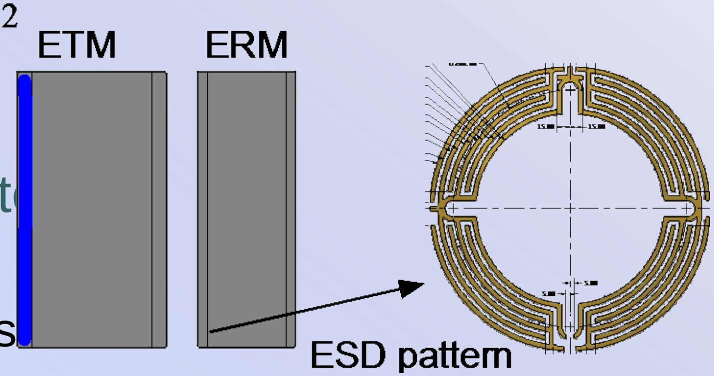


Proposed Timeline to First Observing Run
Worst Case Given Failed ETM Mirror Coating
(based on G1000061, dated 10-Mar-14)

Electro-Static Charging & Actuation

- Each End Test Mass has electro-static actuation, via electrodes on the adjacent reaction mass

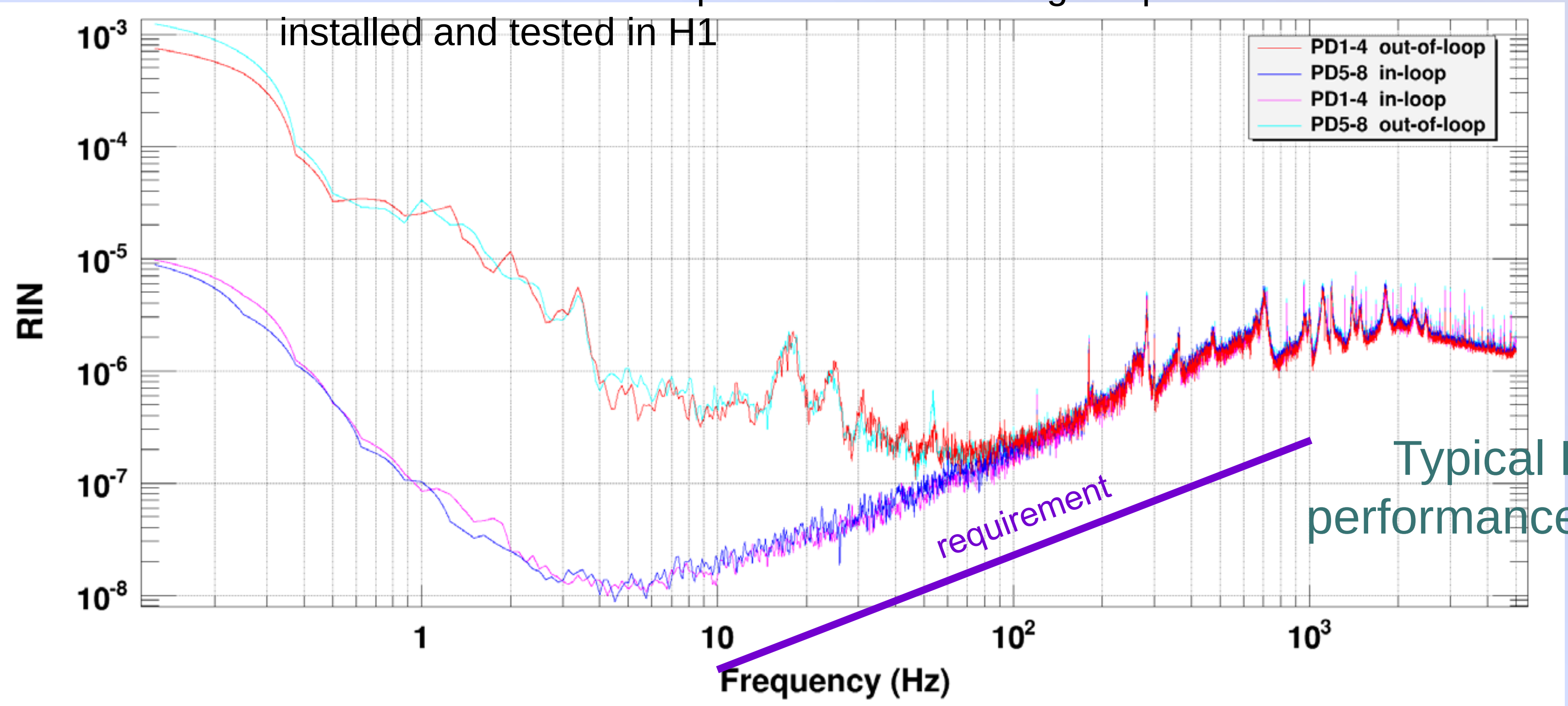
$$Force \propto (V_{bias} - V_{signal})^2$$



- Measurements of force vs bias indicates there is static charge present, equivalent t 10's to several 100's of volts
  - 'static' charge will fluctuate and create nois
  - Charge is not uniform; makes it hard to lower the bias for low noise
- Work in progress: source of charging not clear
  - Discharging procedure with ion-gun
  - But: recharging after a few hours/days
  - Ion pumps?
- Noise from ESD needs to be reduced: need factor of 3-5x for now
  - Via bias reduction, or lower noise signal path, or both

Laser intensity noise & coupling

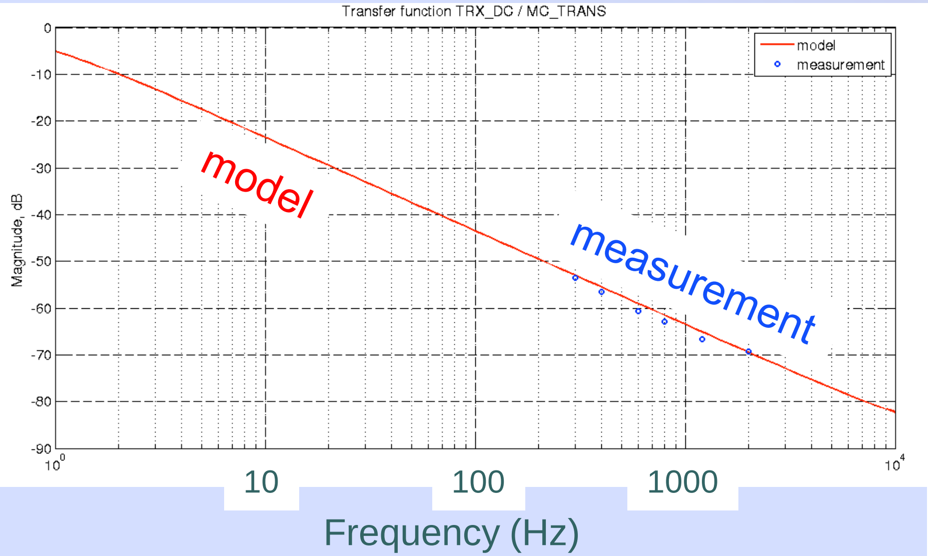
- Laser intensity stabilization is done in 2 stages
  - Second stage detects a sample of the IMC transmitted light in vacuum, to reduce vibration related sensing noise
  - Initial versions of the in-vacuum sensor had several design & assembly problems; essentially non-functional
  - A new version that incorporates several design improvements has been installed and tested in H1



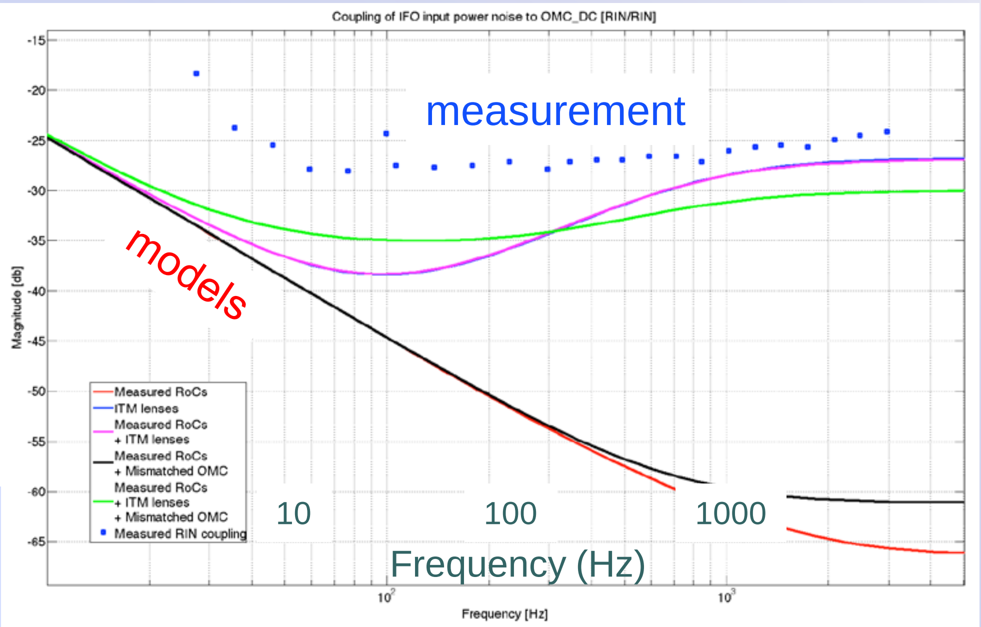
Typical ISS performance on H1

Intensity noise coupling

Transfer function to arm cavity shows expected filtering:



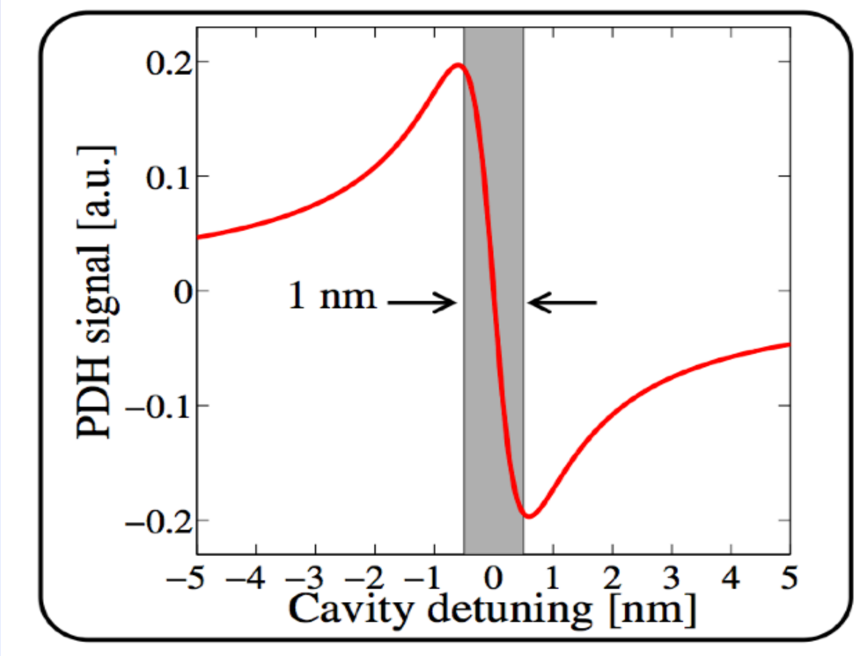
Transfer function to OMC readout does not …



- Increased RIN coupling is due to the carrier higher order modes creates at the dark port by the ITM lenses
- OMC matching plays a significant role, since it will convert higher order modes in input to TEM00 mode in output

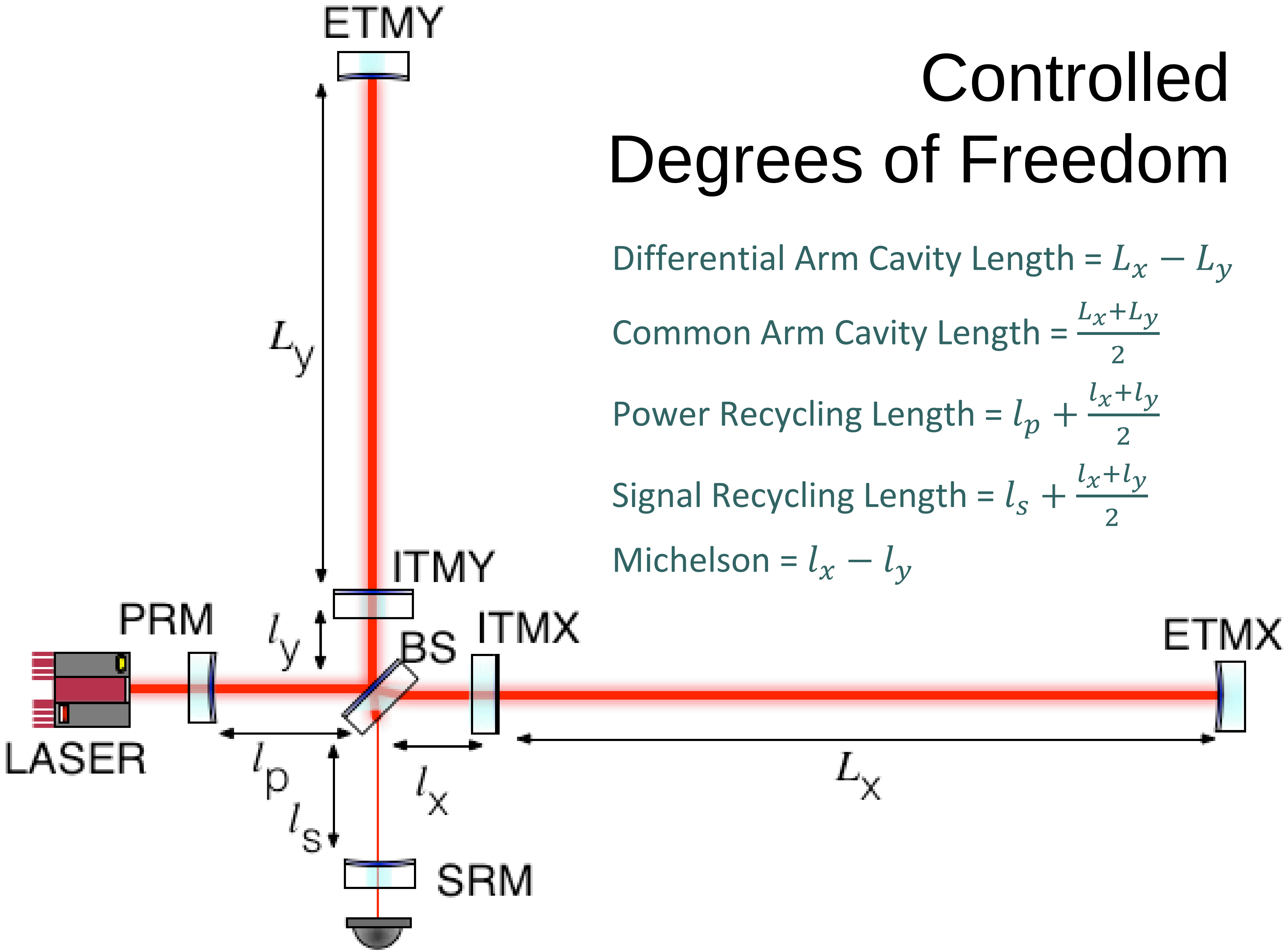
Challenges of Lock Acquisition for Advanced LIGO

- Narrow locking range
- Low noise,
  weak actuators
- Advanced LIGO has
  5 length DOFs:
  the cavities are formed
  by the same optics,
  so the five DOFs are coupled
- Locking one cavity can contaminate the error signal
  used to lock another cavity



