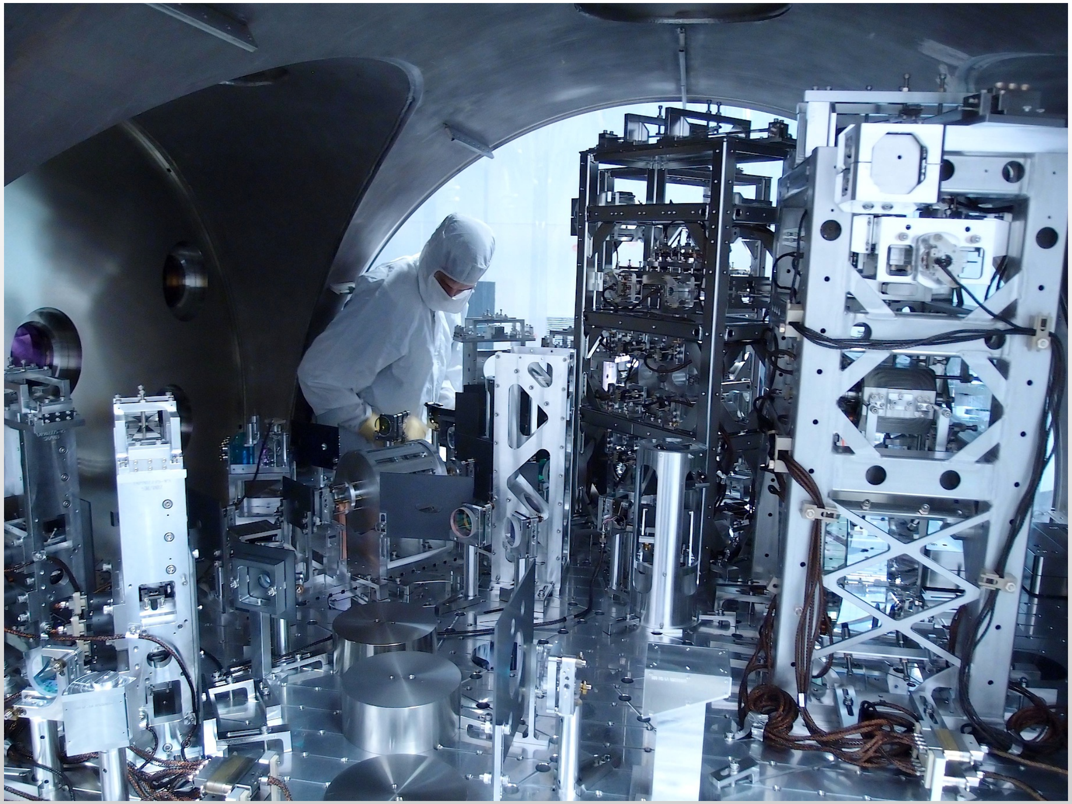
News from LIGO - October 2013



Koji Arai
LIGO Project, California Institute of Technology

Domestic KAGRA Collaboration Meeting (Oct. 9th, 2013)
JGW-G1301893

Advanced LIGO

LIGO Livingston

Dual-recycled Michelson Interferometer (DRMI)

- All interferometer components installed at vertex.
- DRMI locked, PRMI locked with DC Readout (OMC)

Plan:

- End test masses now being installed
- Installation completion in Feb 2014, 2hrs lock by Oct 2014

LIGO Hanford

Half-interferometer (HIFO-Y) completed

- First arm cavity test with the main IR beam
- Demonstration of Arm Length Stabilization (green locking)

Plan:

- To be followed by HIFO-X, HIFO-XY
- DRMI in May 2014
- Installation completion in July 2014, 2hrs lock by Dec 2014

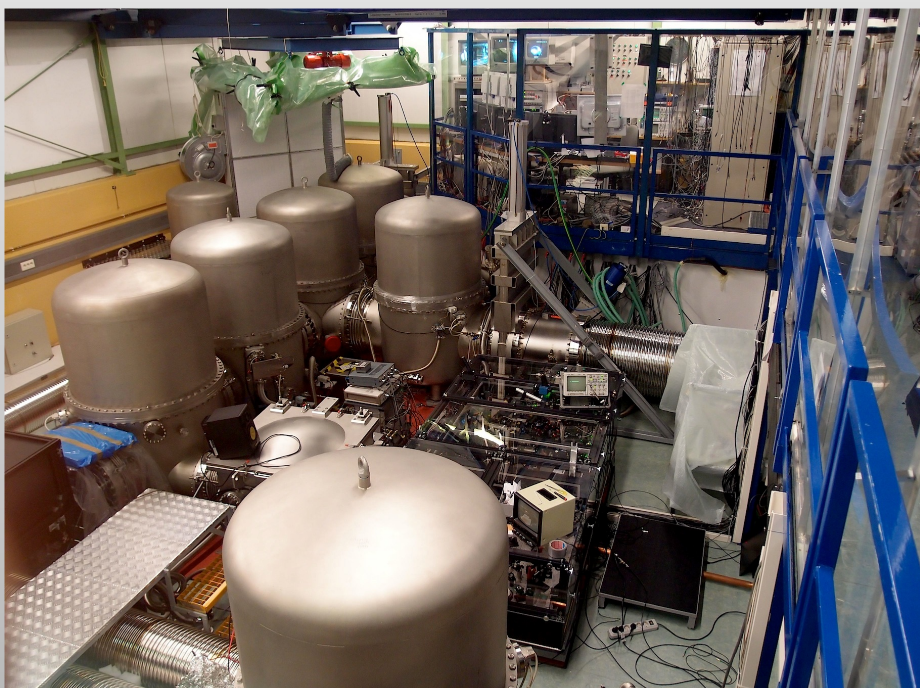
Visiting GEO600

Koji Arai

GEO-HF

- Astrowatch, >1year data with 2~2.5dB squeezing.
- Long-term operation with the sqeezed light (~3yrs at GEO)
- Steady improvement with patience

  Power increase / Thermal Compensation / Scattered light
  OMC control / Squeezing control



Overview

Advanced LIGO Output Mode Cleaner (OMC)

- An optical cavity to remove unwanted optical fields from the interferometer output beam.
- The first aLIGO OMC was built and tested at Caltech, and installed at LLO
- The design, fabrication, and test results

OMC ISC team

Rich Abbott[1], Koji Arai[1], Sam Barnum[3], Peter Fritschel[3], William Korth[1], Jeffrey Lewis[1], Charles Osthelder[1], Sam Waldman[3]

OMC SUS team

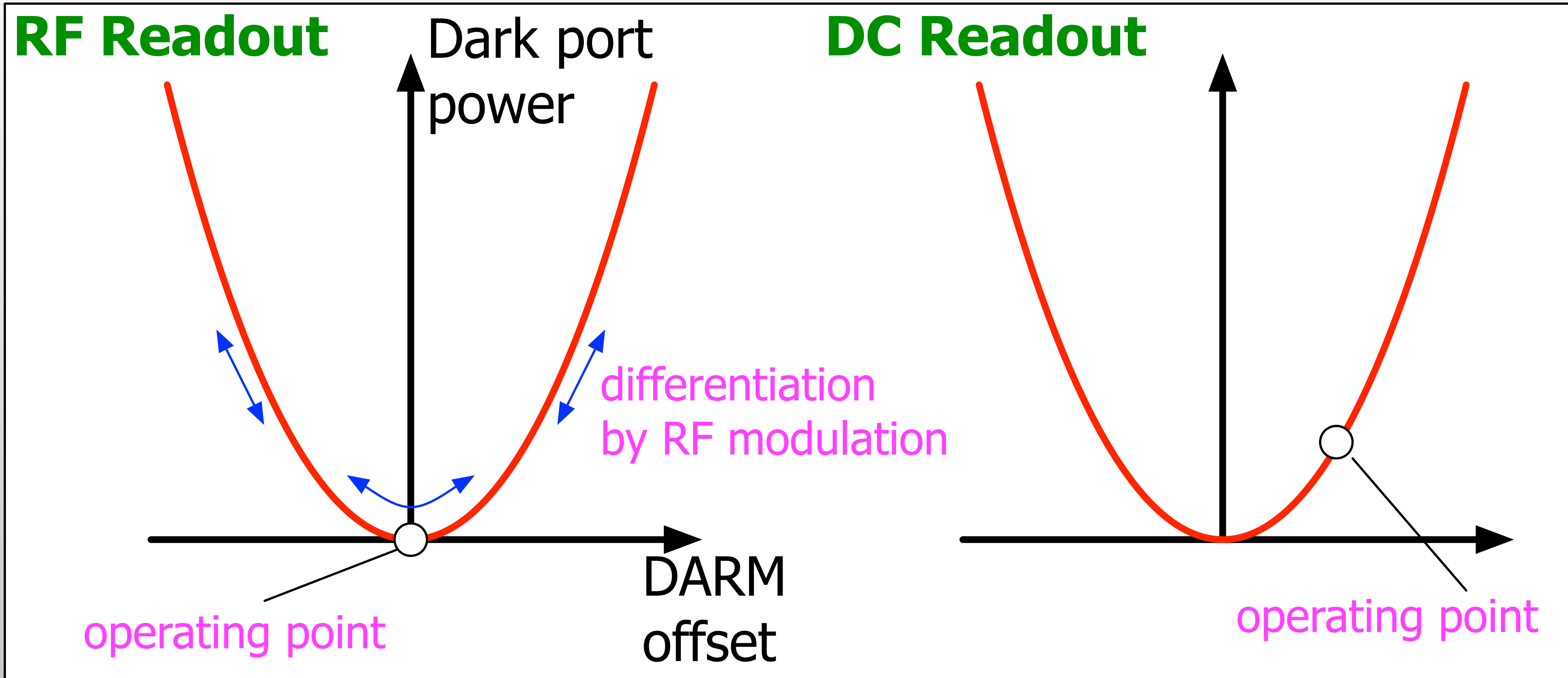
Stuart Aston[2], Jeffrey Bartlett[4], Derek Bridges[2], Jeffrey Kissel[3], Norna Robertson[1]

LIGO Laboratory: California Institute of Technology[1], LIGO Livingston Observatory[2], Massachusetts Institute of Technology[3], LIGO Hanford Observatory[4]

Mission of the OMC

DC Readout

aLIGO employs a DC readout scheme for sensing of GW signals



DC Readout is good:

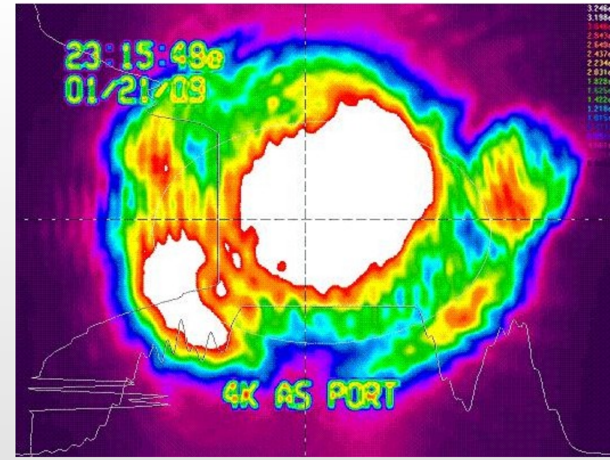
- removes nonstationary shot noise
- mitigates technical noises associated with the RF sidebands

Mission of the OMC

Enemies of the DC Readout

- Carrier HOMs (higher-order modes)
- RF modulation sidebands (any spacial modes)

do not contribute to the signal
and increase the shot noise



eLIGO AS port beam

Output mode cleaner

the idea is to use a short (~1m) optical cavity for the filtering

Filtering performance

higher finesse

Trade-off ⇕

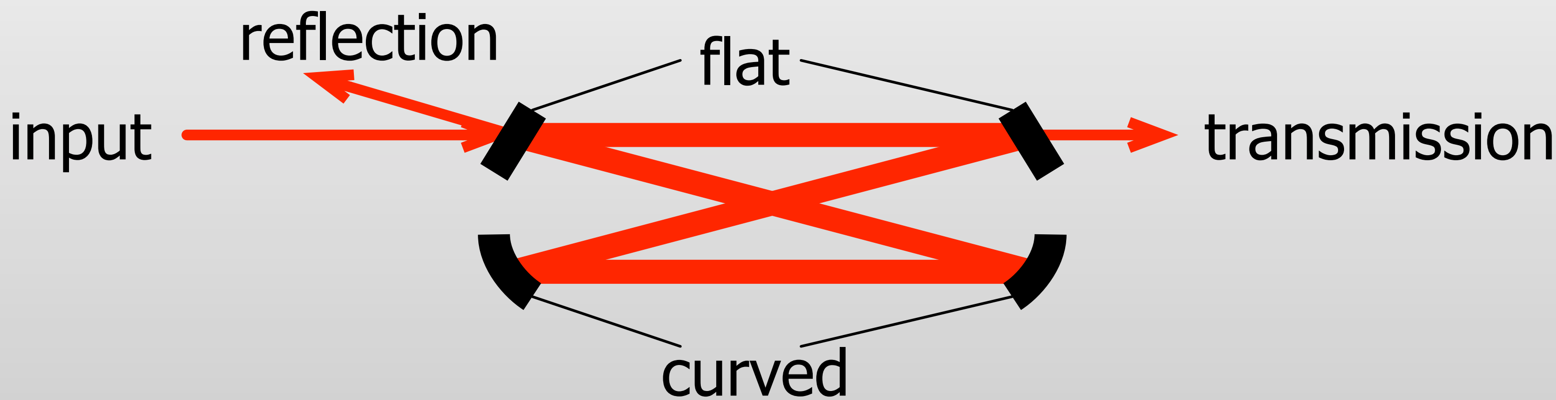
lower finesse

Signal transmittance

OMC cavity design

Basically eLIGO OMC design was followed

- Bowtie 4-mirror ring cavity
  even mirrors => simpler HOM structure
  ring cavity => less back scattering

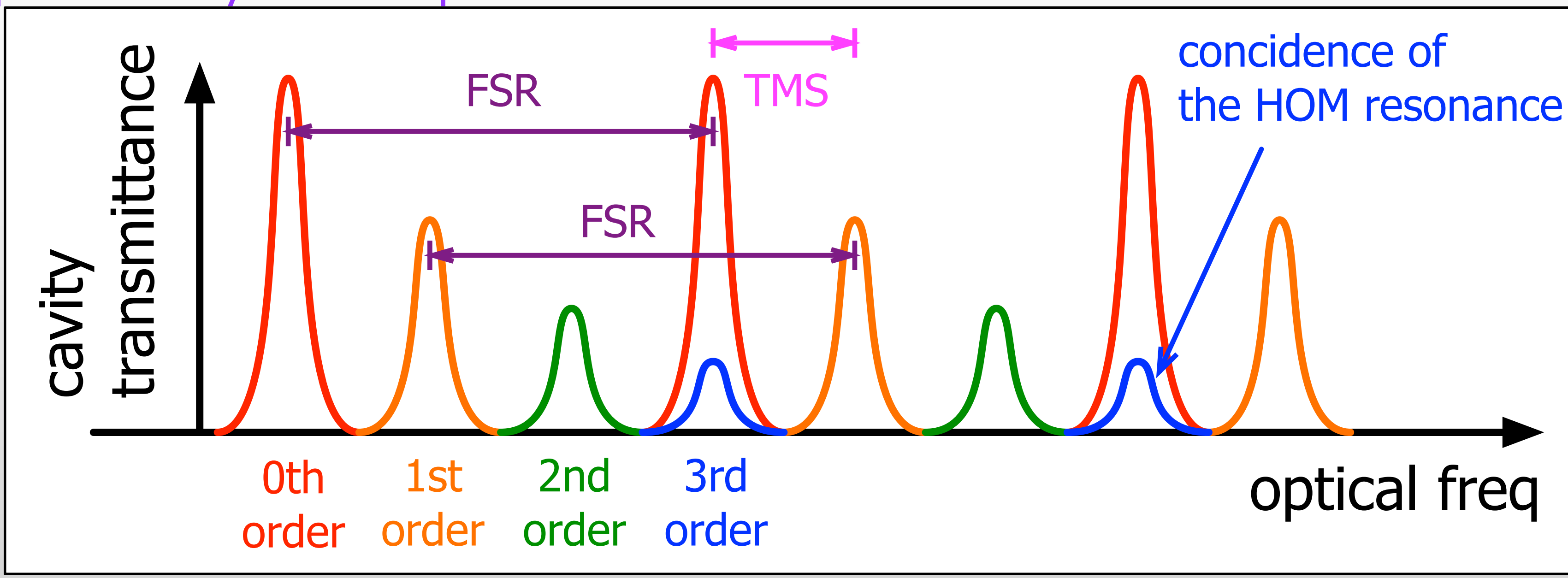


- Finesse: ~400 (for ~98% transmission)
  Roundtrip length ~1m (the breadboard size)
  Curved mirror radius ~2.5m

Filtering Performance

Important parameter: Transverse Mode Spacing (TMS)

An optical cavity has a repetitive resonant structure



If TMS/FSR is a rational number (m/n) , n-th order HOMs get transmitted

MOREOVER: The vertical and horizontal modes have different TMSs due to astigmatism of the curved mirrors (i.e. non-zero incident angle)
=>The higer the mode number, the wider the resonance is.

TMS/FSR is dependent on the cavity geometry
=>Careful adjustment of TMS/FSR is the key to avoid HOMs

Filtering Performance

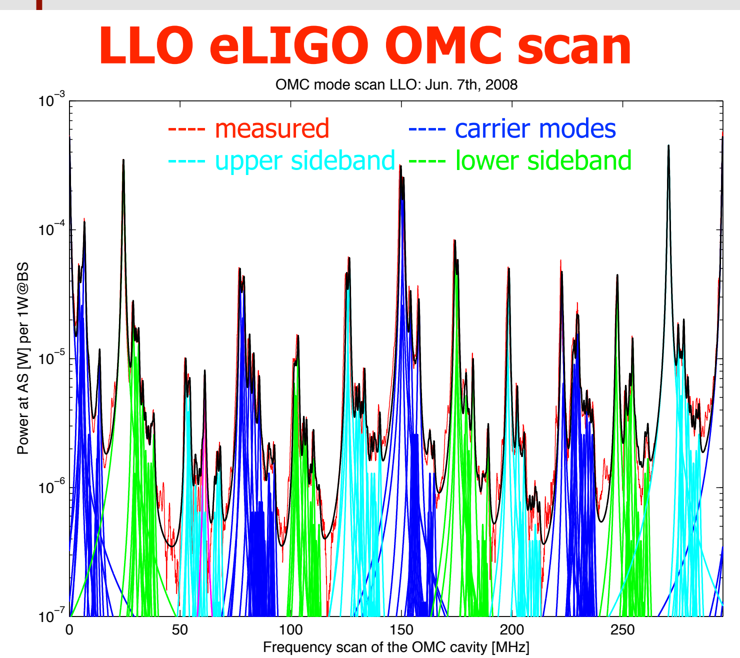
Estimation of the filtering performance

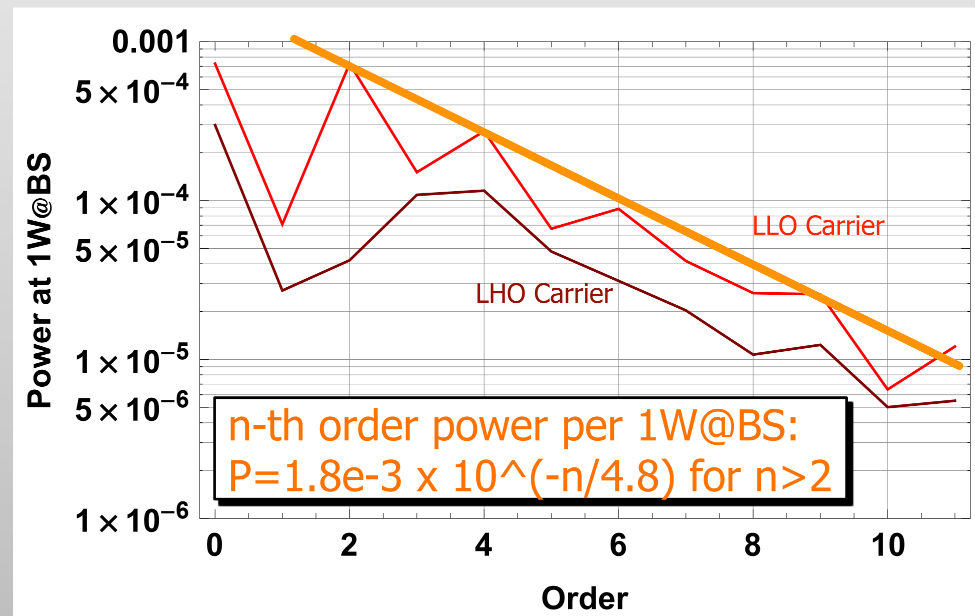
Total transmitted power

= $\sum$(power in each mode) x (transmission of each mode)

