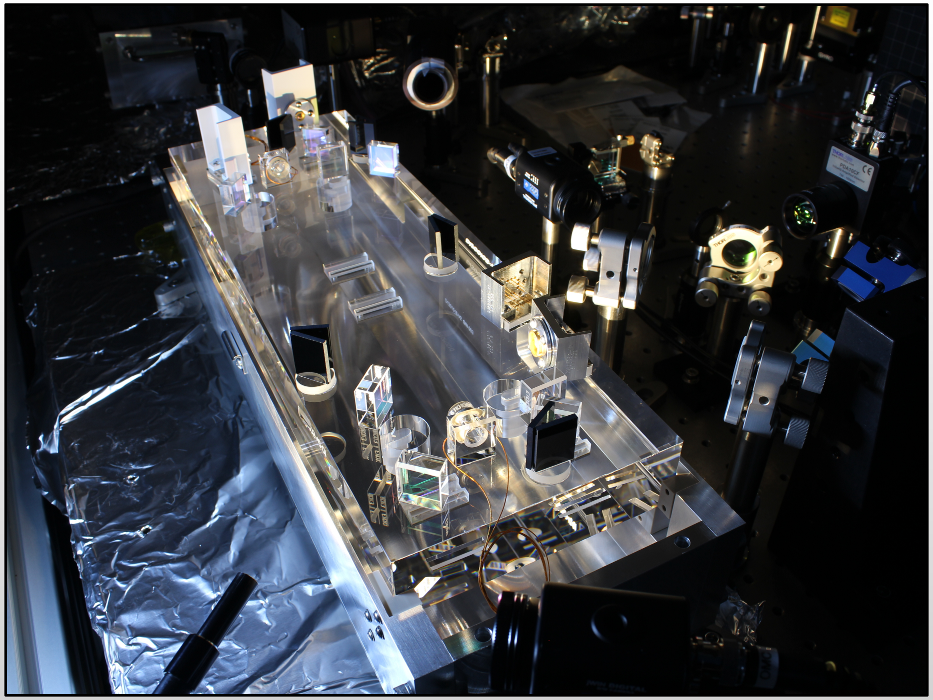
Advanced LIGO Output Mode Cleaner: Design, Fabrication and Installation



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LVC meeting 2013 September @ Hannover
LIGO-G1301001

Overview

Advanced LIGO Output Mode Cleaner (OMC)

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

OMC ISC team

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OMC SUS team

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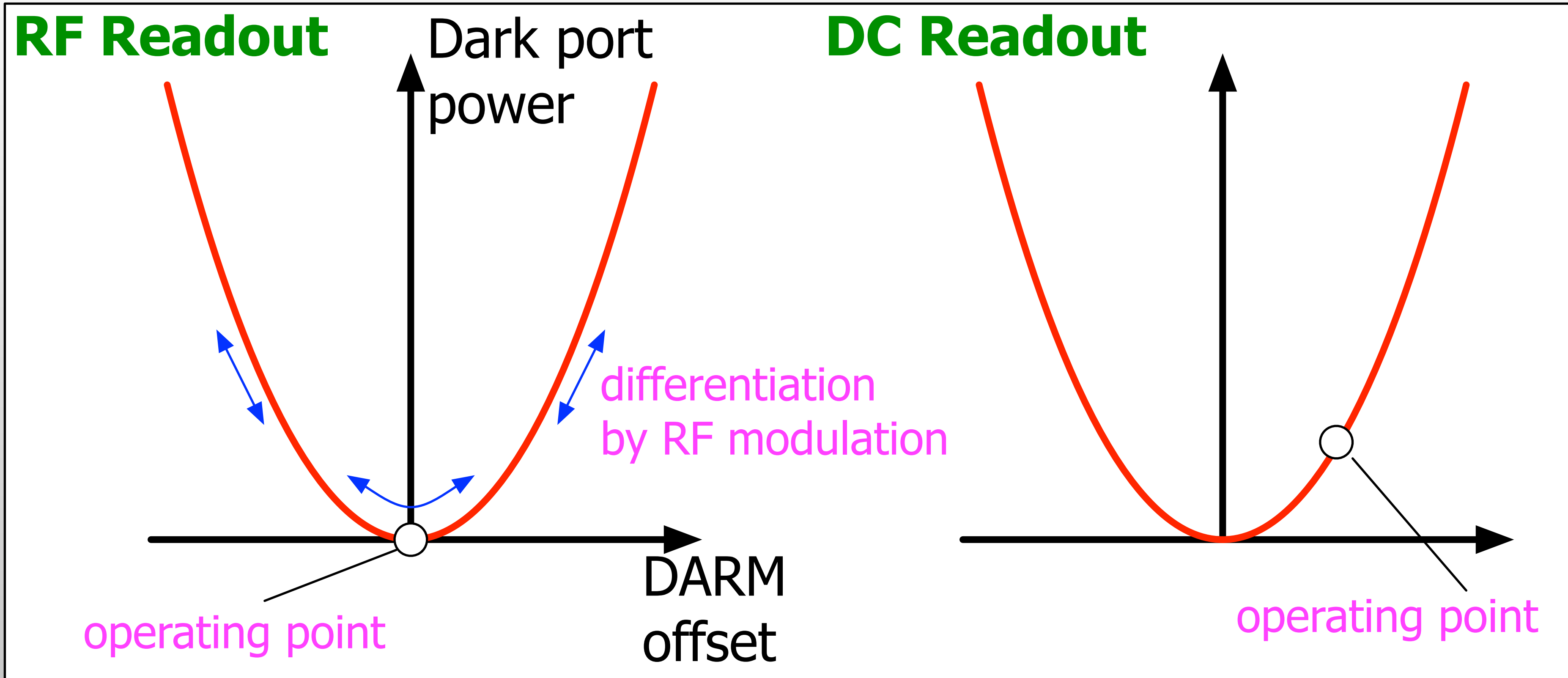
Mission of the OMC

DC Readout

aLIGO employs a DC readout scheme for sensing of GW signals



DC Readout is good:

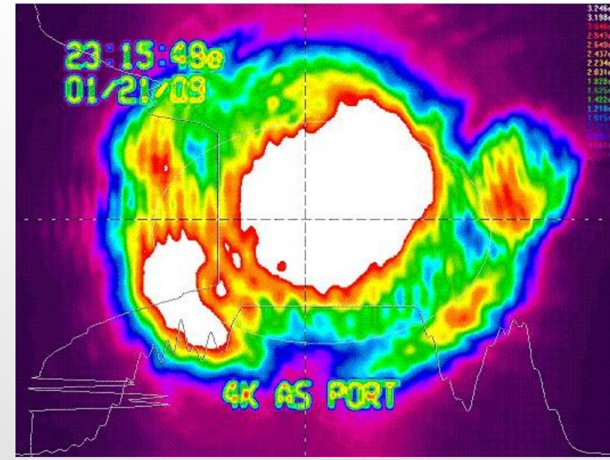
- removes nonstationary shot noise
- mitigates technical noises associated with the RF sidebands