LIGO-G1300524

Controlled Degrees of Freedom



Differential Arm Cavity Length = $L_x - L_y$

Common Arm Cavity Length = $\frac{L_x+L_y}{2}$

Power Recycling Length = $l_p + \frac{l_x+l_y}{2}$

Signal Recycling Length = $l_s + \frac{l_x+l_y}{2}$

Michelson = $l_x - l_y$

Arm Length Stabilization System

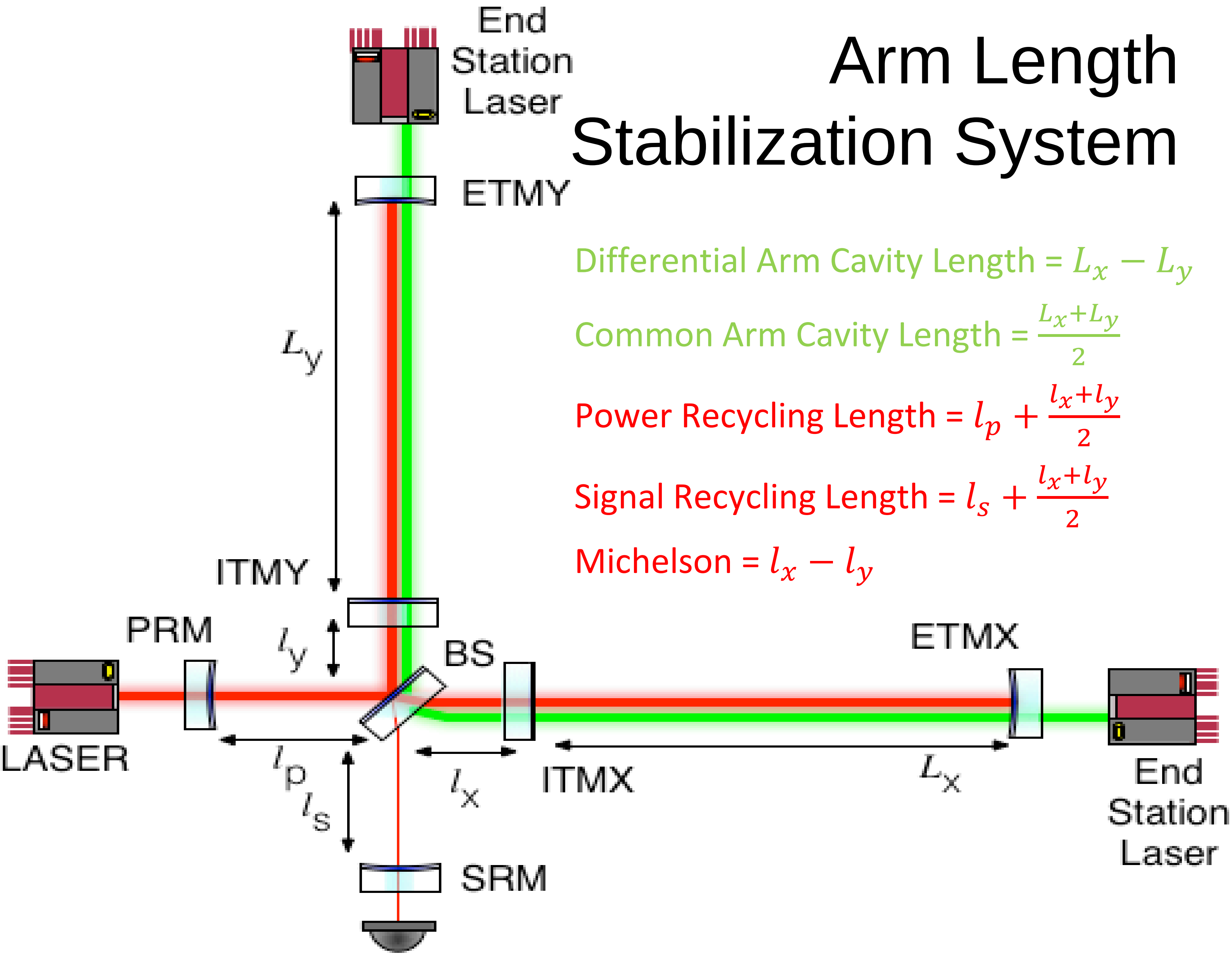
Differential Arm Cavity Length = $L_x - L_y$

Common Arm Cavity Length = $\frac{L_x + L_y}{2}$

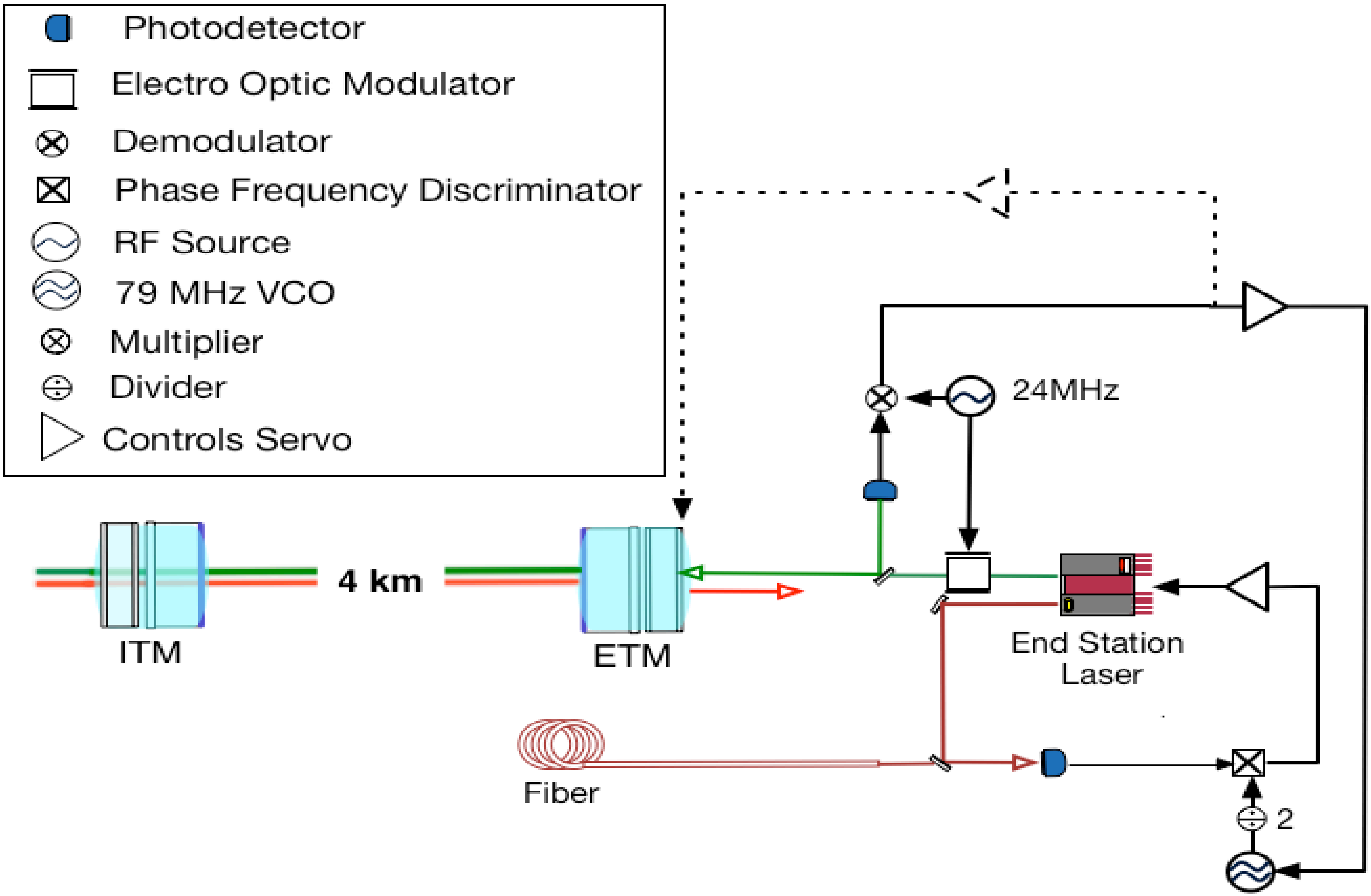
Power Recycling Length = $l_p + \frac{l_x + l_y}{2}$