- Modeling of the interferometer output beam (details in G1201111)

power laws based on the eLIGO performance of the IFO optics



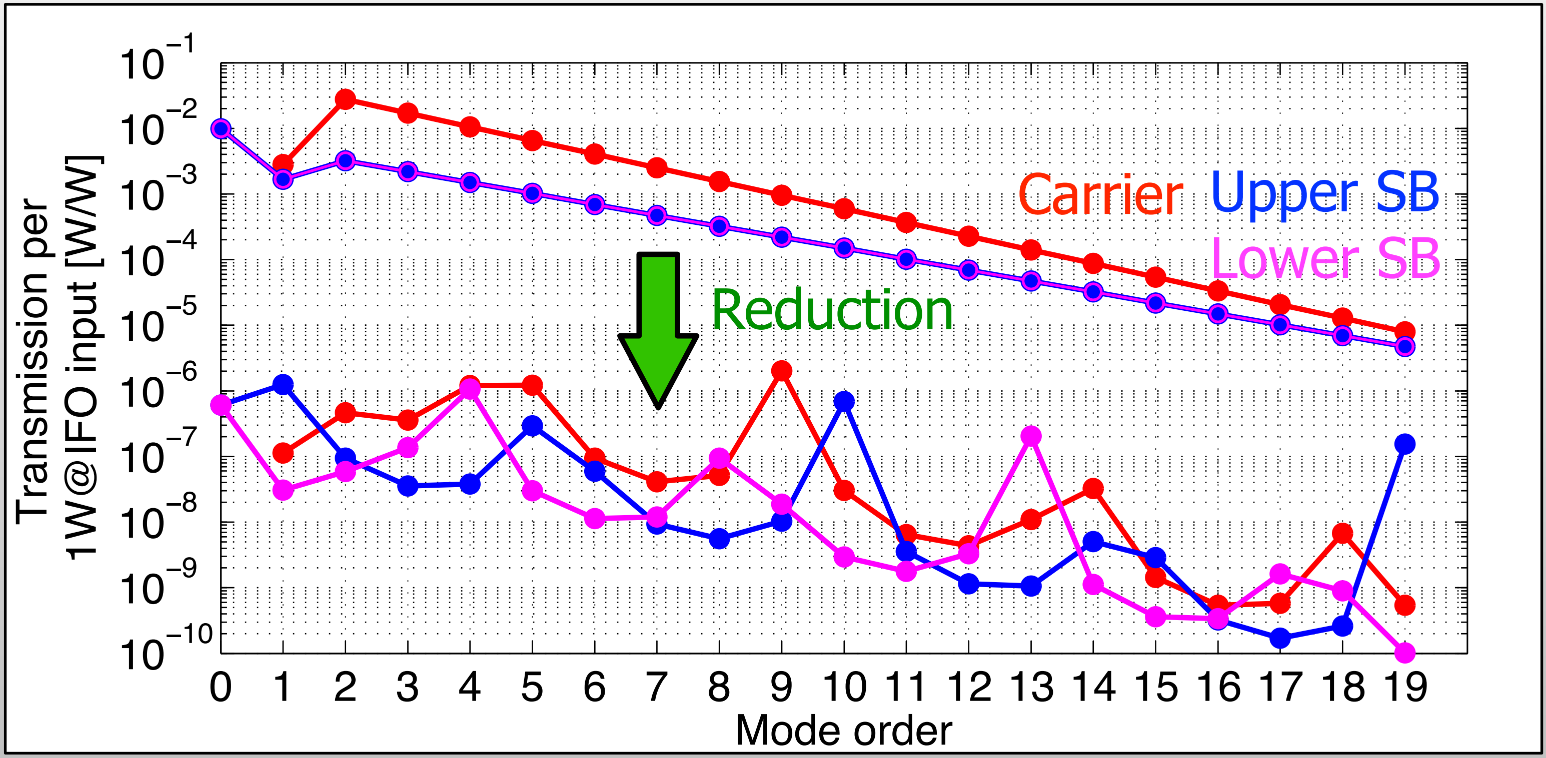


This wouldn't be a prediction, but have some usefulness, anyway

Filtering Performance

Estimated filtering performance

- Expected junk light power at the dark port (100W input = 4kW @BS)
  ~12W leakage => filtered down to 1mW. Well within the PD capability.
  This could become better thanks to mode healing and better optics in aLIGO

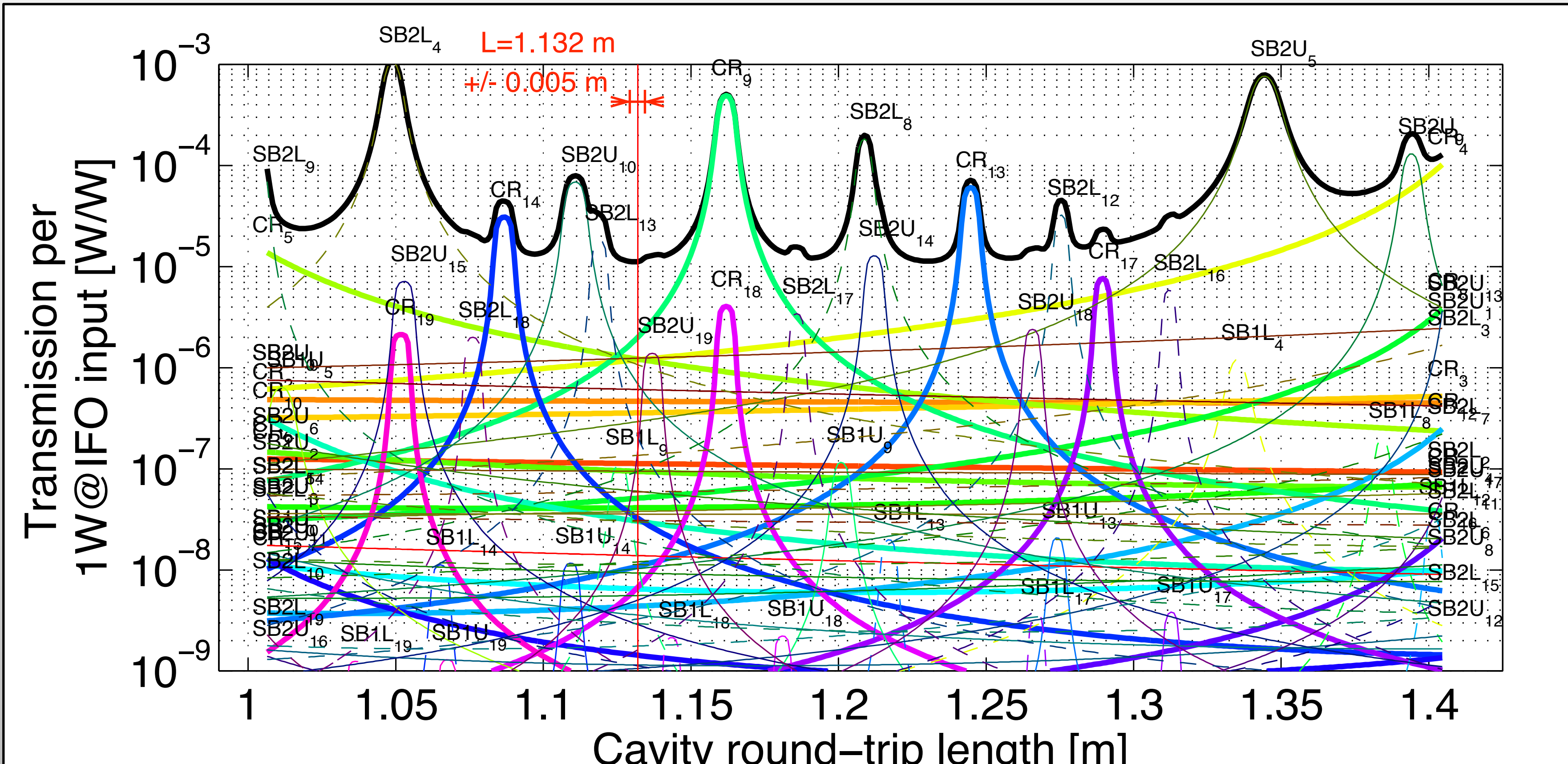


9MHz sidebands omitted in the plot due to small contribution

Filtering Performance

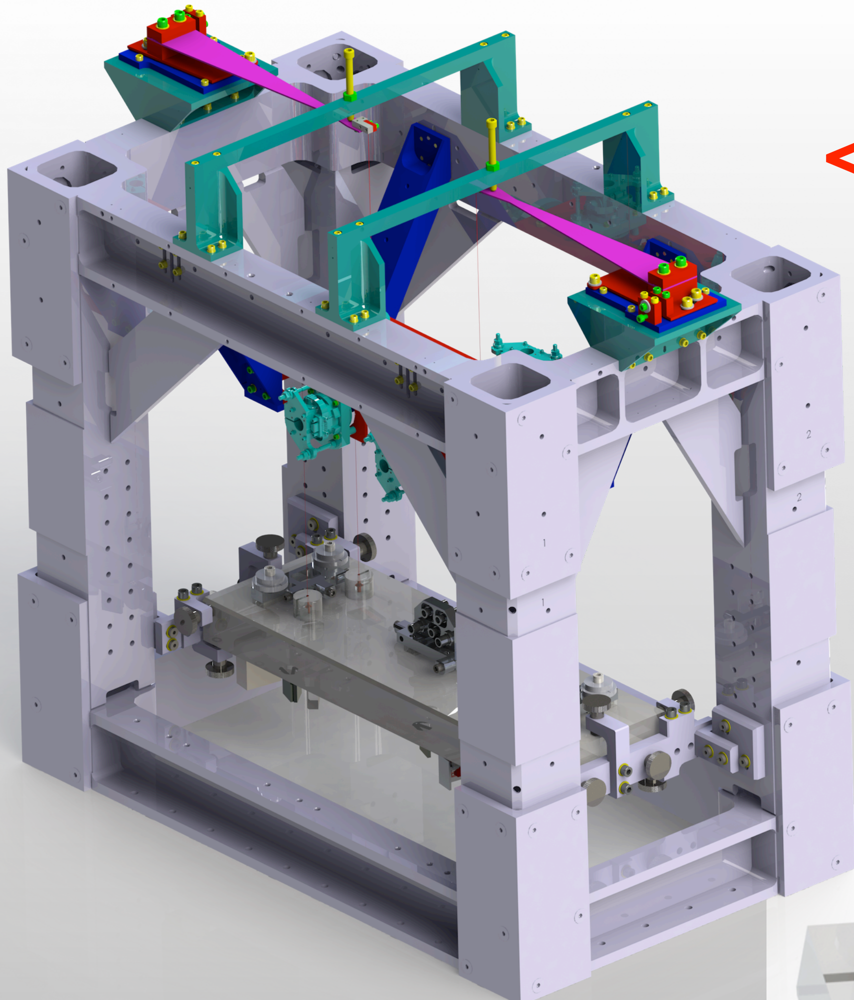
Parameter torelance

- Cavity length tolerance: L=1.132 +/− 0.005 [m]
- Mirror RoC tolerance: R=2.575 +/− 0.015 [m]