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 ↕

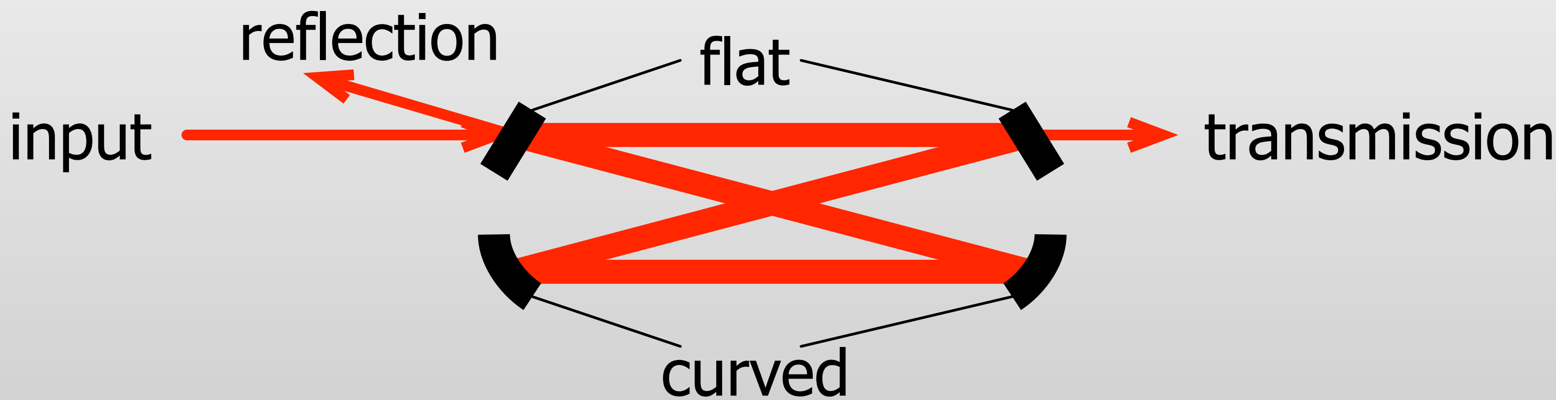
lower finesse

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

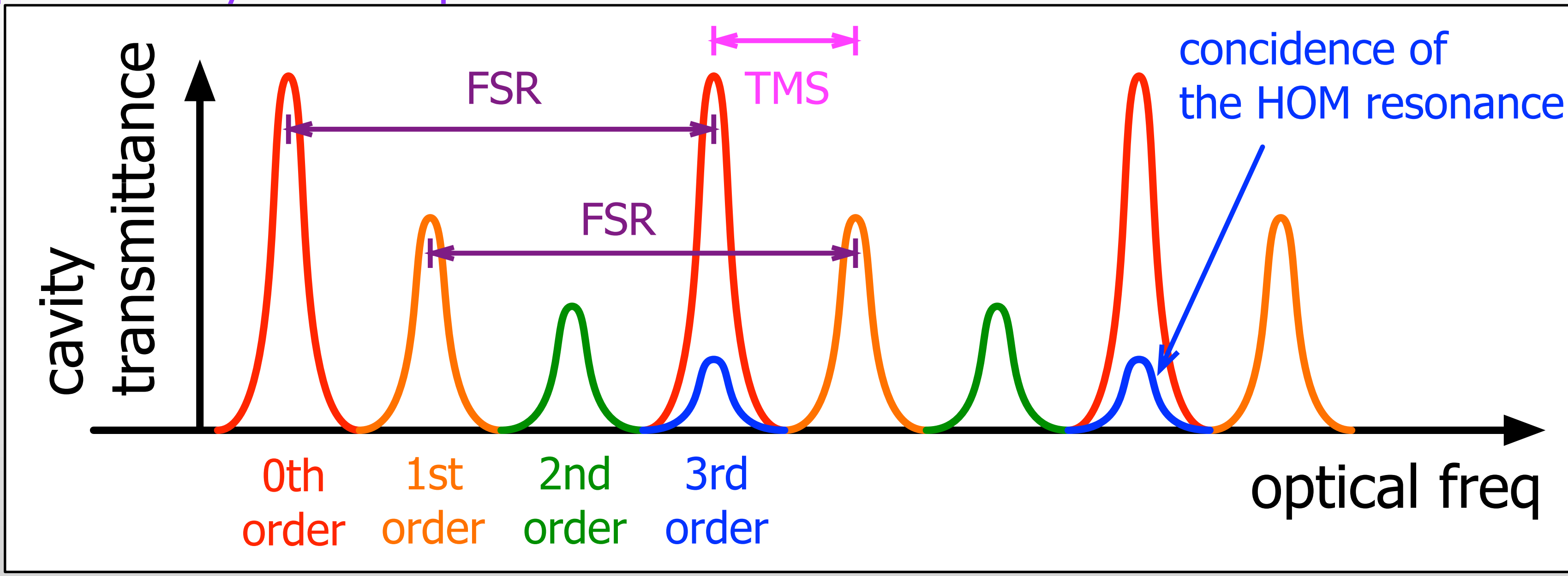


- Finesse: ~400 (for ~98% transmission)
  Roundtrip length ~1m (the breadboard size)
  Curved mirror radius ~2.5m