Signal Recycling Length = $l_s + \frac{l_x + l_y}{2}$

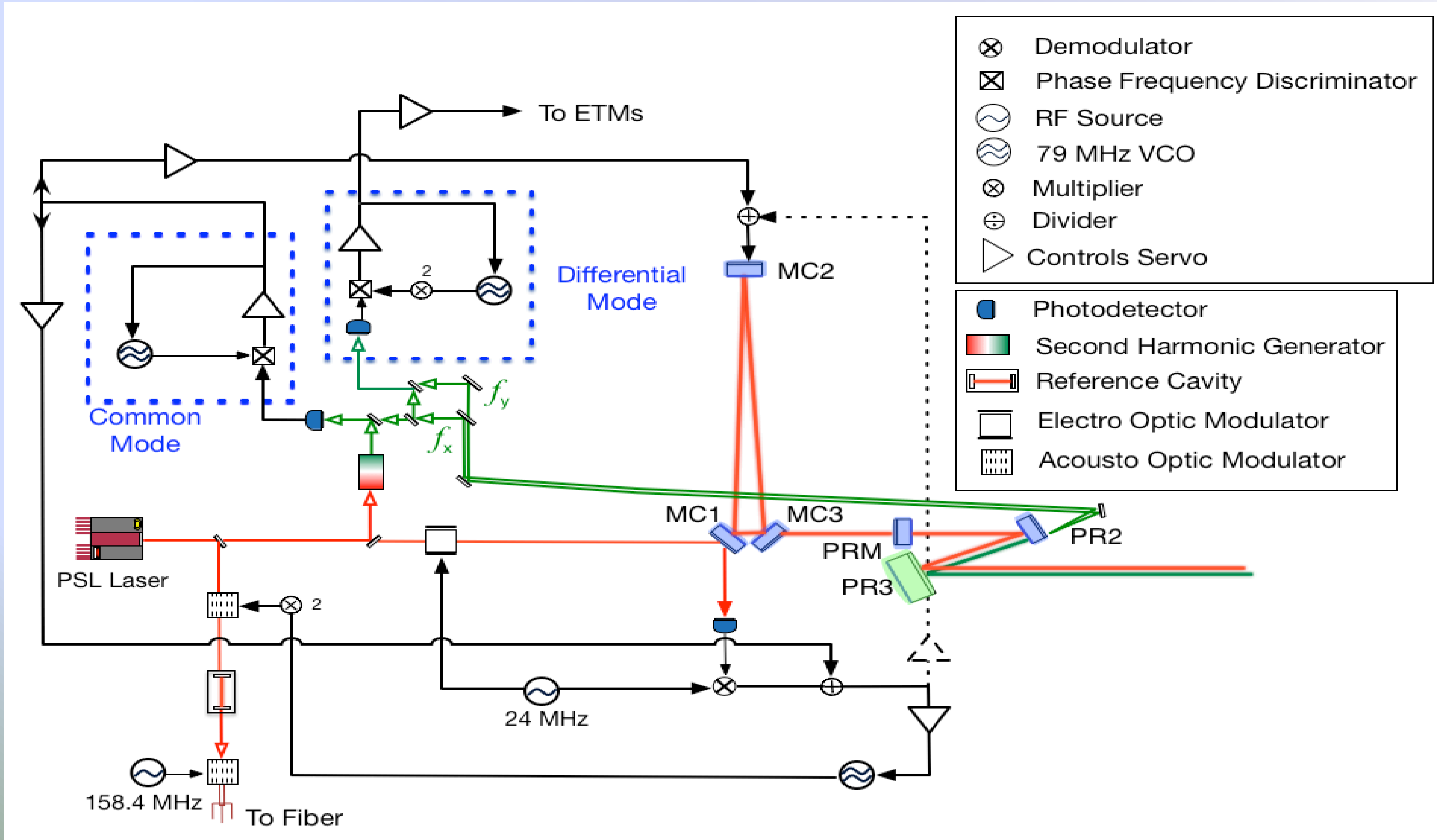
Michelson = $l_x - l_y$

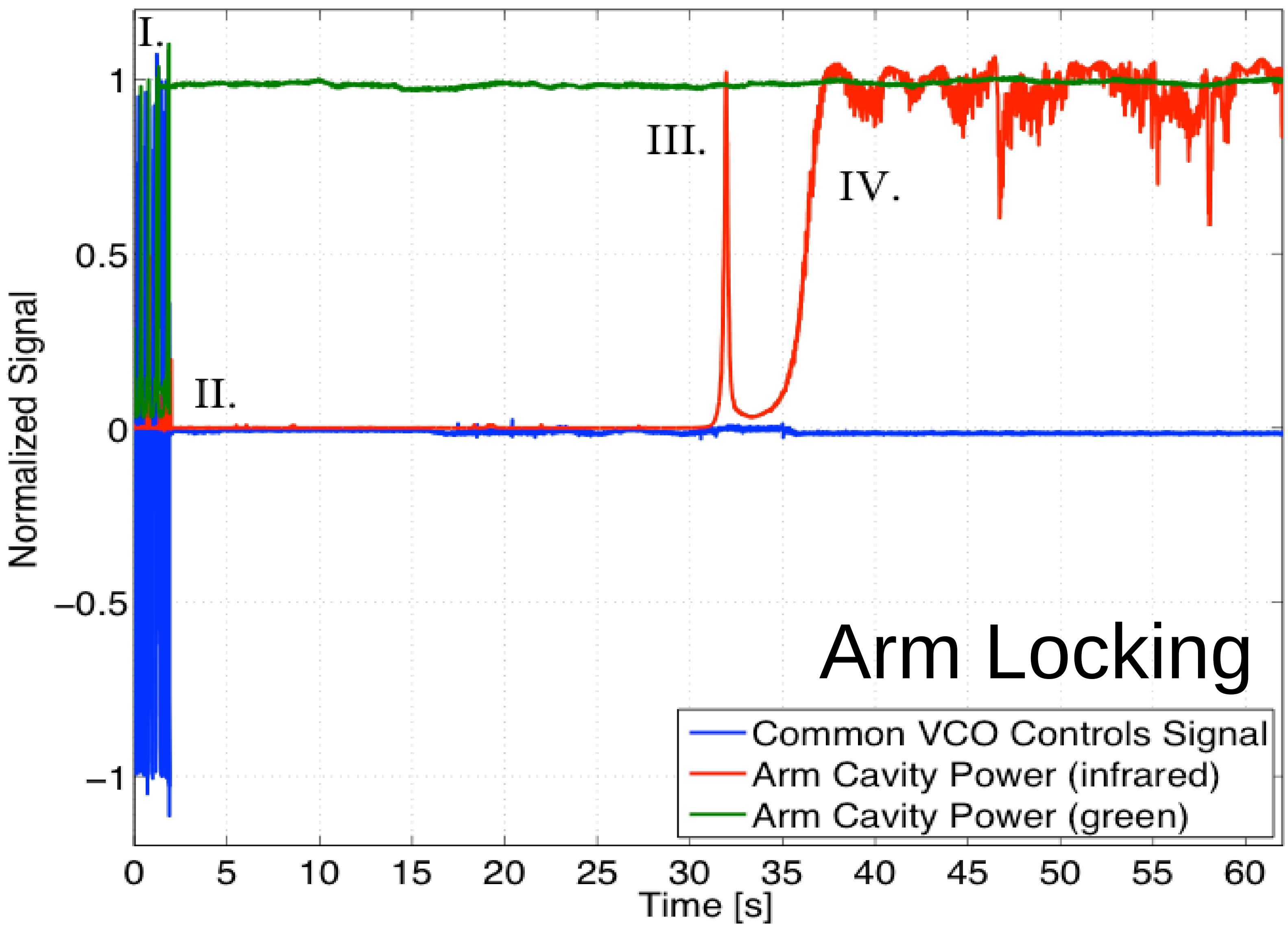


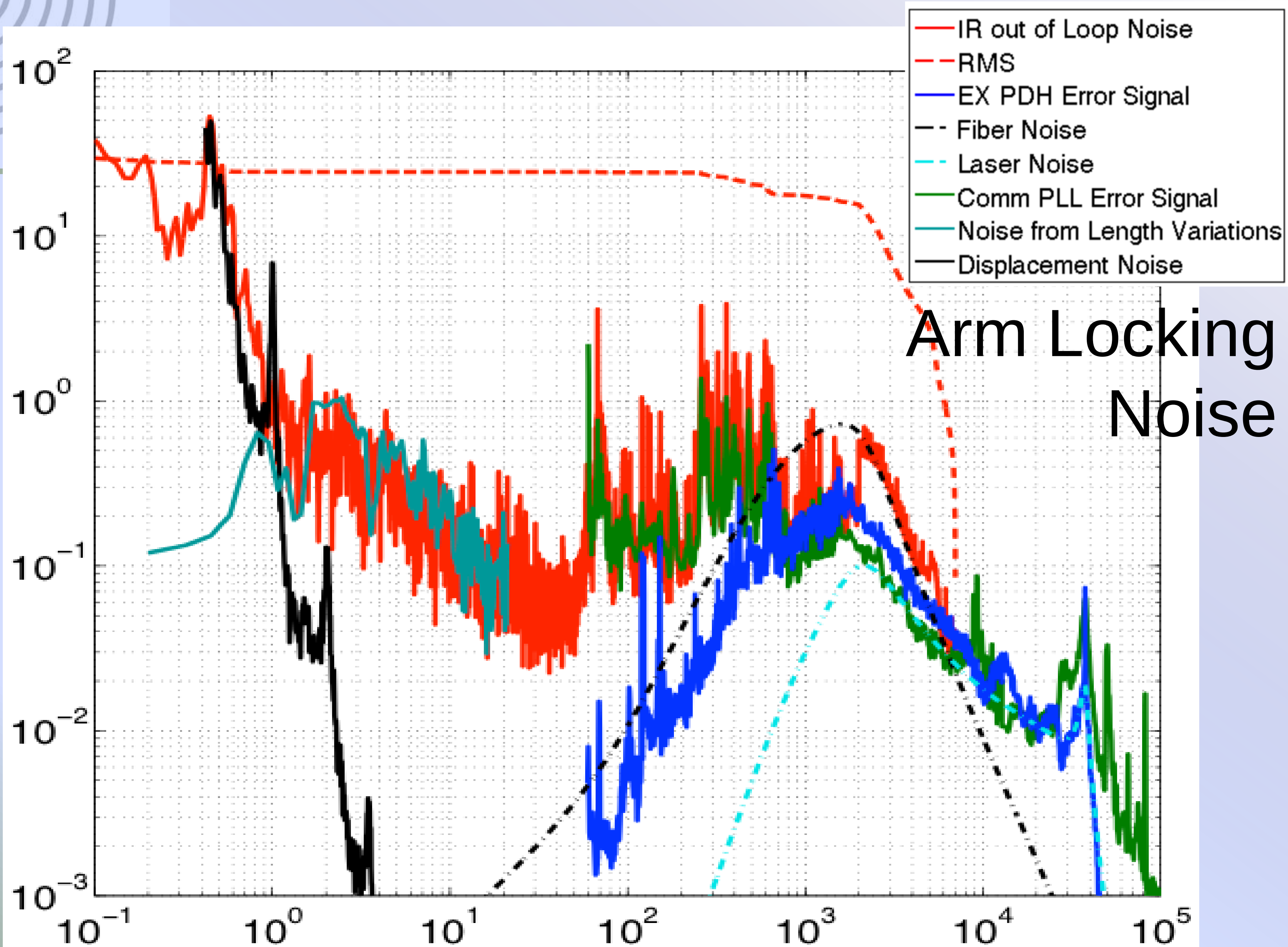