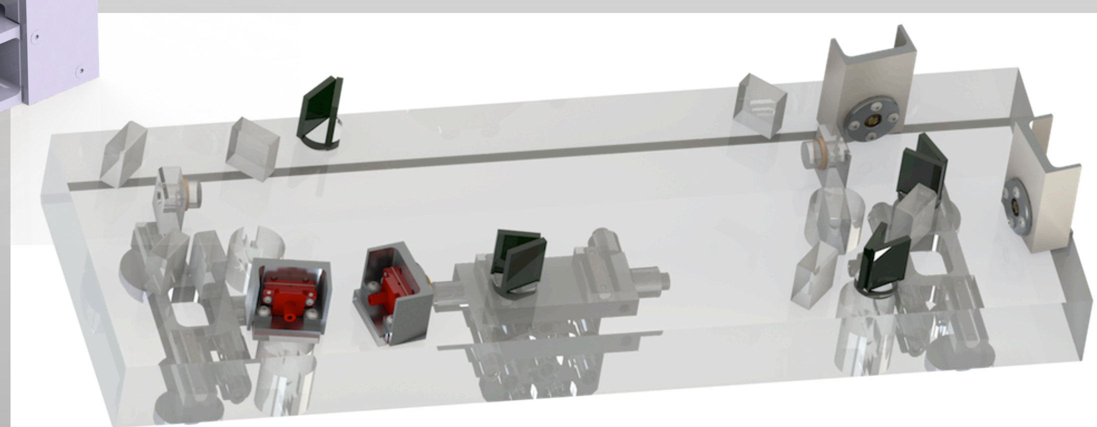
CRn - carrier n-th mode, SB(1,2)(U,L)n - sideband n-th mode,
SB1 - 9MHzSB, SB2 - 45MHz SB, U - upper SB, L - lower SB

Fabrication



<- OMC Suspension

v- OMC Breadboard



Fabrication

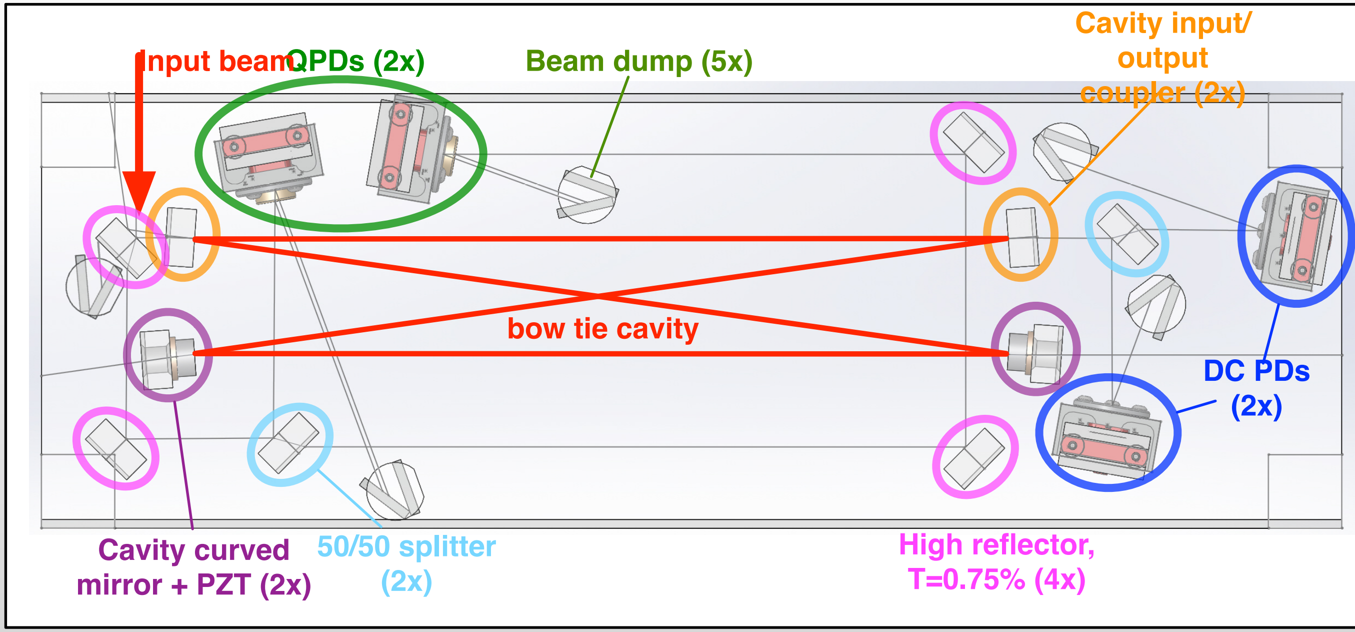
Comparison between eLIGO/aLIGO OMCs

	eLIGO	aLIGO
Cavity design:	semi-monolithic	same (for flexibility of the cavity parameters)
Breadboard material:	ULE	fused silica (dT of the order of 0.1K -> just 0.06um)
Mirrors	Glued on the back side of the fused silica prisms	Glued on the front side of the fused silica prisms (better access)
Actuators	1 PZT + 1 heater	Two PZTs (for redundancy)
Suspension	double pendulum (actively damped)	same
Wire clamps	screwed on the breadboard	glass wire blacket on the top side

Fabrication

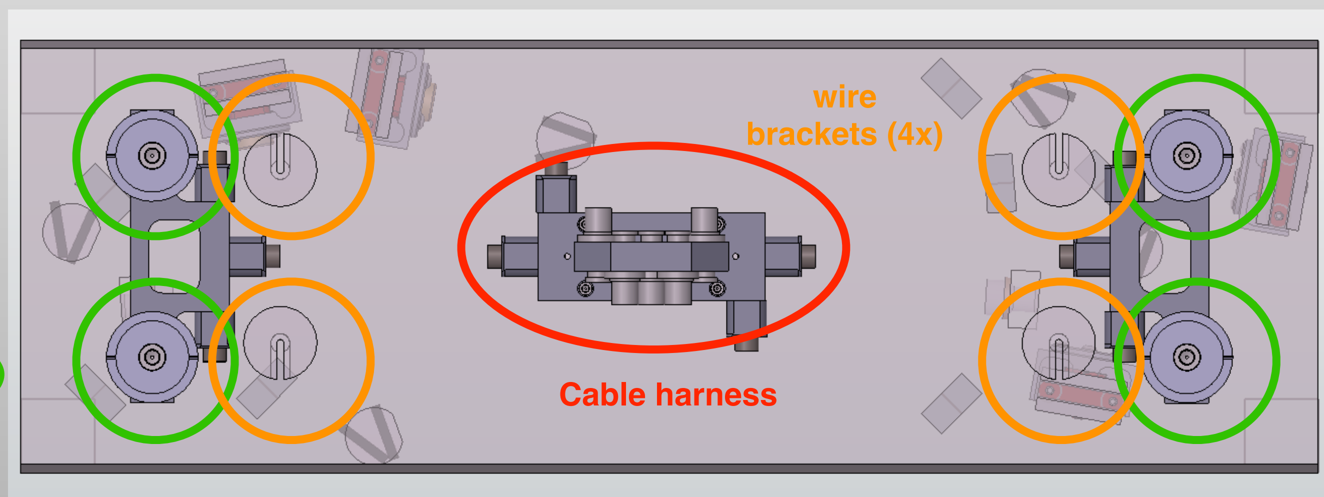
How the OMC breadboard looks like

Bottom side (cavity side)



Top side (cable side)

balance weight (4x)