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

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LVC Hannover Sep. 24, 2013

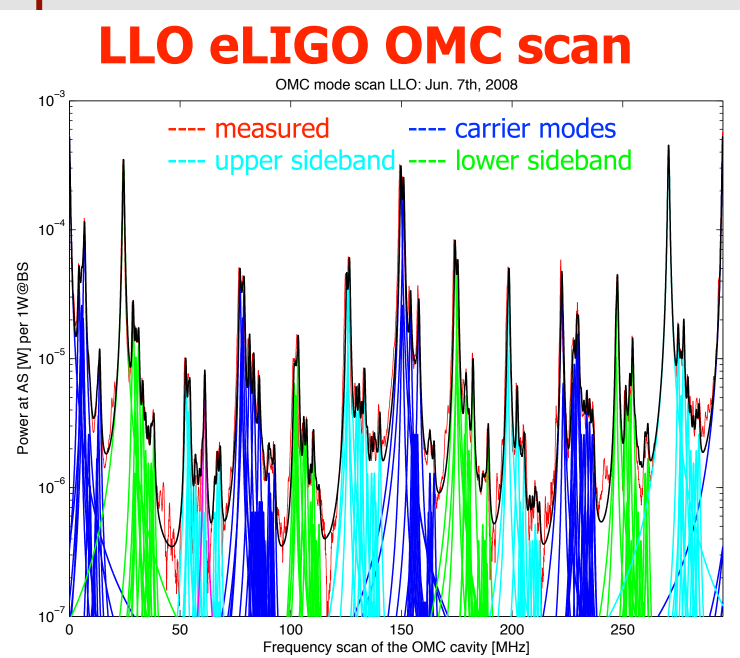
Estimation of the filtering performance

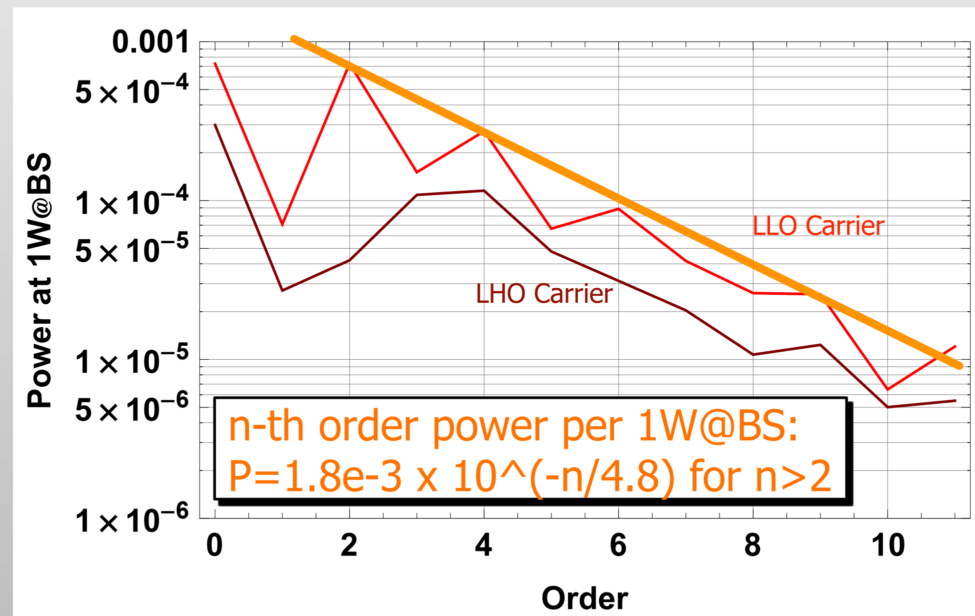
Total transmitted power

$= \sum$(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



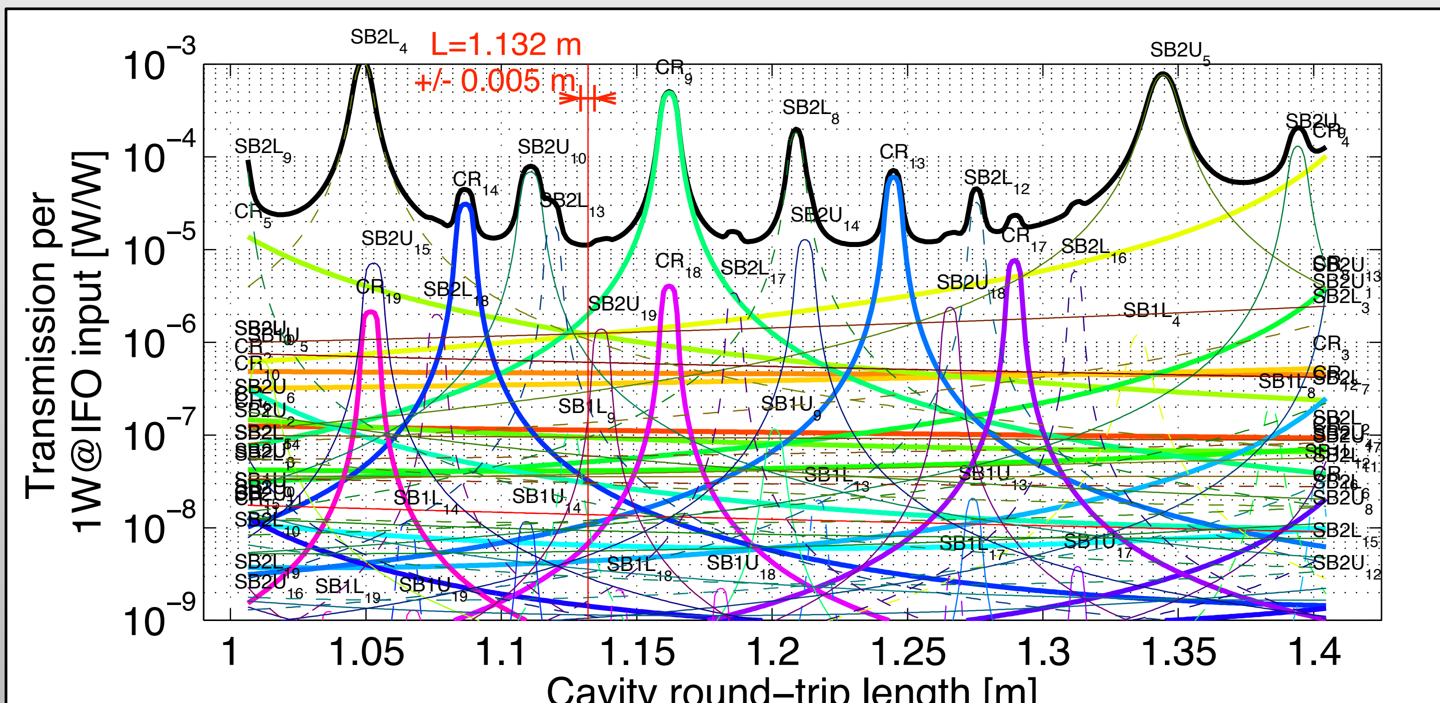


This wouldn't be a prediction, but have some usefulness, anyway

Filtering Performance

Estimated filtering performance

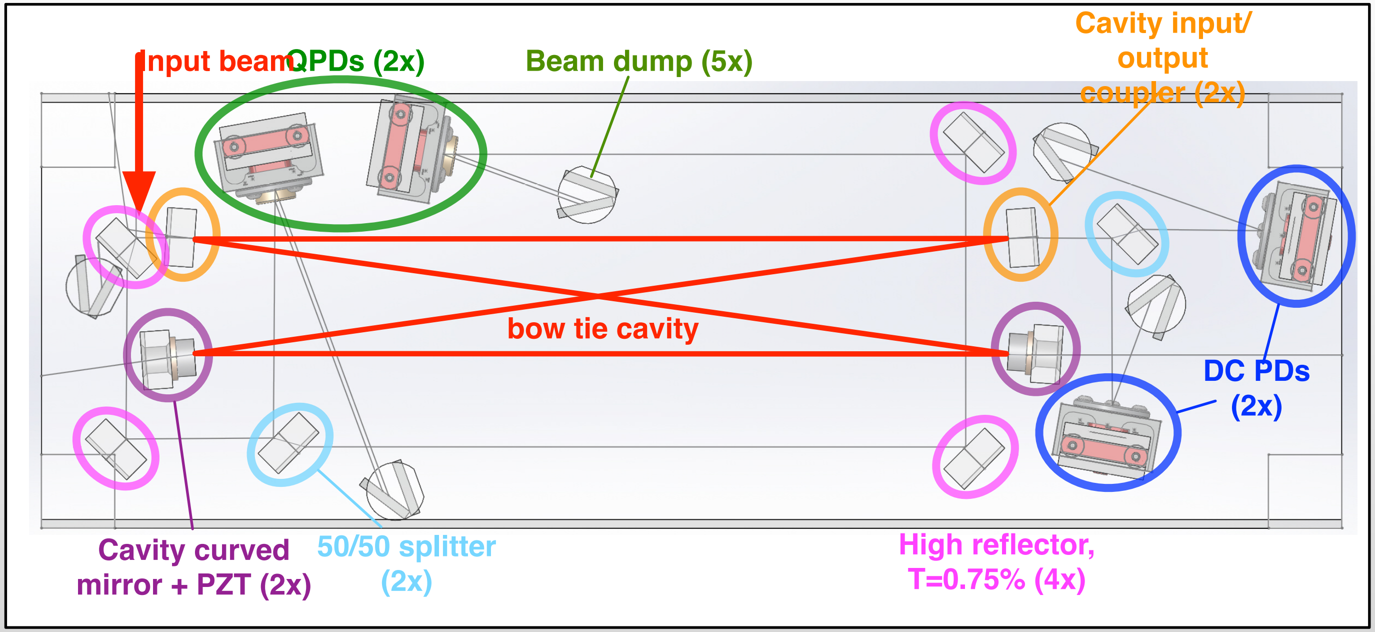
- Expected junk light power at the dark port (100W input = 4kW @BS)
  ~12W leakage => filtered down to 1mW. <u>Well within the PD capability.</u>
  This could become better thanks to mode healing and better optics in aLIGO
- Cavity length tolerance: L=1.132 +/– 0.005 [m]
- Mirror RoC tolerance: R=2.575 +/– 0.015 [m]



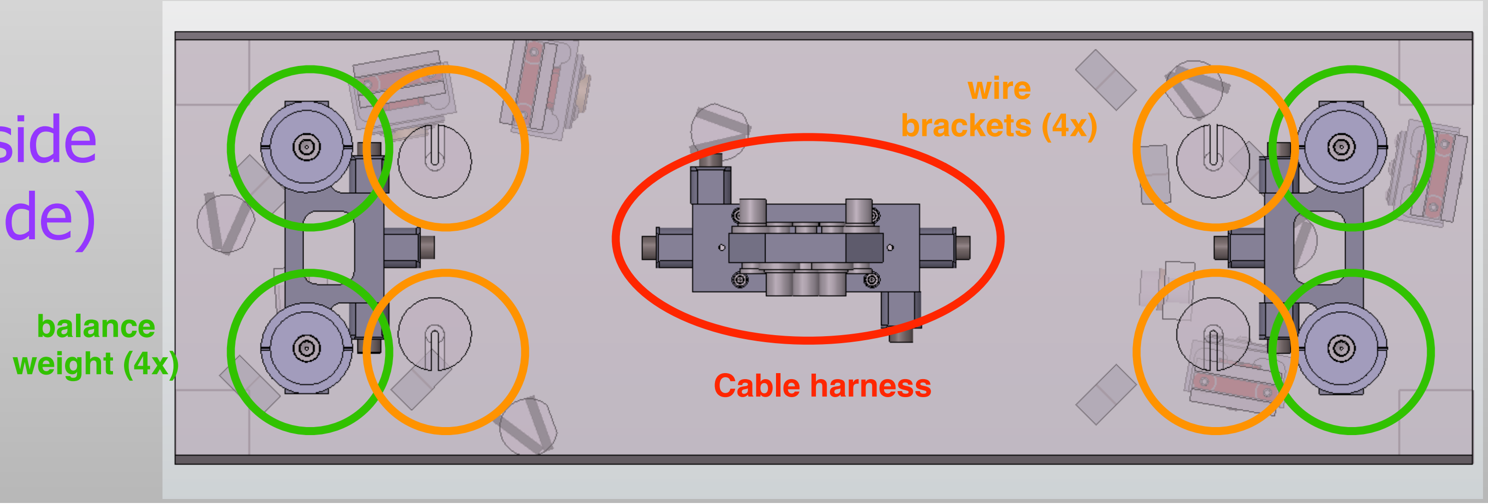
CRn - carrier n-th mode, SB(1,2)(U,L)n - sideband n-th mode,
SB1 - 9MHzSB, SB2 - 45MHz SB, U - upper SB, L - lower SB

How the OMC breadboard looks like

Bottom side (cavity side)



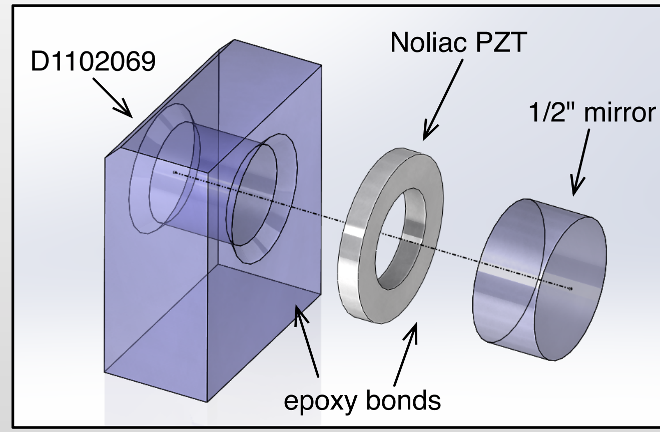
Top side (cable side)