End Station Servos



Common Mode Control

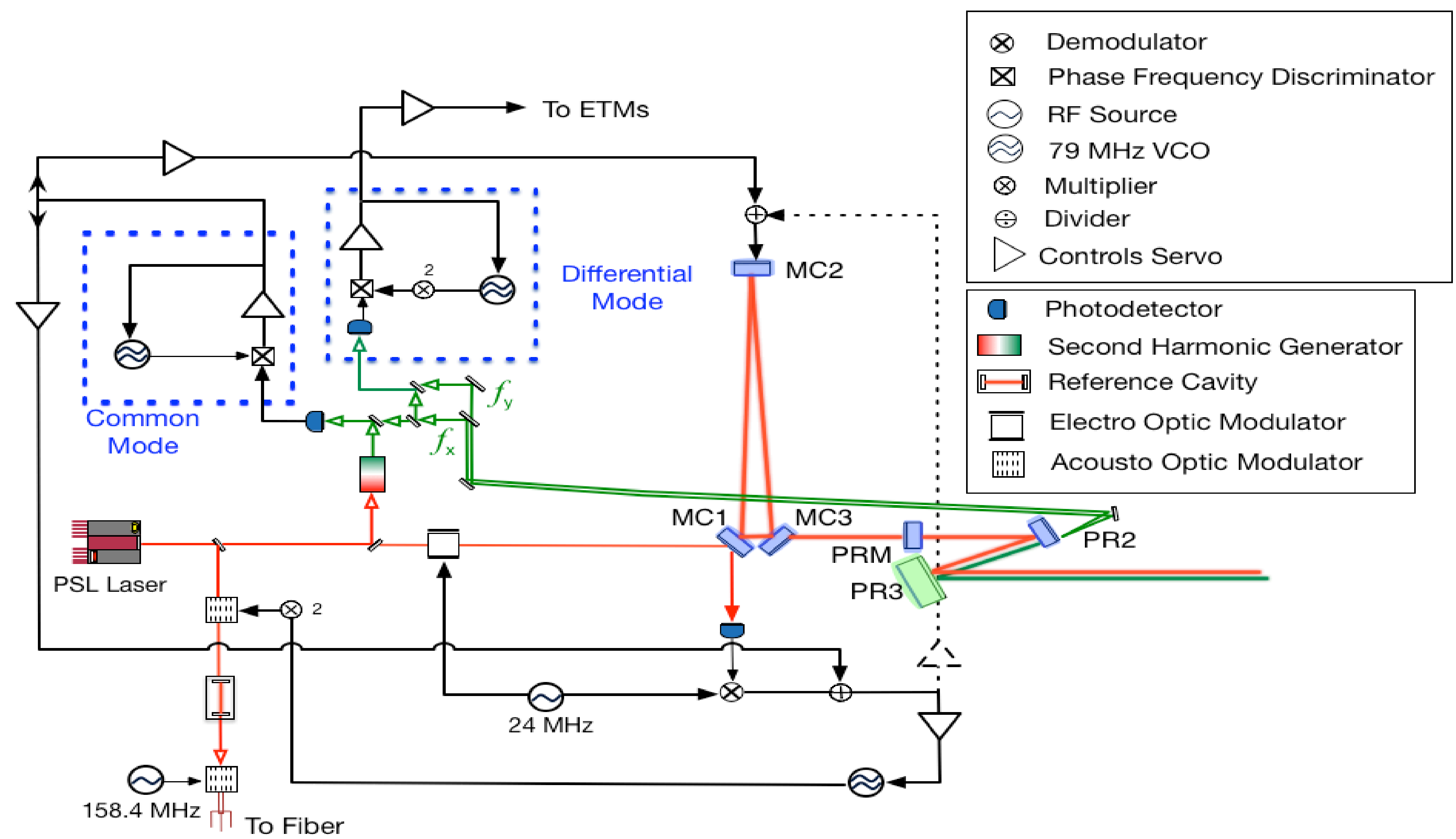



Arm Locking
I.
II.
III.
IV.
Normalized Signal
Time [s]
Common VCO Controls Signal
Arm Cavity Power (infrared)
Arm Cavity Power (green)