Fabrication

Procedure

- PZT & curved mirrror sub-assembly

- Bottom (cavity) side gluing

- Top (suspension) side gluing

- Vacuum bake

- Optical test

- Cabling

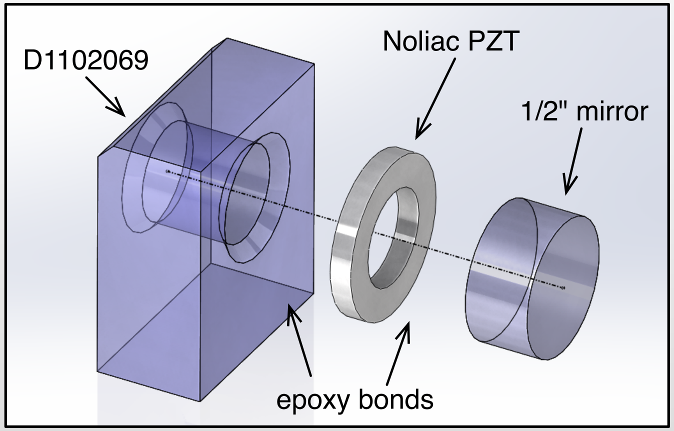
- Shipping

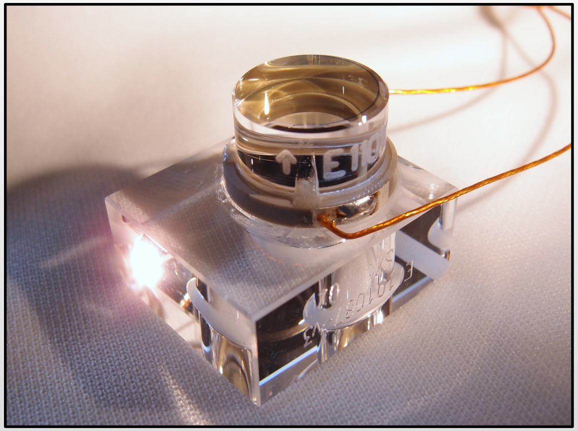
- Installation

Fabrication

PZT-curved mirror subassembly

- PZT + 1/2" curved mirror

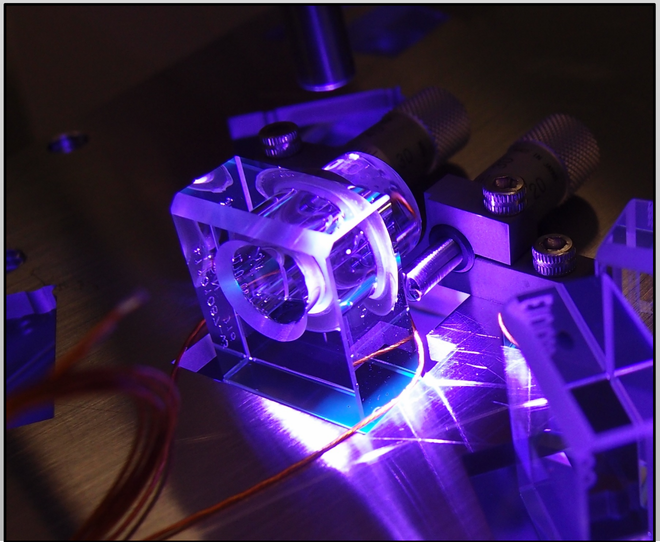




Cavity side gluing

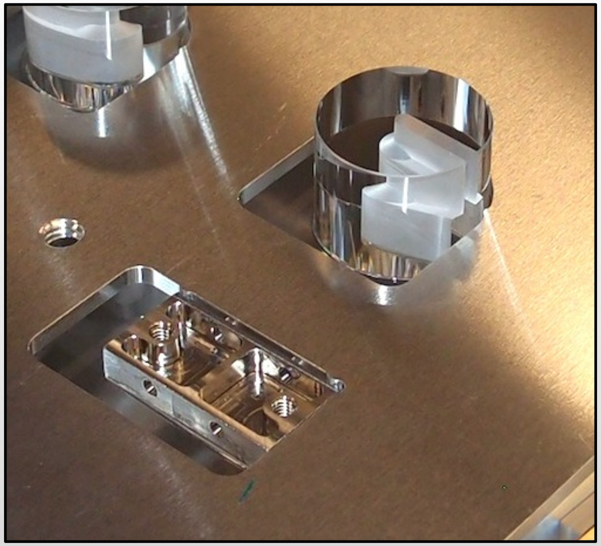
- Template
- UV epoxy

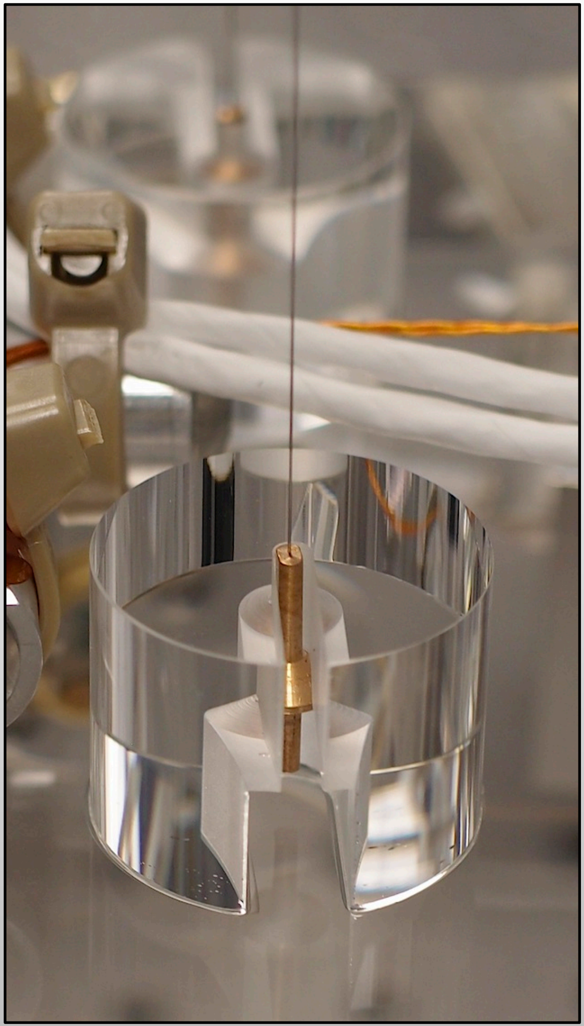
- Bonding while the cavity is monitored

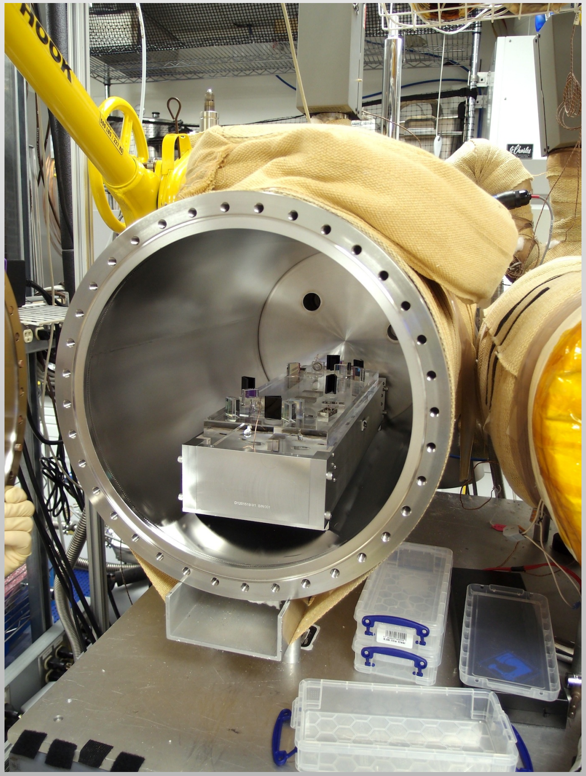


Top (cable) side gluing

- Suspension interface
- Mounting blocks







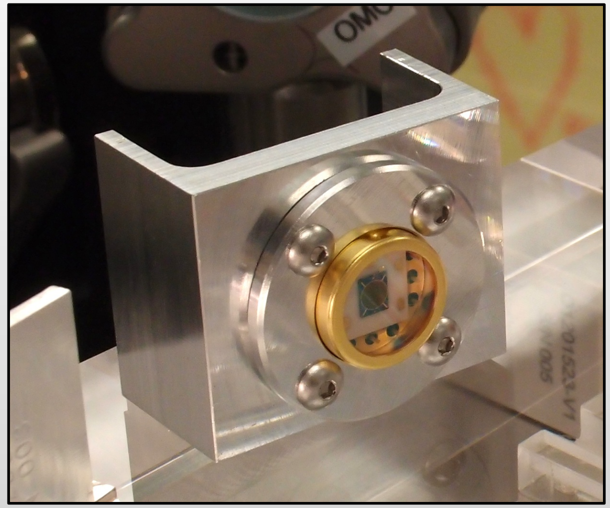
Vacuum Bake

- reduce outgass
- completion of epoxy cure

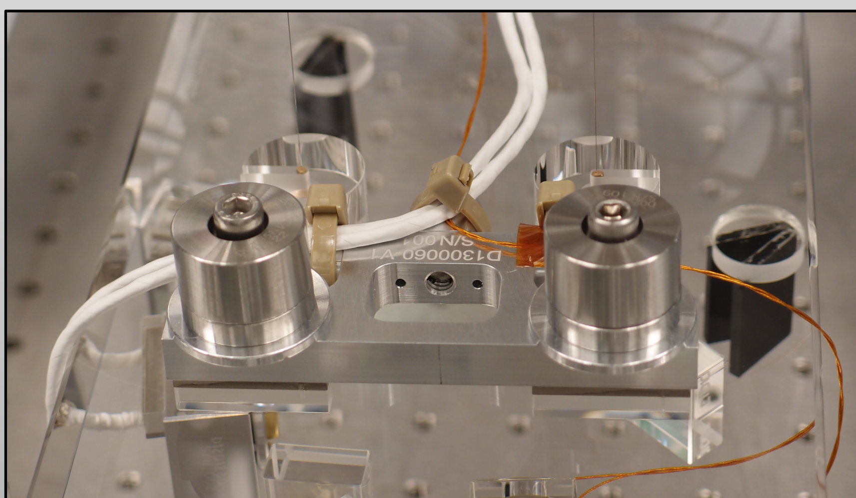
Fabrication

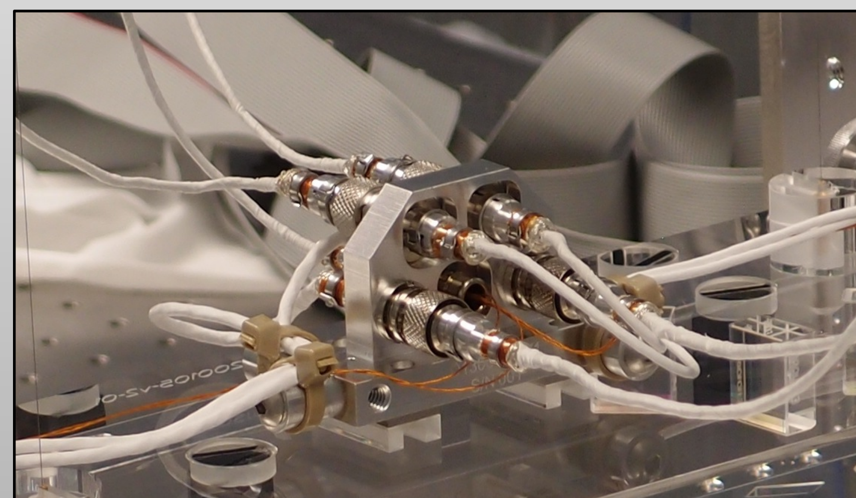
Attaching peripheral components:

- DC photodiodes / QPDs



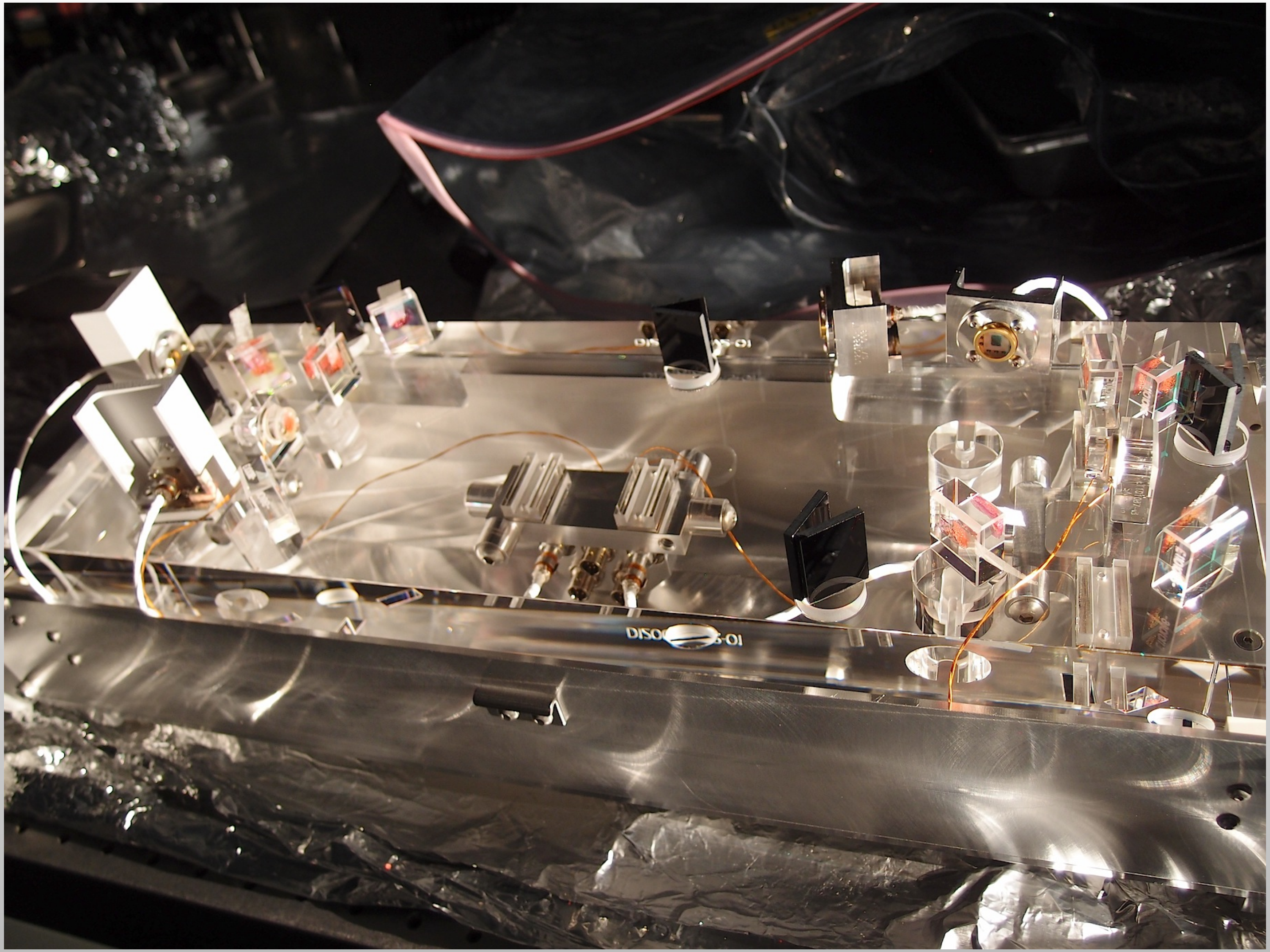
- Cables





Fabrication

OMC ready for the shipment



Optical testing

Power Budget

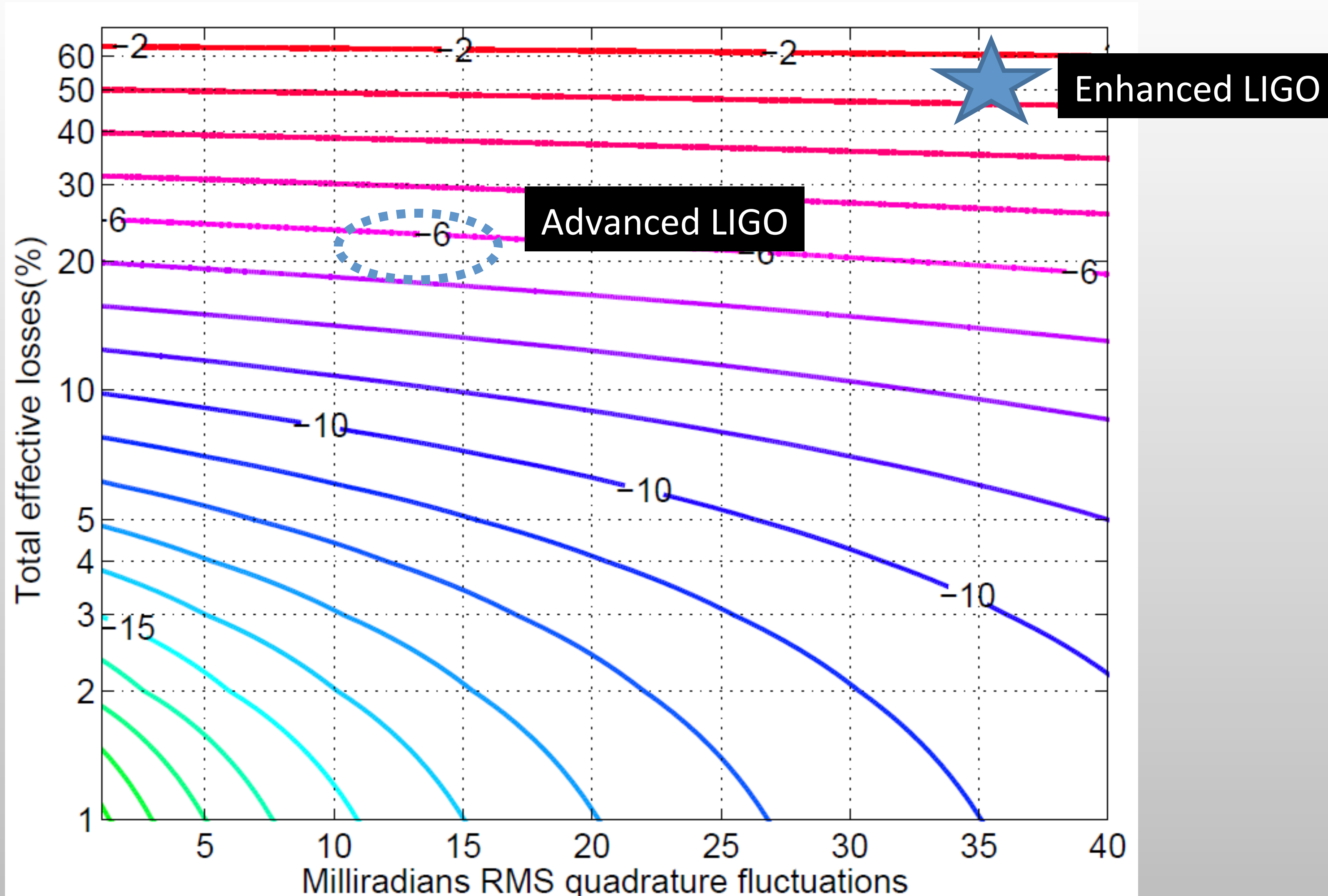
Estimated from the input power, transmitted power, visibility, and cavity finesse

		Specfication
Cavity transmission for TEM_{00}:	97.8 %	98.4 %
Curved mirror transmission:	42 ppm	50 ppm
Loss per bounce:	22.3 ppm	10 ppm
Loss per roundtrip:	173 ppm	140 ppm
PD Q.E.	92%	
Total thruput of TEM_{00}	90%	(PD Q.E. = 92%)

About 20% total loss allowed for 6dB squeezing.

A half of the budget already eaten up by the OMC. **(not nice)**
These PDs were previously (eLIGO) reported to have Q.E.>95%
Need further investigation (or replacement)

Optical testing



Optical testing

Cavity round-trip length

Cavity length: 1.131421 +/– 3×10^{-6} m
(Spec.: 1.132 +/– 0.005 m)

Finesse: 403.79 +/– 0.07
(Spec. 390)

Transverse Mode Spacing (TMS)

Pitch TMS/FSR: 0.218822 +/– 1×10^{-6}
(Spec. 0.2188)

Yaw TMS/FSR: 0.219218 +/– 1×10^{-6}
(Spec. 0.2194)

N. Uehara and K. Ueda, "Accurate measurement of the radius of curvature of a concave mirror and the power dependence in a high-finesse Fabry-Perot interferometer", Appl. Opt. 34, pp. 5611-5619 (1995).