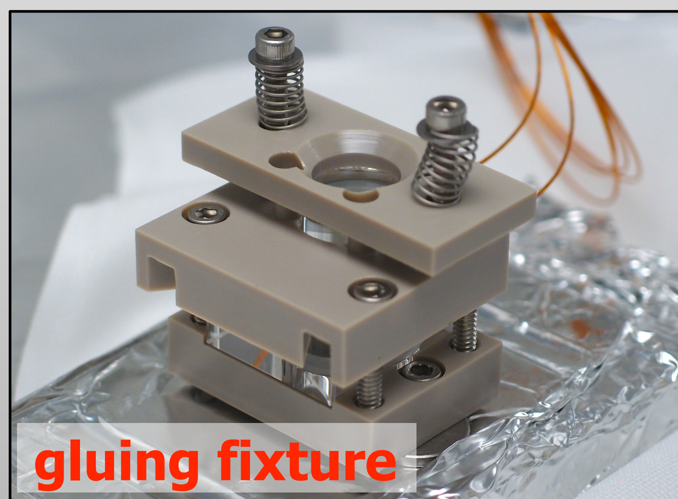
Fabrication

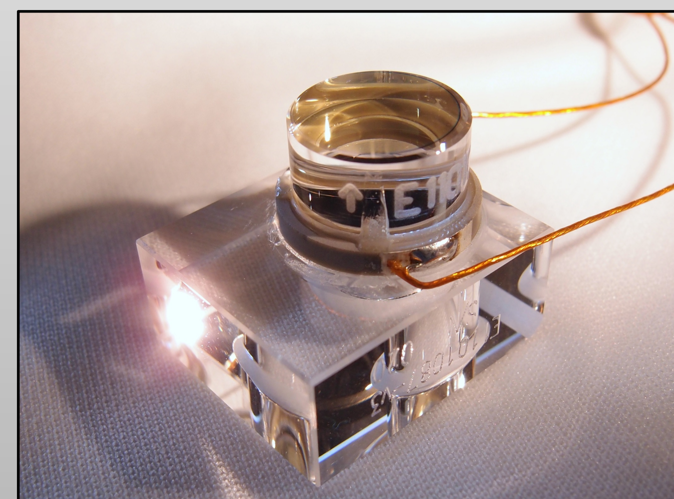
PZT-curved mirror subassembly

- PZT + 1/2" curved mirror: Glued on a mounting prism
- Bonding: Epoxy with borosilicate glass spheres (75-90um dia.)



- Wedging of the components:
  Characterized and arranged to minimize pitch misalignment of the cavity


gluing fixture



Fabrication

Bottom (cavity) side gluing

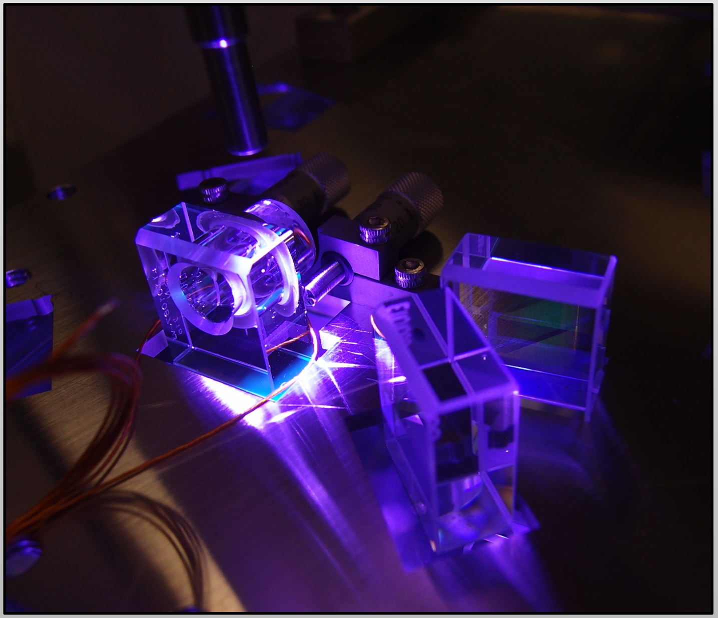
- Breadboard: held in a transport fixture
- Flat optics: Fused silica prisms
  with mirror coatings

- Template: for optics alignment

- Fine alignment:
  each curved mirrors were aligned
  with two micrometers on the template

- Monitoring of the FSR and TMS
  with an optical testing setup

- Bonding:
  UV-cure epoxy & UV illumination

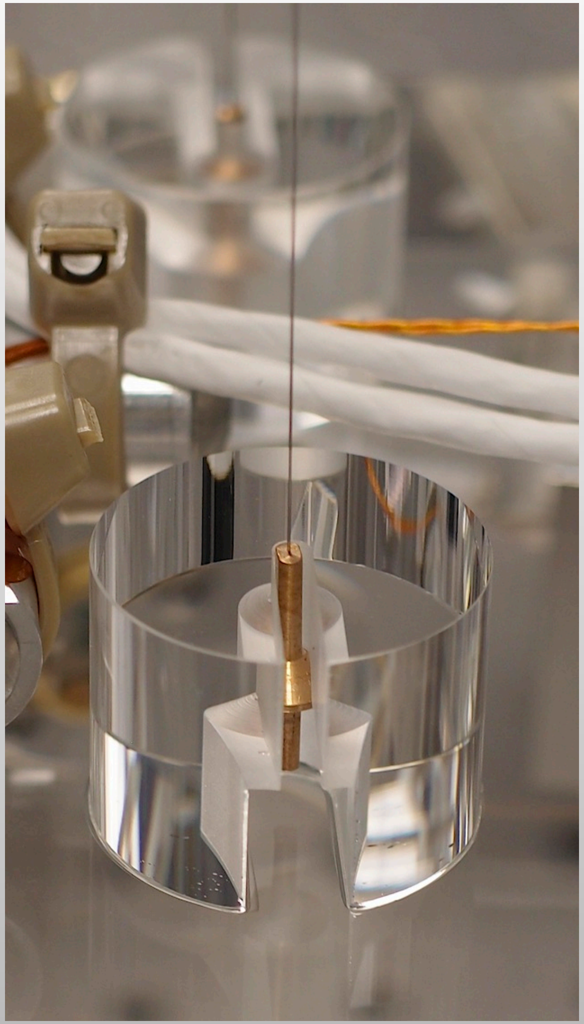


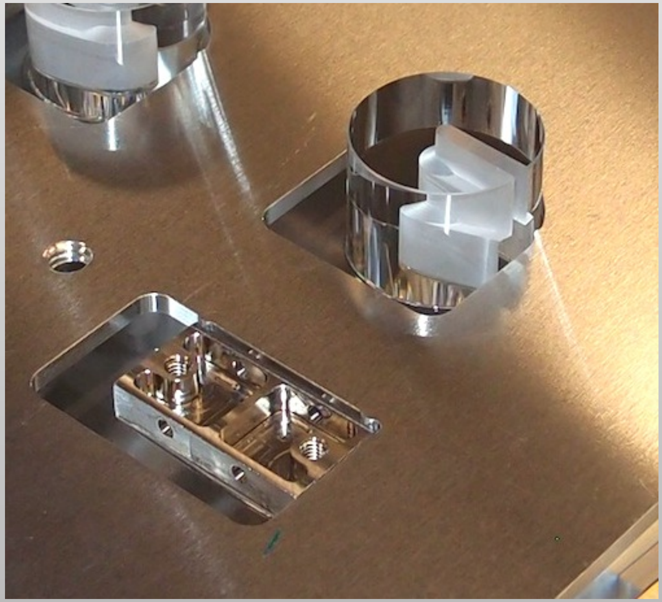
Fabrication

Top (cable) side gluing

- Suspension interface: Glass wire brackets
  To hook the suspension wires
  with conical clamps crimped