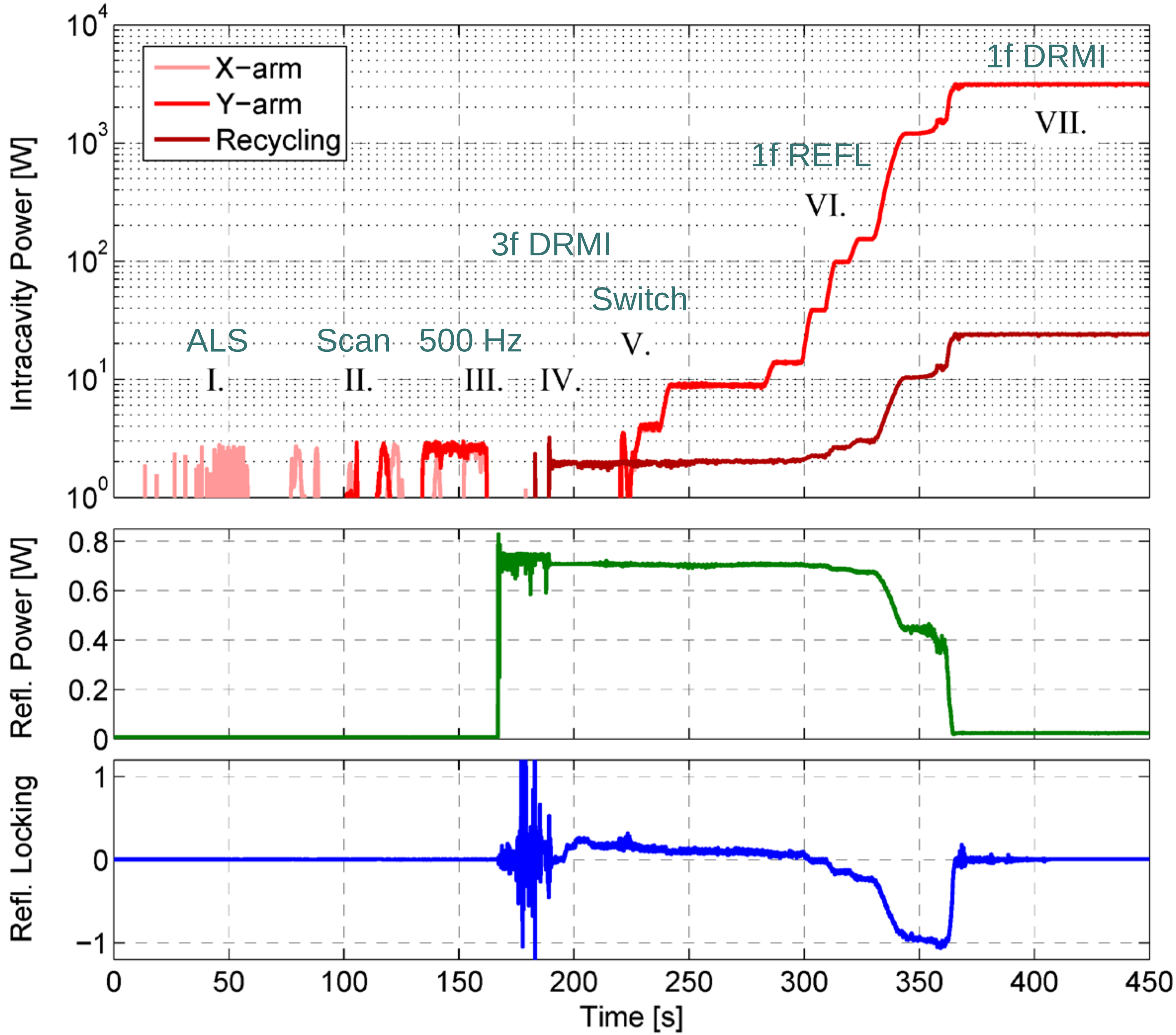


Arm Locking Noise

Differential Mode Control



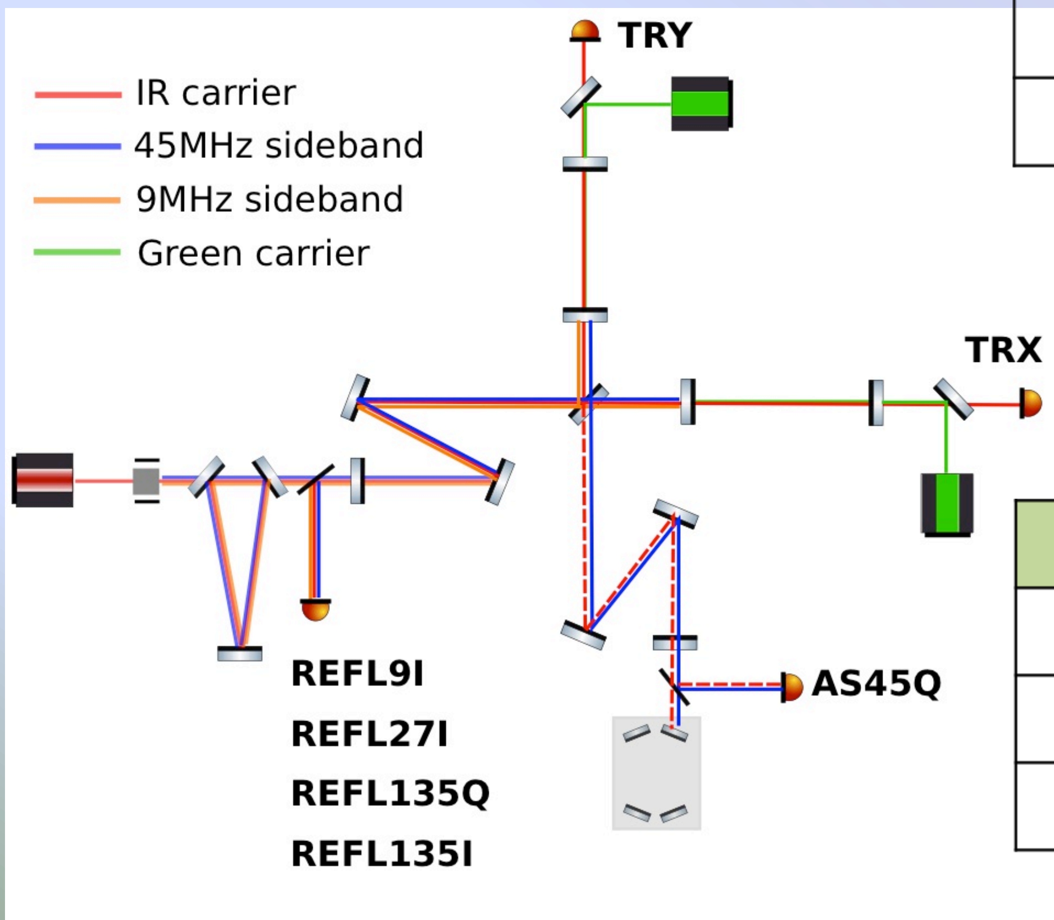
Full Lock Sequence



Common Arm Offset Reduction

CARM offset	DARM signal	Actuation
10nm - 100pm	ALS DIFF	ETMX - ETMY
100pm - 0pm	AS45Q	ETMX - ETMY

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



Should be able to use AO from beginning

DRMI Length Control

	Error signal	Actuation
PRCL	REFL_27_I	PRM, PR2
MICH	REFL_135_Q	BS
SRCL	REFL_135_I	SRM, SR2

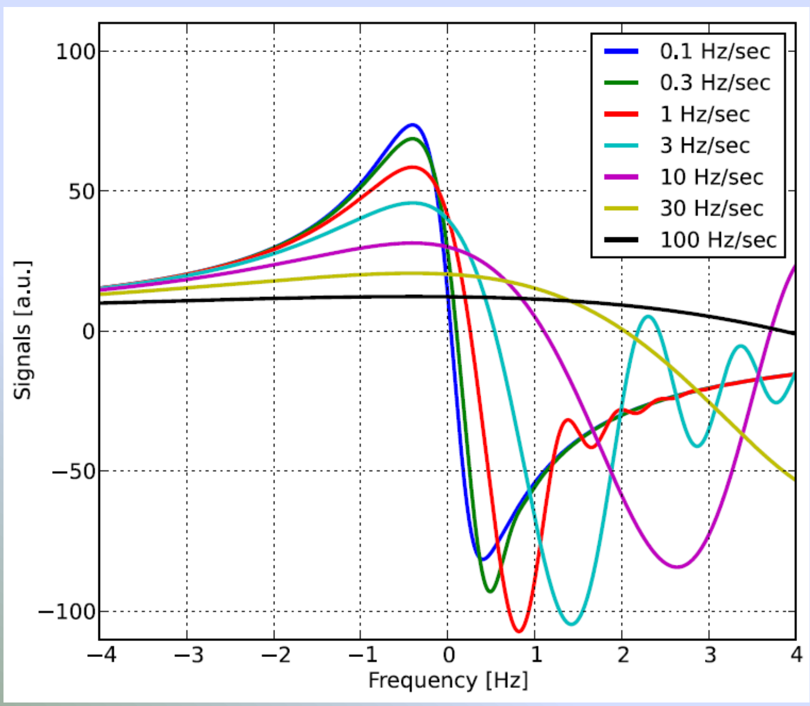
Exact Frequencies

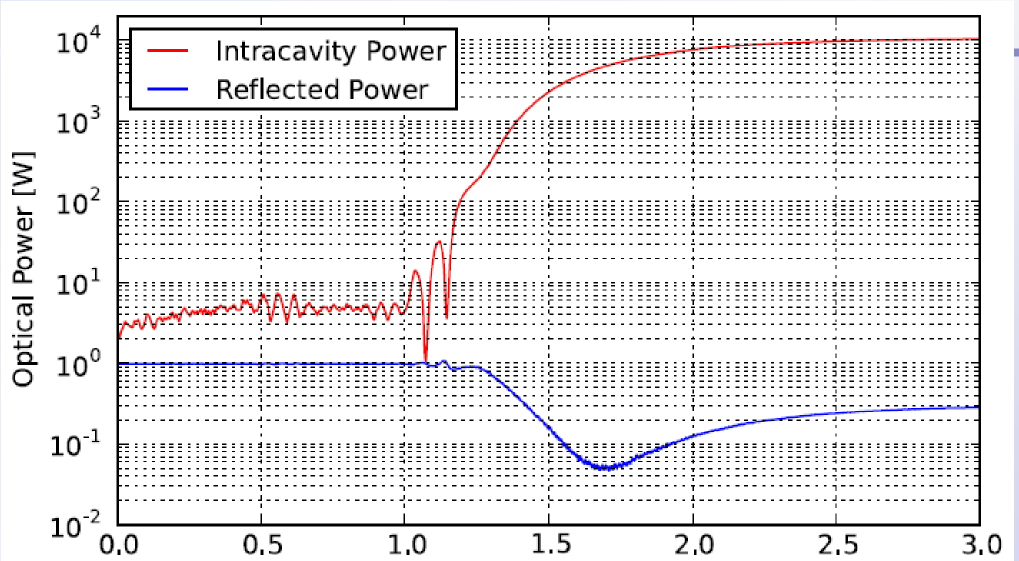
Location	Freq. (MHz)	Deviation	Comment
Main Laser	0	$2\Delta f_{main}$	set by main laser VCO
Reference Cavity	316.8	fixed	frequency reference
Fiber	0	fixed	shifted back
X-arm laser	-78.92	Δf_x	down-shifted
Y-arm laser	78.92	Δf_y	up-shifted
Differential beat note	157.84	$\Delta f_y - \Delta f_x$	controlled to zero
Common beat note	-78.92	$2\Delta f_{main} - \Delta f_x$	offset from resonance

- All frequency measured ±1 Hz
- Ambiguous: 1 IR resonance for 2 GR resonances
- Depends somewhat on green alignment