TMS/FSR was successfully adjusted such that the HOMs were avoided until 32nd order.
...BUT

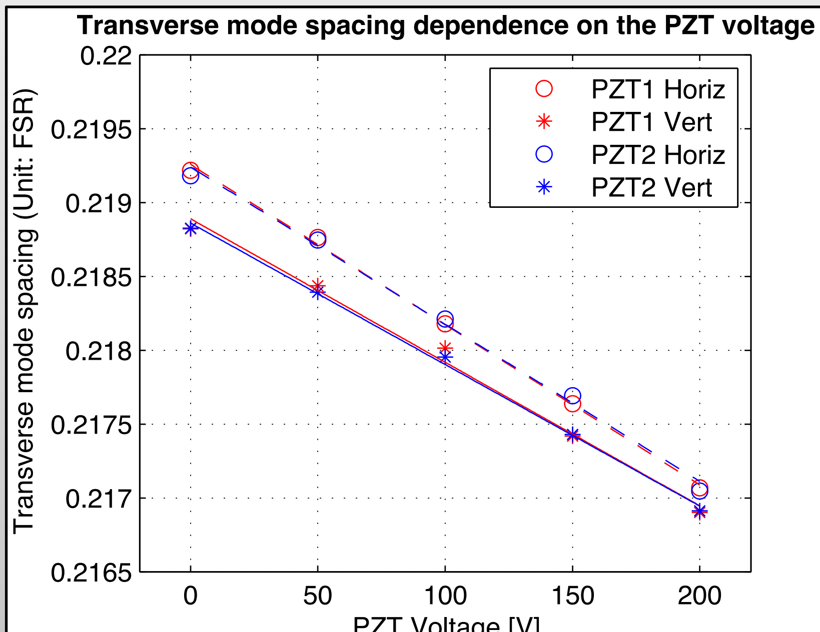
Optical testing

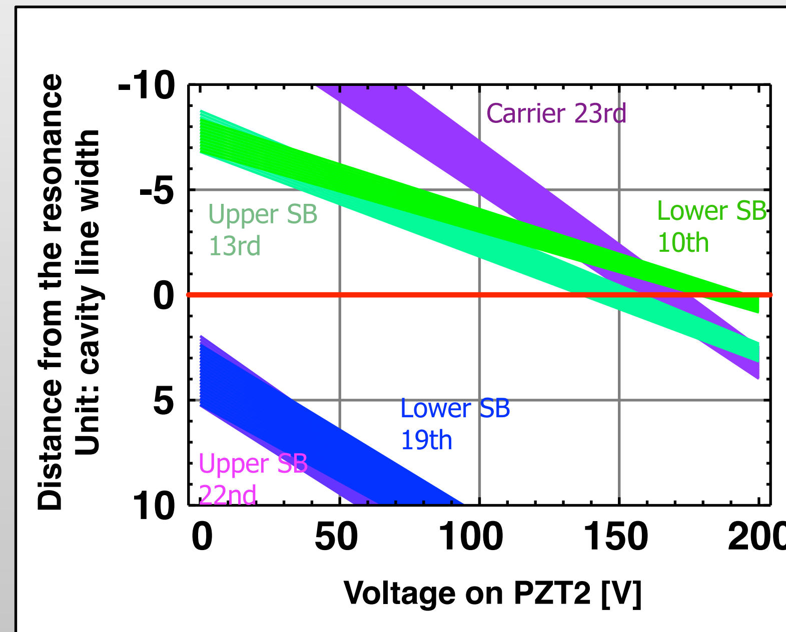
TMS depend on the PZT voltage

- 3D deformation of the ring PZT?

Pitch TMS/FSR: $0.2189 - 9.7\times10^{-6}\,V_{PZT1} - 9.6\times10^{-6}\,V_{PZT2}$

Yaw TMS/FSR: $0.2192 - 10.8\times10^{-6}\,V_{PZT1} - 10.6\times10^{-6}\,V_{PZT2}$





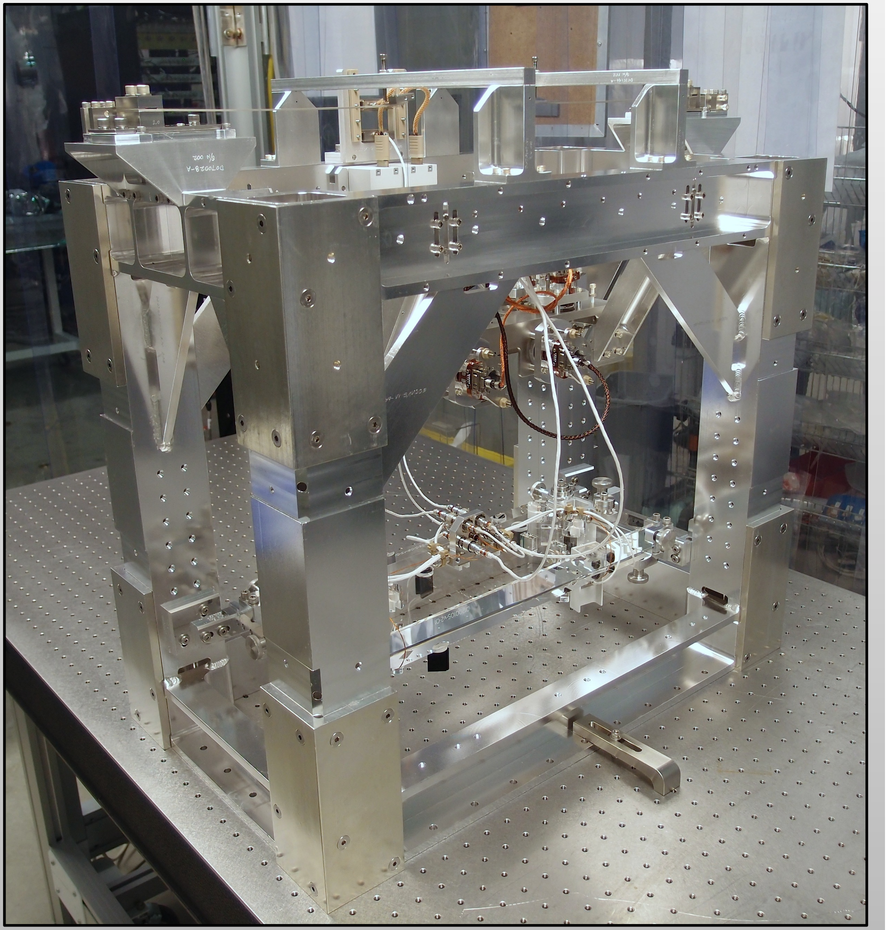
The HOMs comes into the resonance at PZT voltage of ~150V.

This actually does not happen as we limit the PZT voltage to 100V because of some other reason

Installation @LLO

Integration with the OMC suspension (OMCS)

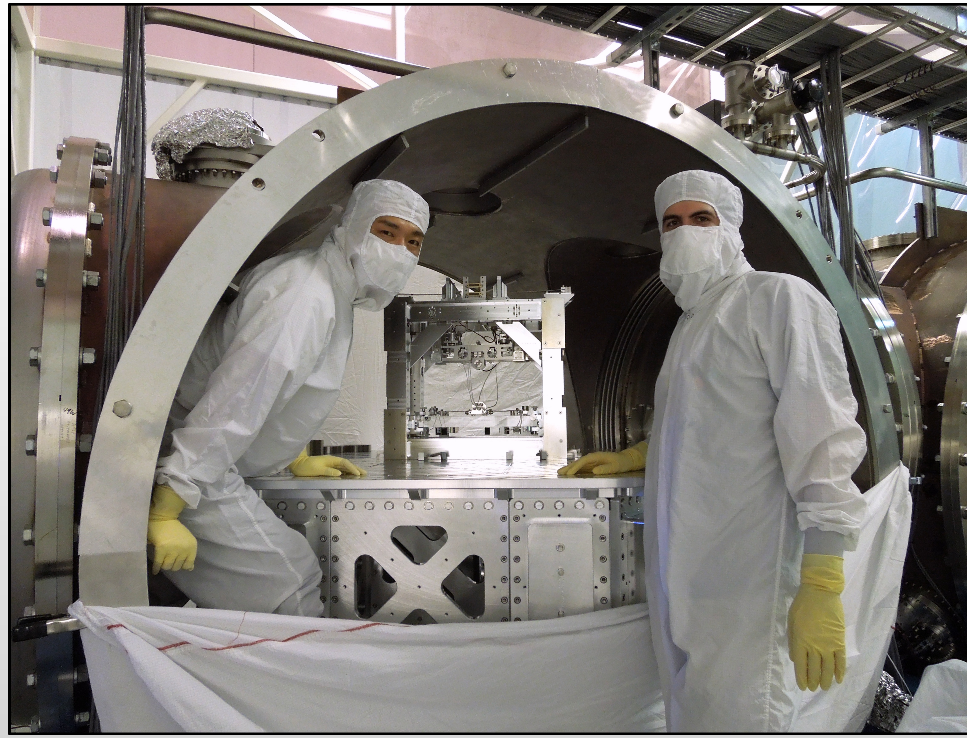
- OMCS prepared with a metal bench
- Swapped the metal bench with the glass bench at LVEA
- Cabling / Weight balance
- Suspension tests in LVEA
  - transfer functions
  - damping control

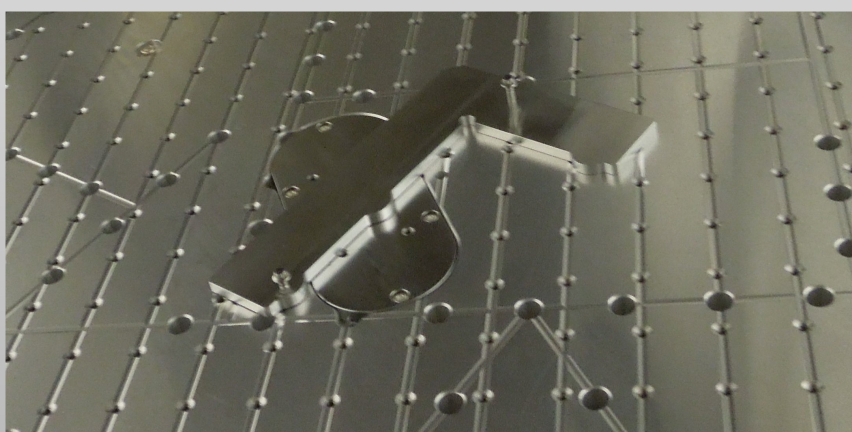


Placement on HAM6

- Loading on the ISI
  - a compact lift truck
  - to raise the OMCS
- "Cookie cutter"
- Suspension tests in HAM6