- Mounting blocks:
  Made of Invar to minimize CTE difference



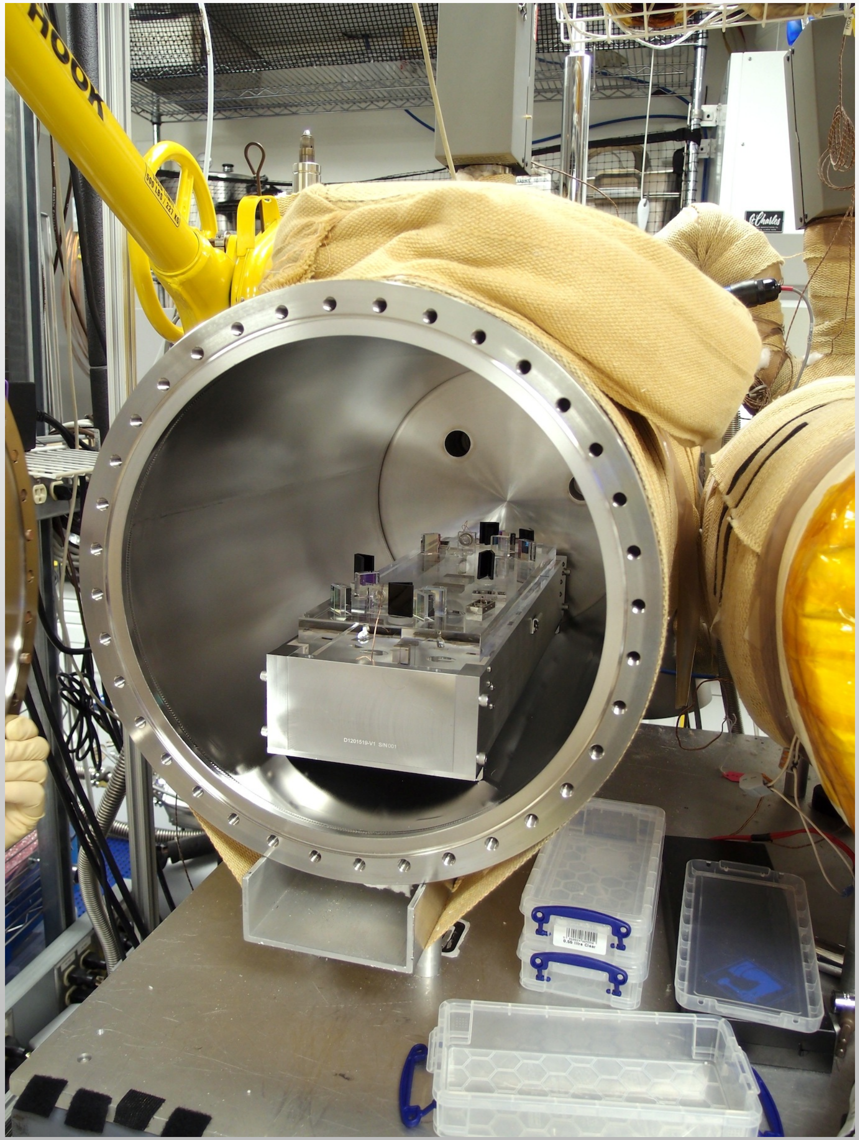


Fabrication

Vacuum Baking

at 80degC for 48 hours

- completion of curing epoxy
- reduce surface outgass

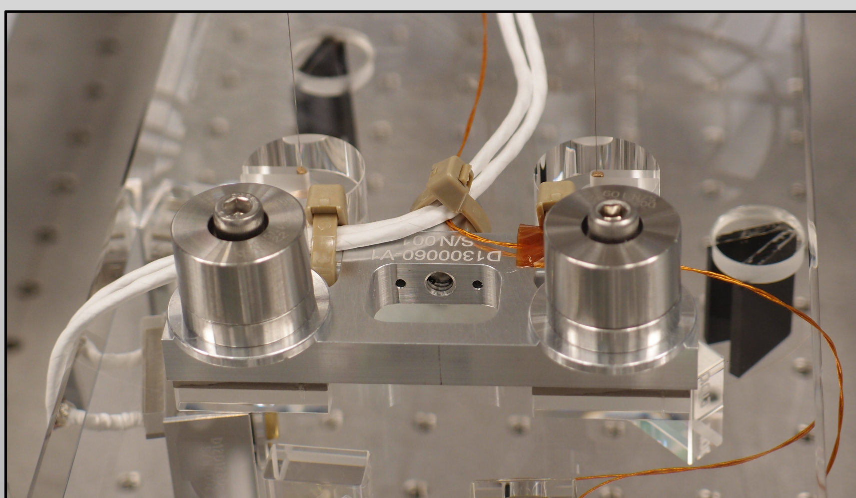


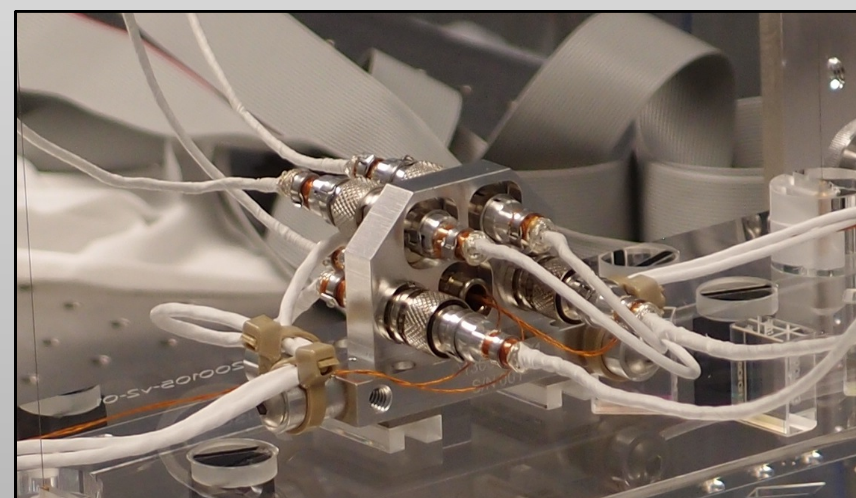
Fabrication

Attaching peripheral components:

- DC photodiodes / QPDs
  - Housings mounted on invar blocks
  - Height adjusted by shims
  - DCPD housing coated with Alumina

- Cables
  - Routed to the cable harness





Fabrication

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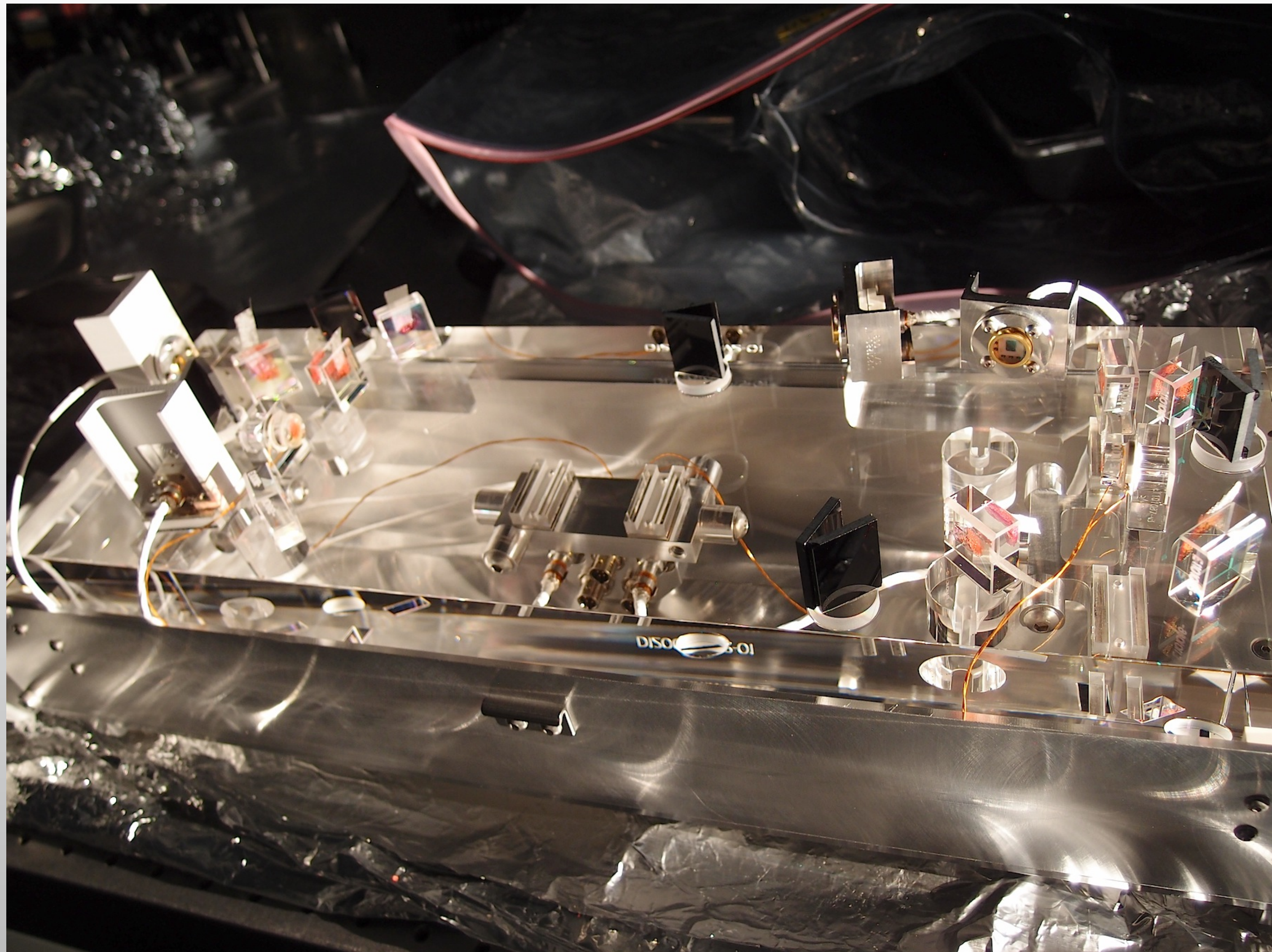
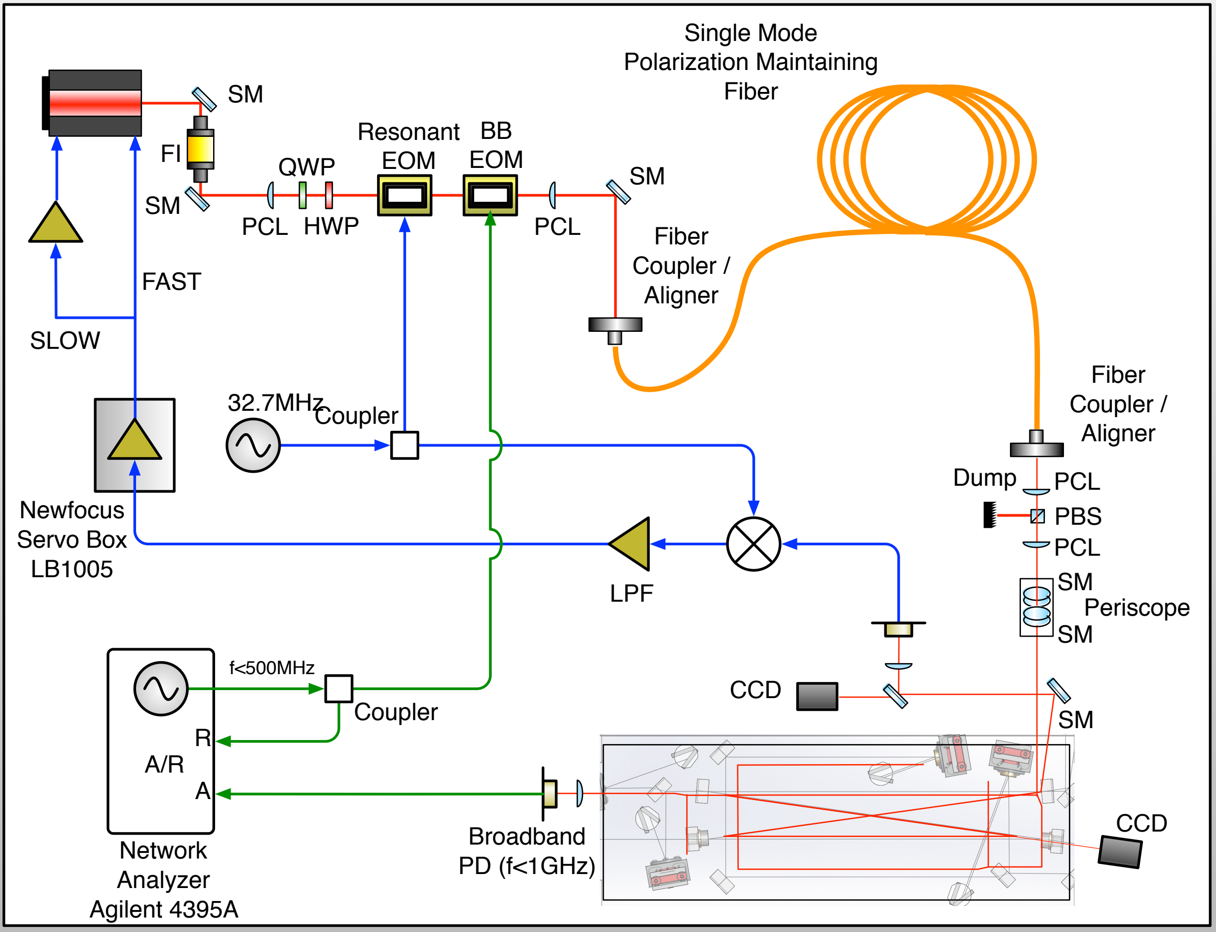
OMC ready for the shipment