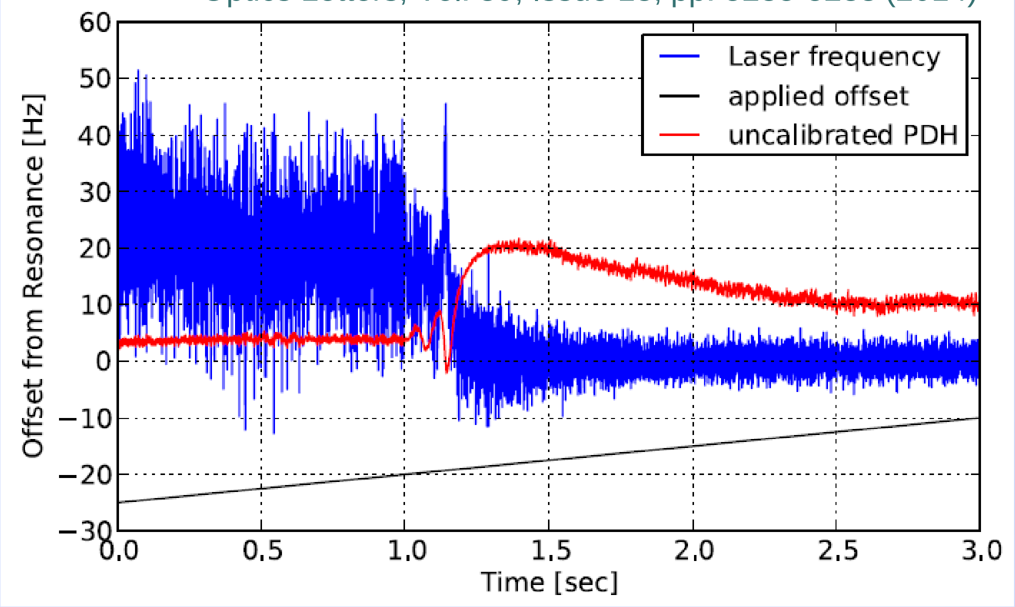
Self-Amplified Lock

- Combine a “noisy” wide range sensor (ALS) with good narrow range sensor (REFL)
- Once cavity power builds up, REFL gain will dominate





Optics Letters, Vol. 39, Issue 18, pp. 5285-5288 (2014)

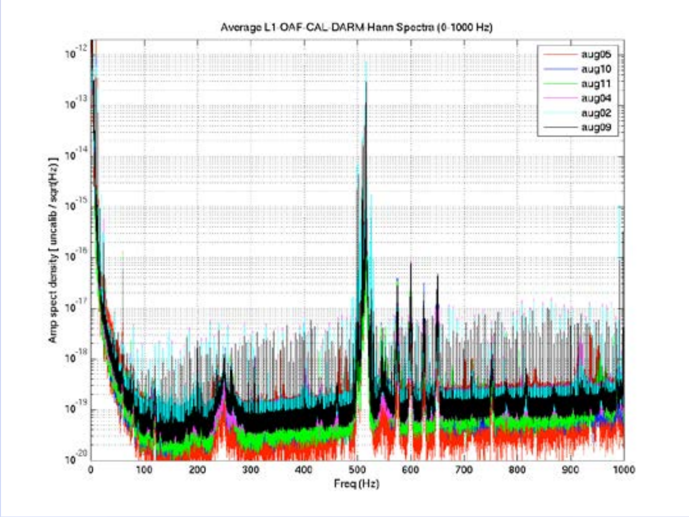


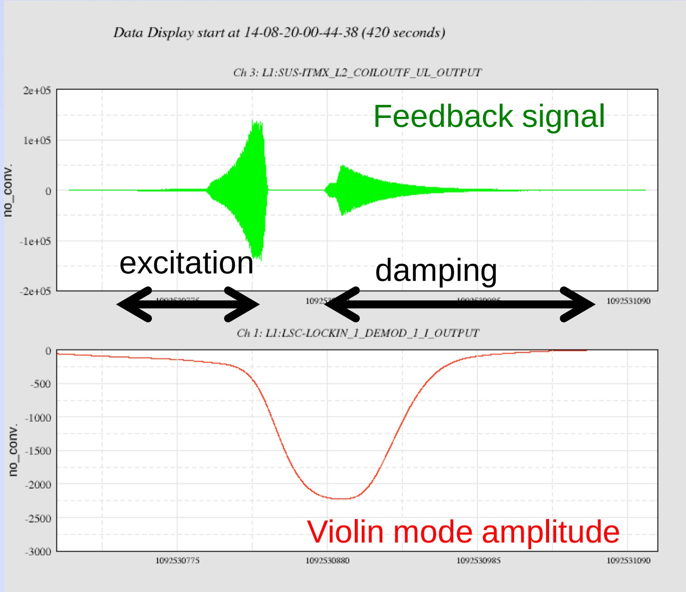
In Conclusion

- Initial commissioning has progressed quickly
  - The only significant delay was due to the green coating issue.
  - Arm Length Stabilization successfully decouples arm cavities from the interferometer for lock acquisition.
  - Arm Length Stabilization noise well understood.
  - Advanced LIGO can be locked with Arm Length Stabilization!
- Next up: get H1 caught up with L1
  - H1 will test some ideas for improving the locking scheme
  - H1 has the improved second stage detector for the laser intensity stabilization in place
  - Full lock immanent
- L1 has reached the Advanced LIGO project milestone for integration: 2 hour lock

Suspension violin modes

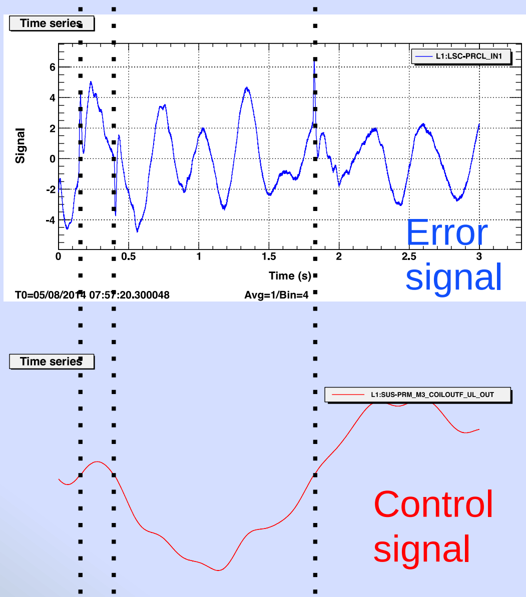
- Test mass suspension violin modes, at 500 Hz, are excited several orders of magnitude above thermal
- We do not understand why they are vibrating so much
- Prevents us from engaging full whitening on the GW readout channels: excess ADC noise
- Need to actively damp the modes, using interferometer signal to feed back to the quad penultimate stages
  - Should be doable, but it is tricky: 16 very high Q modes in a narrow frequency range
  - Some progress recently on L1 with the DRMI



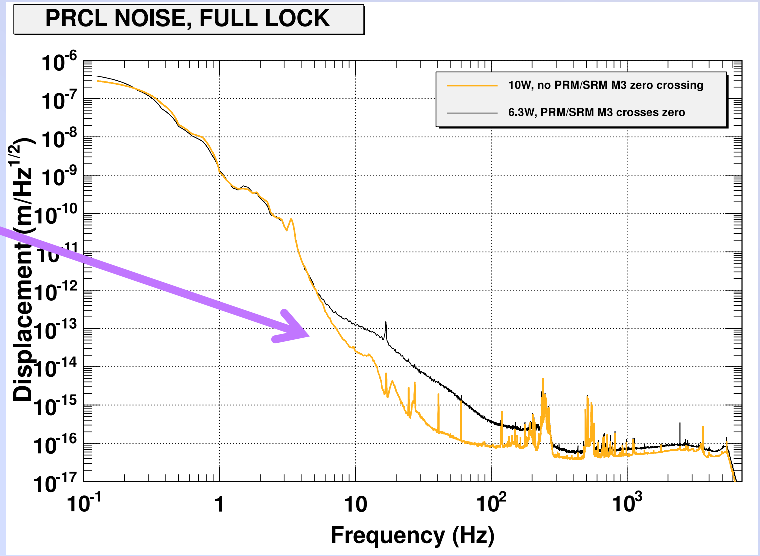


Glitches from digital-to-analog converters

- DAC transitions are accompanied by a step
  - Largest at the zero-crossing (all bits flip), next largest at ¼ & ¾ of full scale
  - DAC needs calibration after restart!
- Observed to create low frequency noise in the recycling cavity signals