Installation @LLO





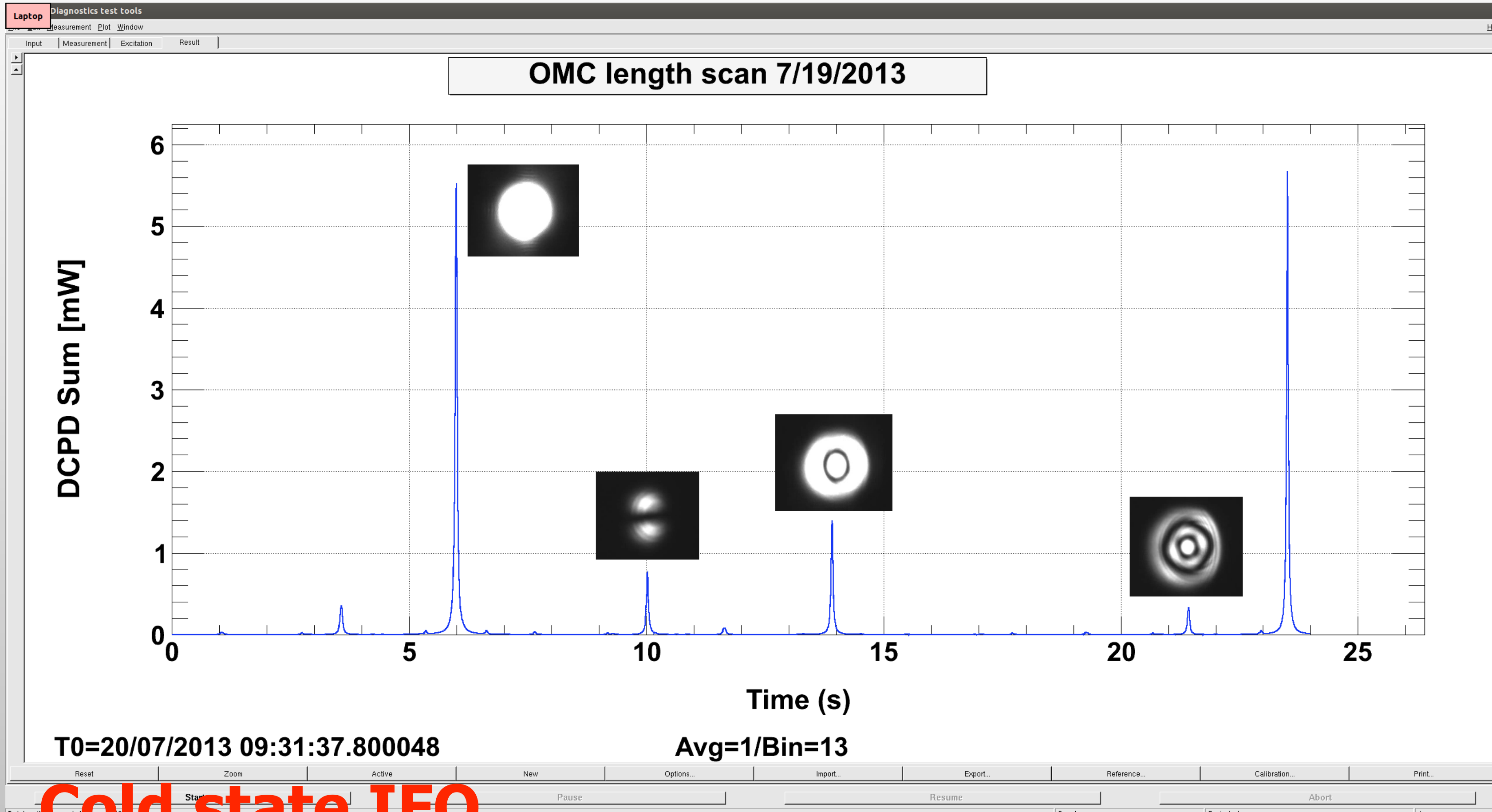
An installed scientist

Lift truck

Cookie cutter

Koji Arai
KAGRA meeting, Oct. 9, 2013

MODE MISMATCH?

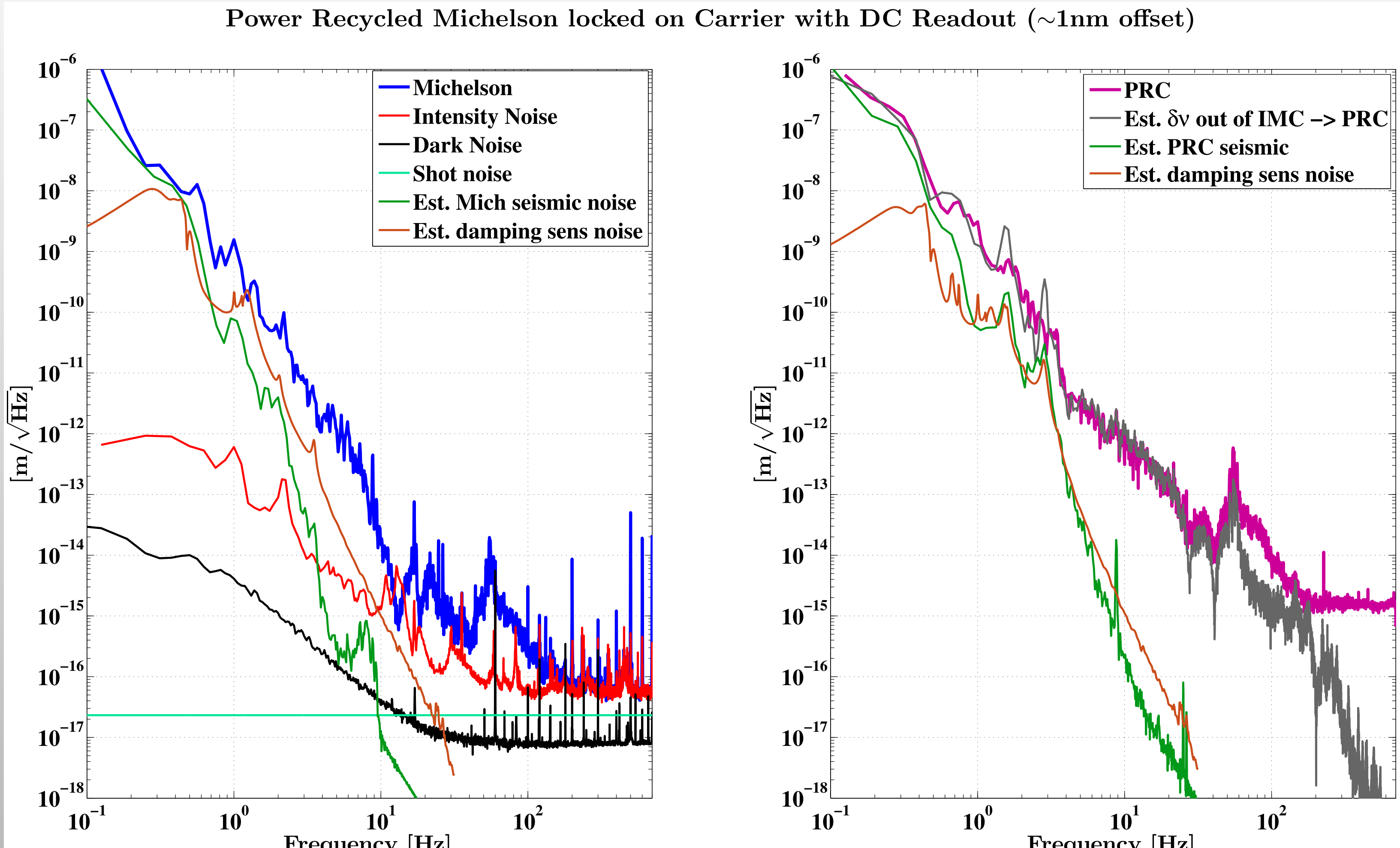


- Cold state IFO
- Difference of the arms emphasized by the incorrect PR2/3 distance?

Performance

- By locking the PRMI with an offset we can use DC readout to improve the sensing noise

5x10^{-17}m/rtHz above 100Hz, Intensity noise limited



OMC Team

Jeff Lewis (Engineer)

Koji Arai (Scientist)

Zach Korth (PhD student)

OMC Team

Jeff

Fabrication procedure
Mechanical design
Engineering issues

Installation issues
Preparation@LLO

Koji

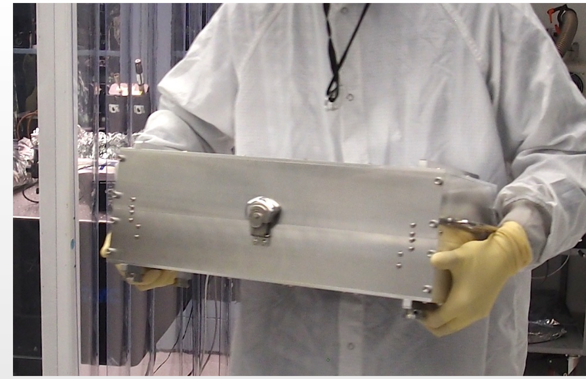
Zach

Optical design
Feedback control
Scientific requirements
Optical tests

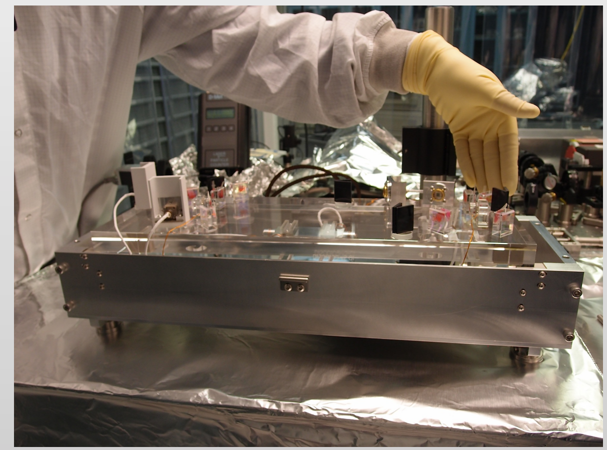
Encounter with engineers

- **CAD**
- **Project control**
- **Sense of mechanics**
  - easy-to-use / precisions / cost
  - e.g. transport fixture
- **Specifications**
  - PZT
  - Bonding
    - EP30 glass sphere bond-liner
    - UV cure
    - Bonding tests
  - Torquing
  - Thermal expansion coefficients
  - Thermal radiation
  - Contamination control

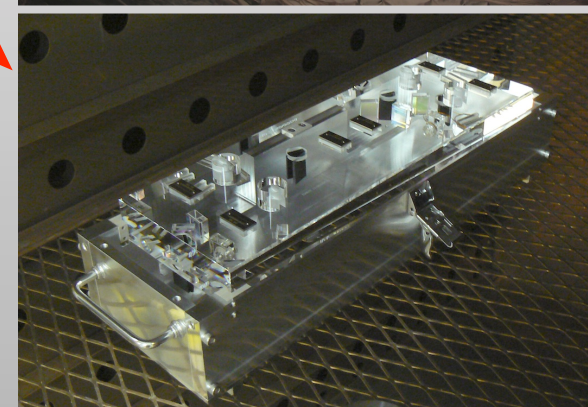
transport



testing



baking



Engineers are complimentary to scientists!