Optical testing

A tabletop setup@CIT

- fine parameter adjustment during the gluing
- characterization after the baking
  - Power budget
  - PZT responses
- A broadband EOM
  - FSR, finesse,
  - and HOM structure



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%)

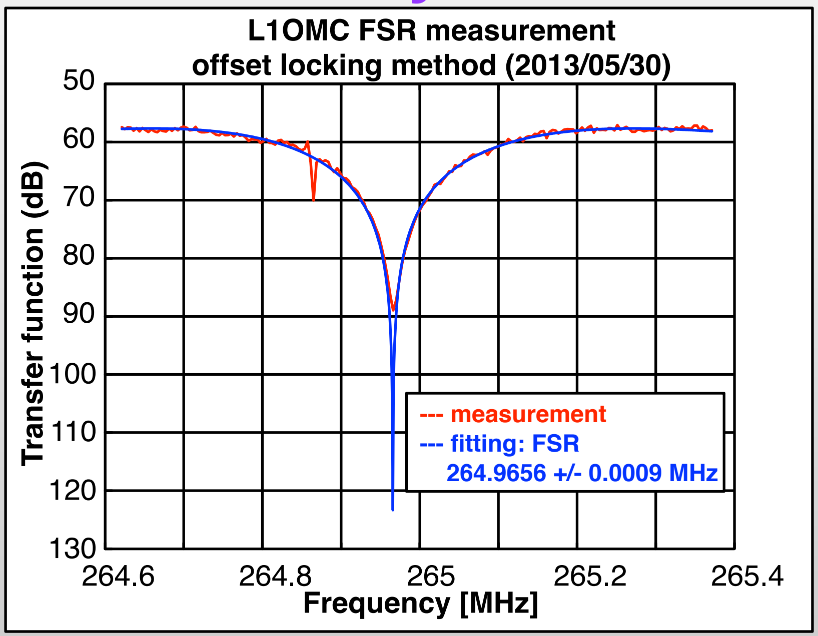
About 20% total loss allowed for 6dB squeezing.

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)

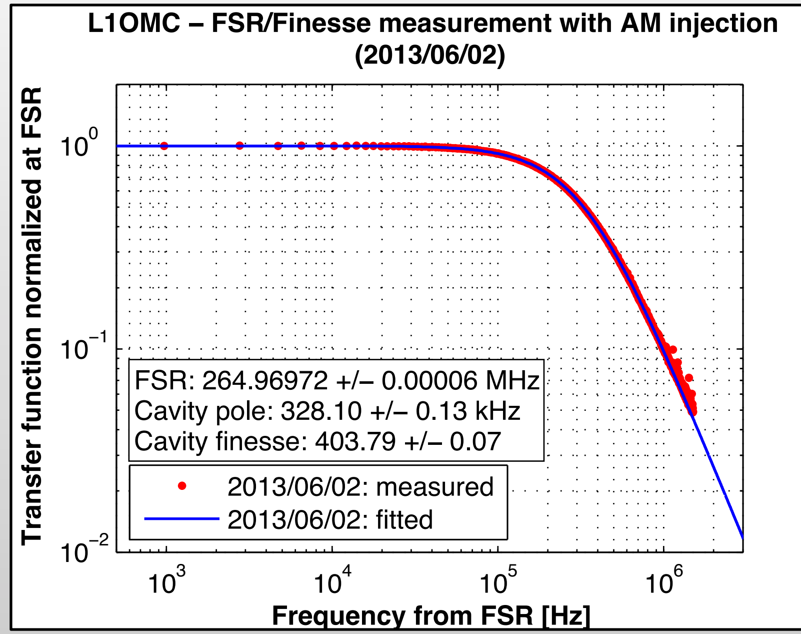
Optical testing

Cavity round-trip length ~ two methods

1) Offset locking: FM-AM conversion at around the FSR
2) AM sideband injection



Method1



Method2

Cavity length: (Spec.: 1.132 +/– 0.005 m)

1.131438 +/– 4×10^{-6} m 1.131421 +/– 3×10^{-6} m

Finesse: (Spec. 390) 403.79 +/– 0.07

Optical testing

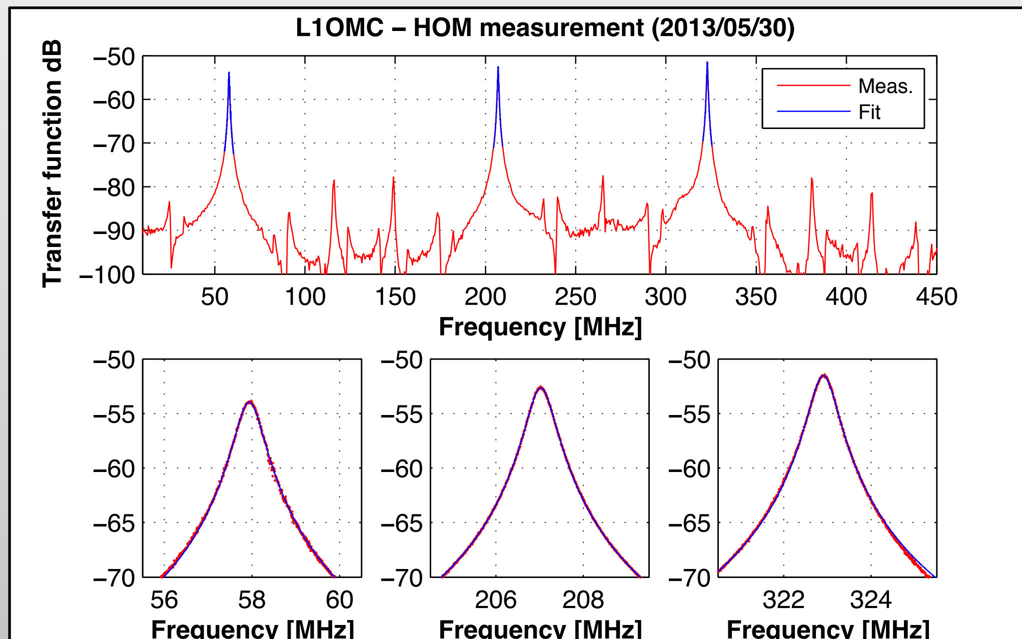
Transverse Mode Spacing (TMS)

PM sideband injection, intentional misalignment of the input beam

-> Carrier TEM_{00} and RF HOM get resonant

Intentional clipping at the transmission PD

-> RF signal on the PD



Result:		Spec.
Pitch TMS/FSR:	$0.218822 \pm 1\times10^{-6}$	0.2188
Yaw TMS/FSR:	$0.219218 \pm 1\times10^{-6}$	0.2194