Noise mechanism not completely clear

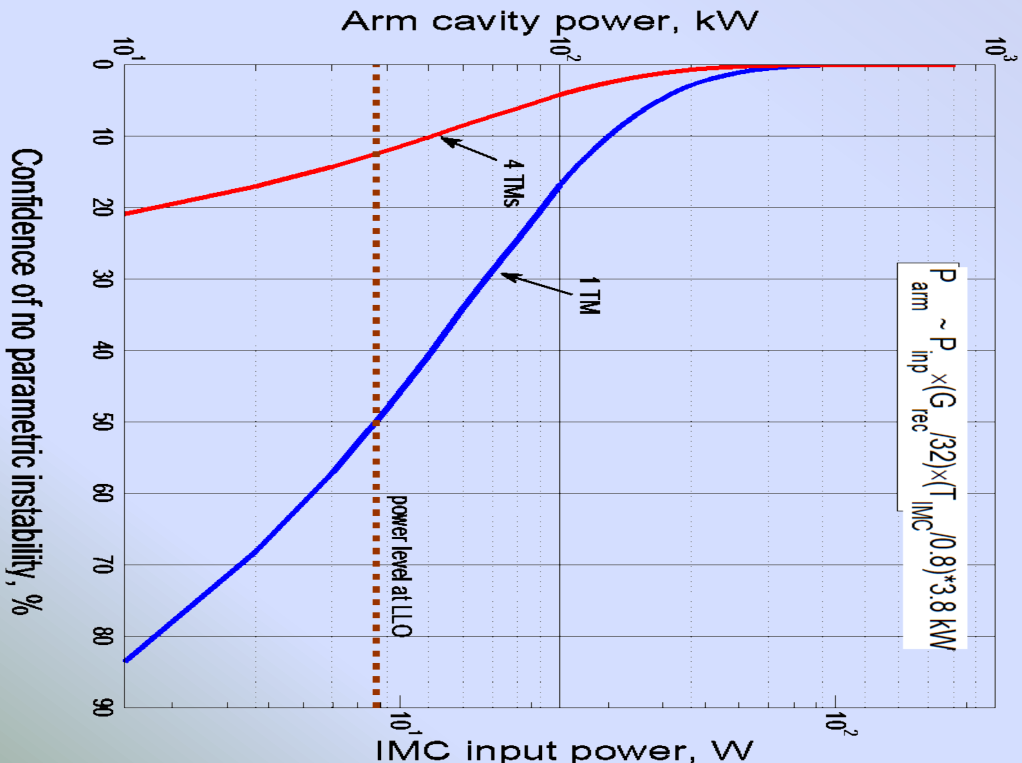


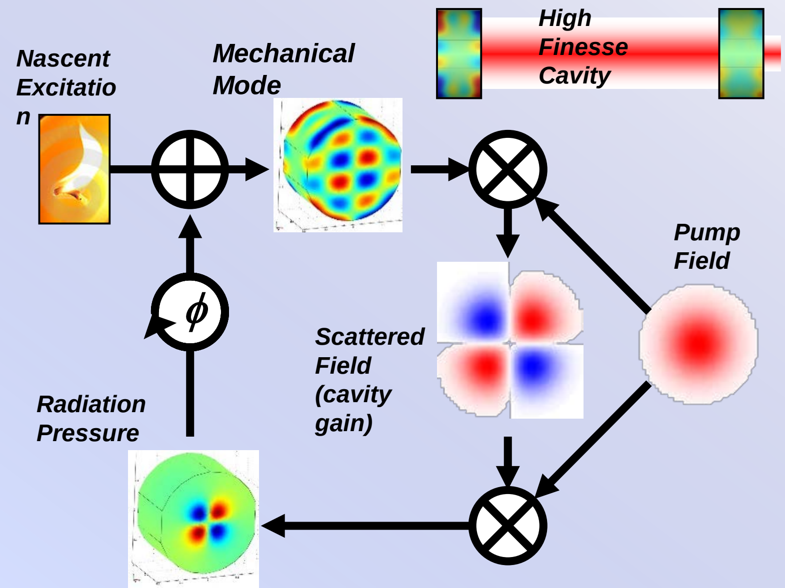
Solutions:
- Offsets on control signals
- Low pass filters after DAC

- Also an issue for ESD feedback, at ¾ range transition

Parametric Instabilities

Combination of high stored optical power and low mechanical loss could cause an instability

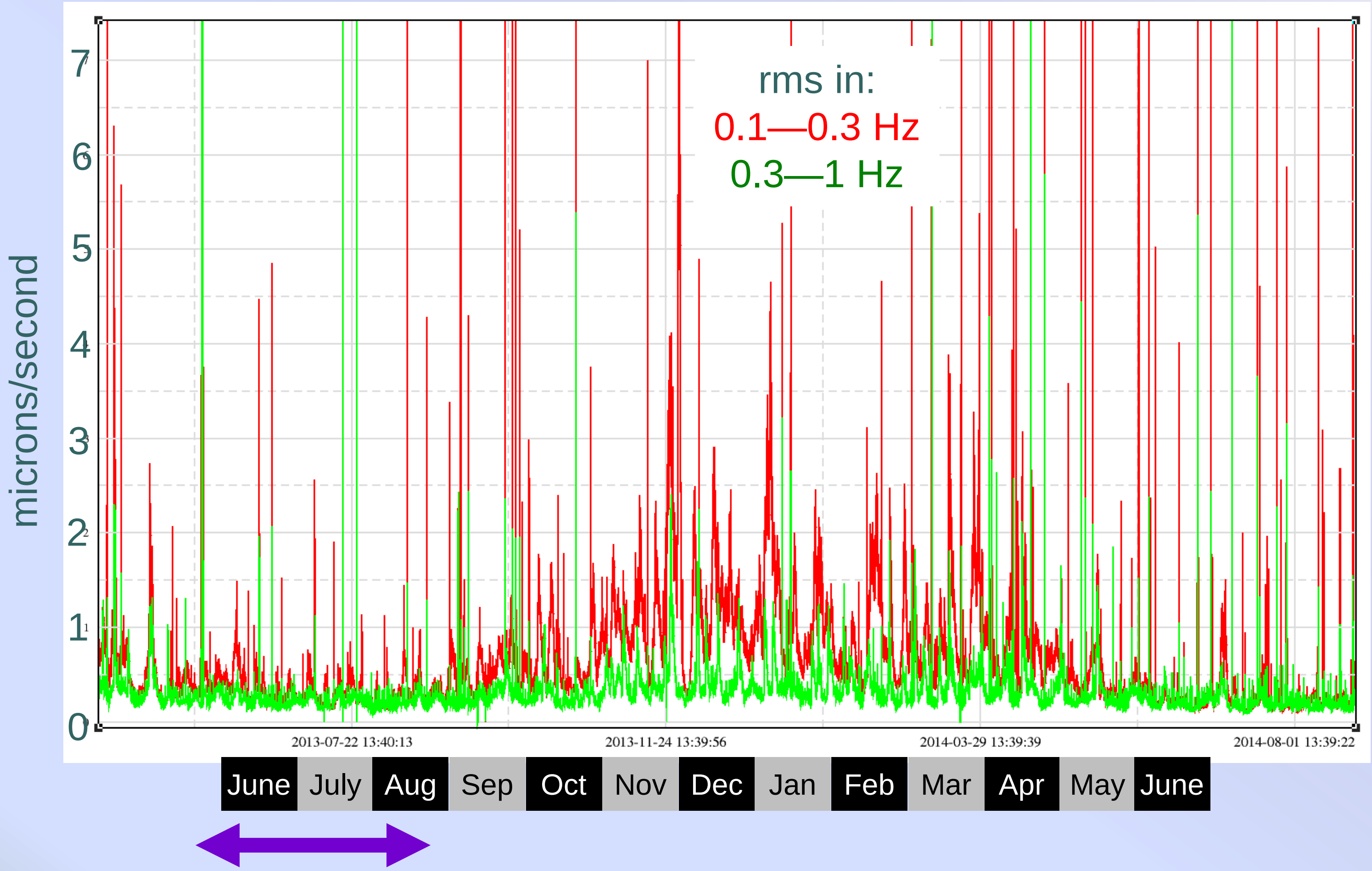




- Latest analysis (S Gras) suggests we are more prone to PI than we thought
  - MC simulation with distribution of RoC's and acoustic mode frequencies of test masses
- Start to look for risky modes even before they become unstable (UWA idea)

Seasonal variability of ground motion

LLO ground motion over 500 days



So far, commissioning has been during periods of low microseism

Impact of higher ground motion

- Arm Length Stabilization could suffer
  - Arm cavity finesse at 532 nm is much lower than desired:
    - ETMs have too large a transmission at 532 nm
    - Finesse: 5-10 (actual) vs. 100 (desired)
  - Makes the cavity locking point much more sensitive to alignment and alignment fluctuations
- Replacing the ETMs could be the best solution
  - ETMs now coming out of LMA have the right 532 nm transmission
  - Downside would be a 2 month hit for replacement