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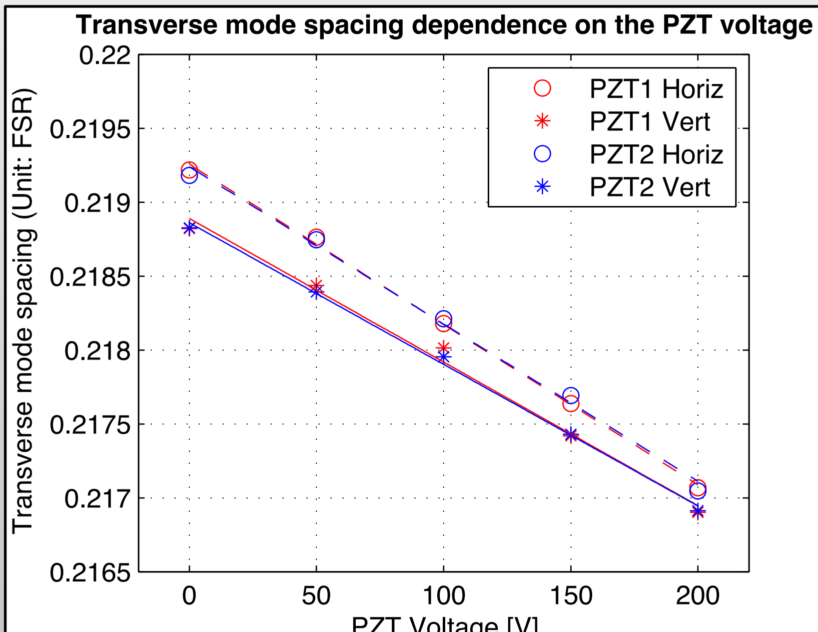
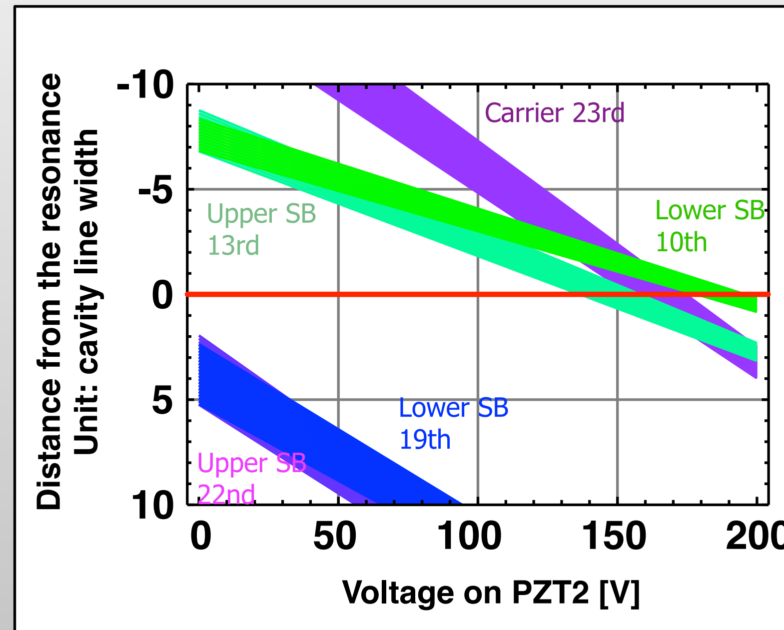
TMS depend on the PZT voltage

- 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

Optical testing @CIT

PZT response

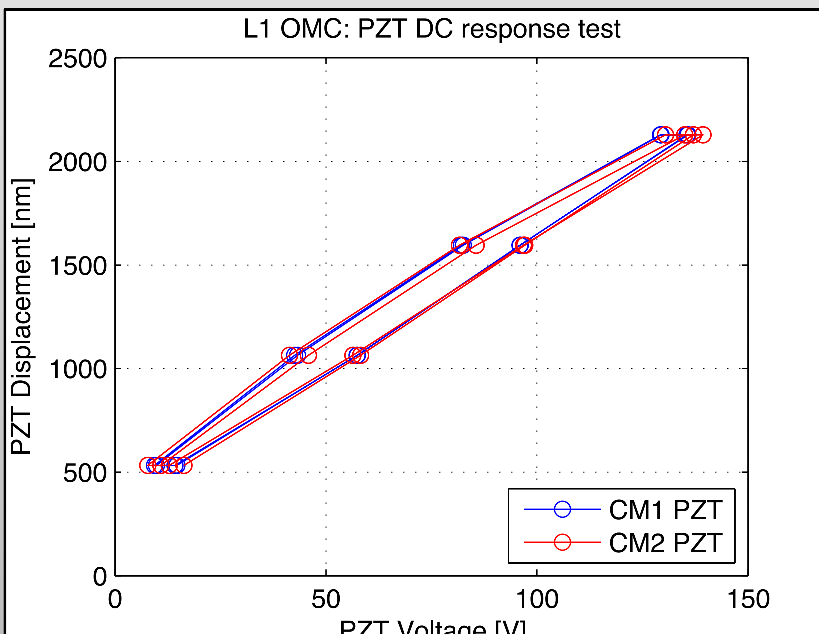
The DC response: checked with free running fringes

The AC response: measured with the cavity locked

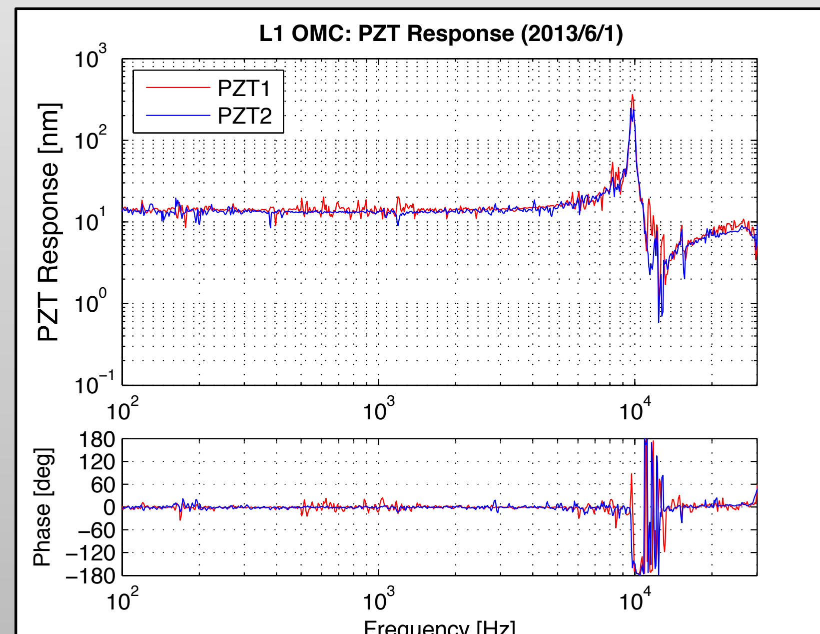
PZT1 response@DC: 13.24 +/− 0.02 nm/V (avg)

PZT2 response@DC: 12.9 +/− 0.1 nm/V (avg)

First resonance: 10 kHz



▲ PZT DC scan

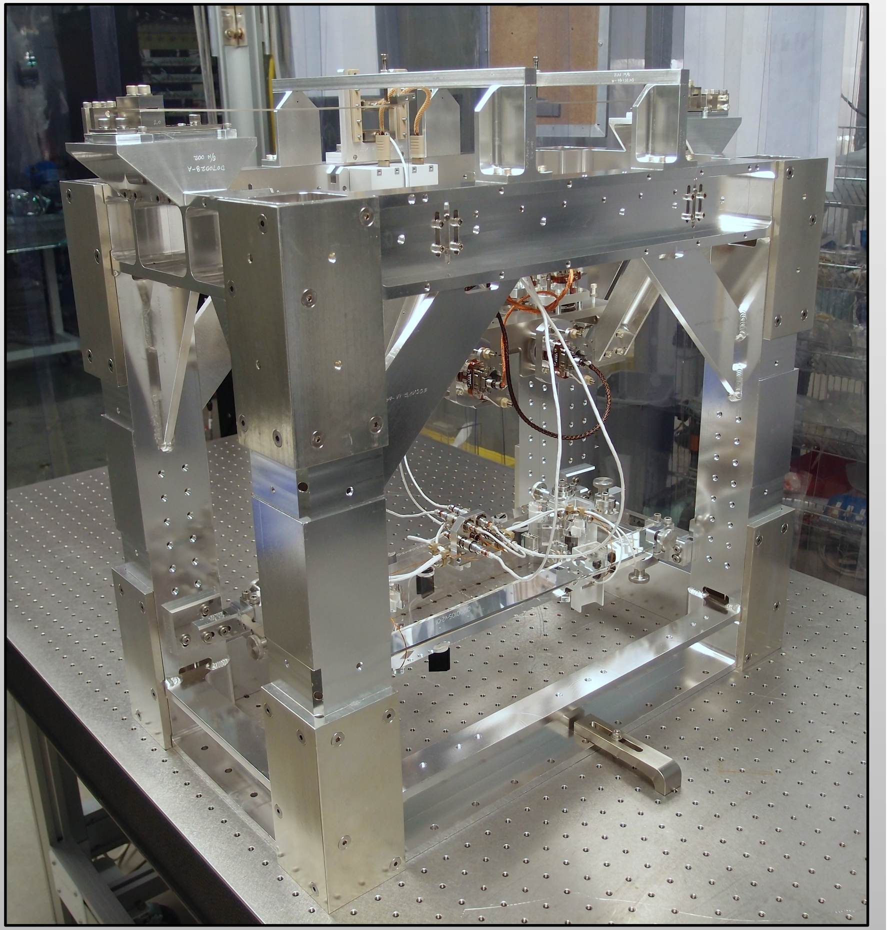


▲ PZT AC response

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
- Suspension tests in HAM6

Summary

aLIGO OMC

Designed based on the eLIGO experience and lessons

The first OMC was built

The building procedure was established

Optical testing

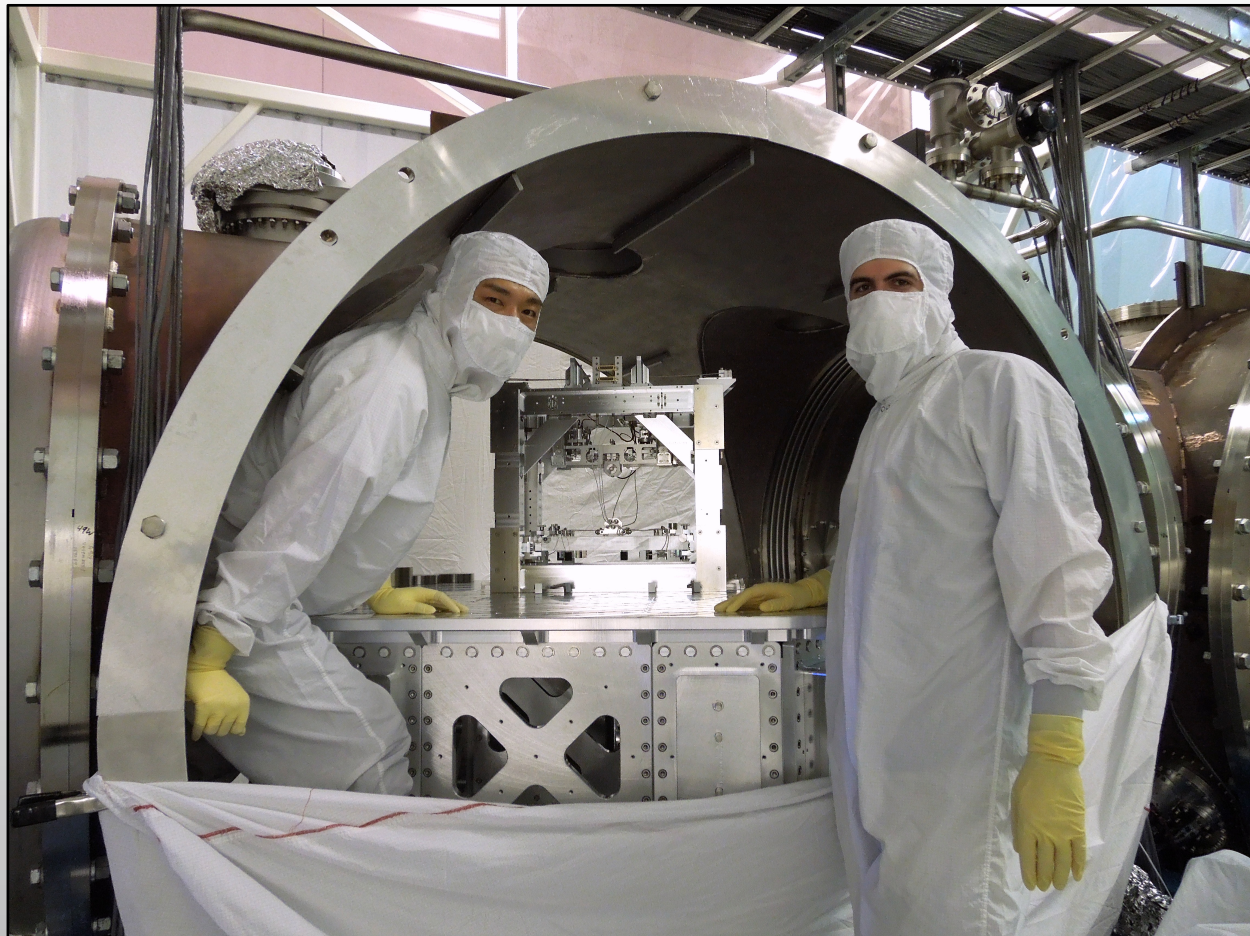
Observed the as-designed cavity transmission of ~98%
Total thruput (for the carrier TEM00): ~90%
Confirmed that avoidance of the low-order HOMs
Found that the TMS is dependent on the PZT voltages.

Installed on LLO HAM6 in Jun 2013

Now in commission at the LLO site!

Summary

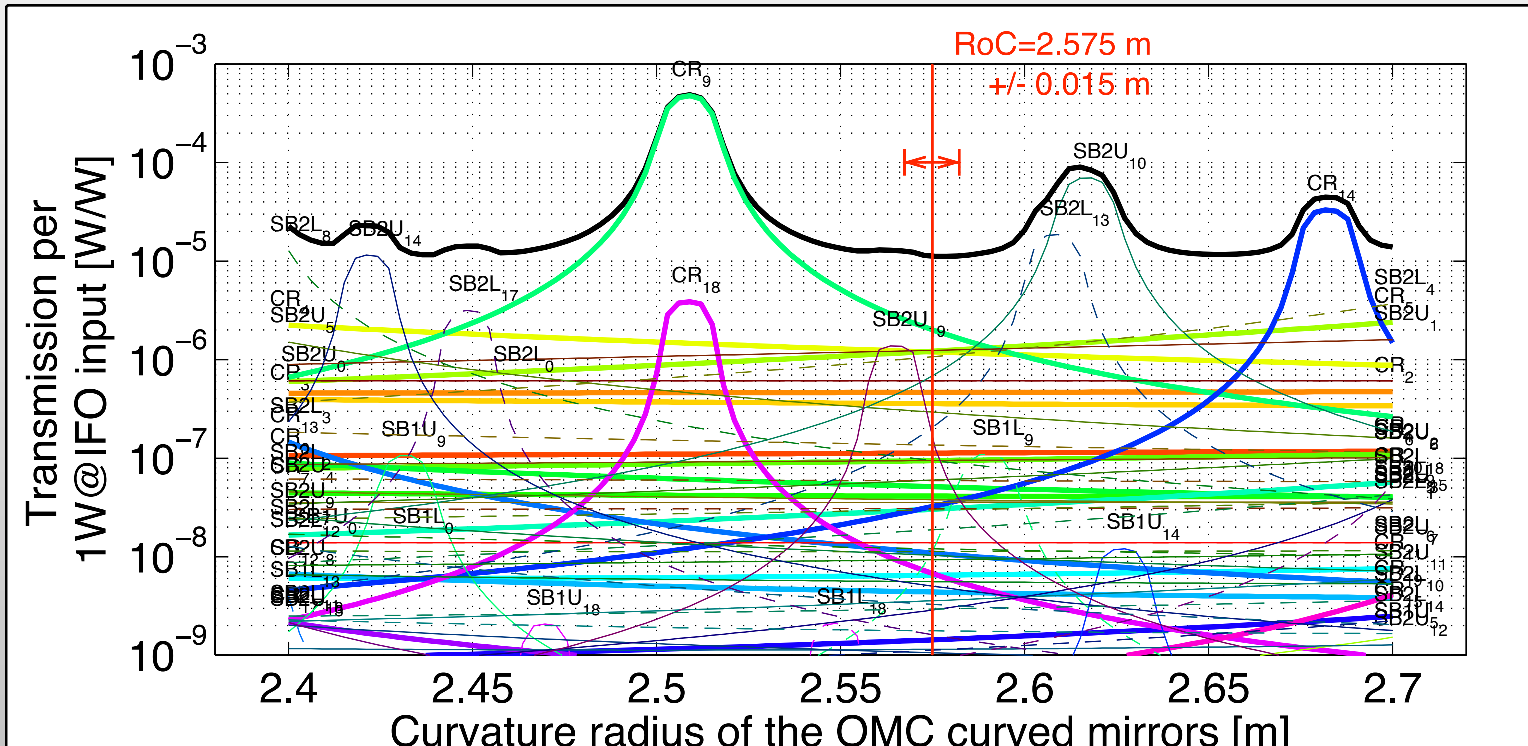
Thank you for your attention!



Filtering Performance

Estimated filtering performance

- 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

Comparison between eLIGO/aLIGO OMCs

	eLIGO	aLIGO	
cavity design:			
	semi monolithic	same	for flexibility of the cavity parameters
breadboard materialcavity design:			
	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	