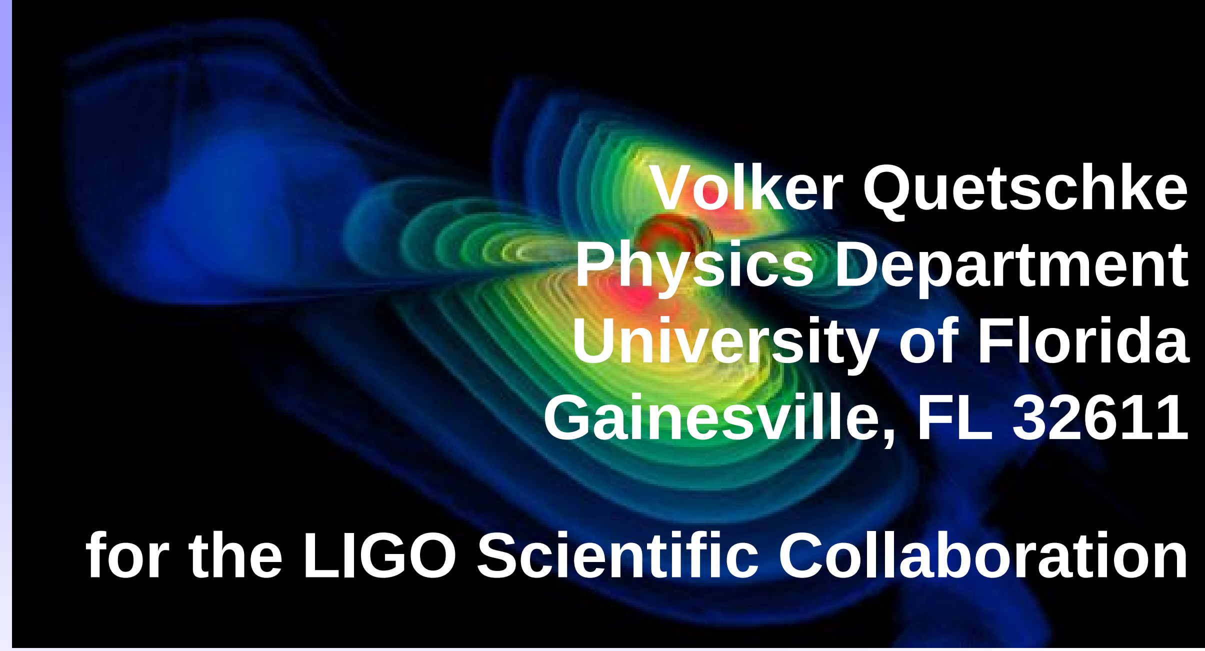
LIGO

Electro Optic Modulators and Modulation for Enhanced LIGO and beyond



“Colliding Black Holes”, Werner Berger, AEI, CCT, LSU

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UF | UNIVERSITY of FLORIDA

LSC

Support: NSF

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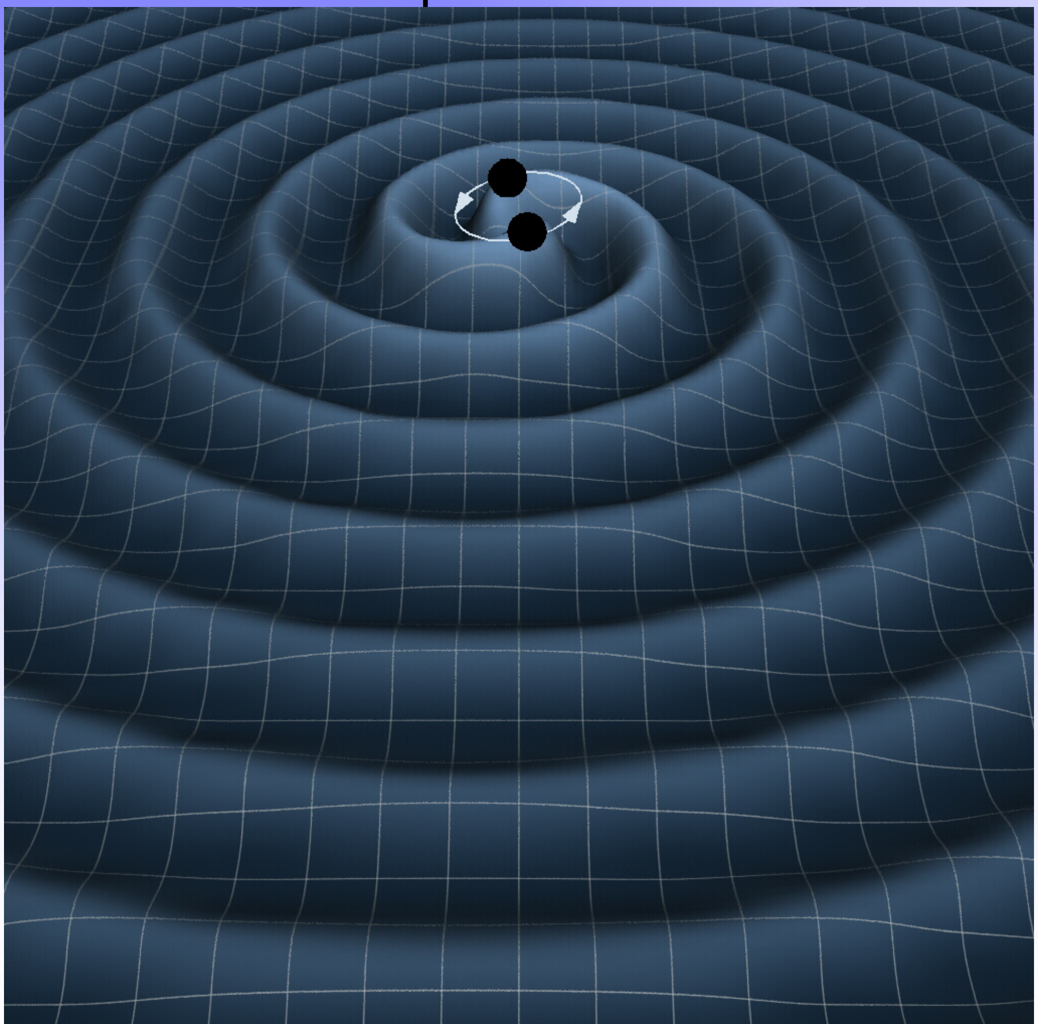
Outline

- Gravitational waves
  - What are they
  - How to measure
- LIGO - the instrument
- Upgrades:
  - Now: Enhanced LIGO
  - Soon: Advanced LIGO
- Phase modulators for LIGO
- Advanced modulation schemes

LIGO Gravitational waves and astrophysics

Predicted by Einstein in 1916, GWs are propagating fluctuations in the curvature of space-time:



- Perturbations of geometry can be expressed as fractional distortion of proper distances:

$$h = \mathrm{d}x / |x|$$

- Calculate emissions from accelerating non-spherical mass distributions:

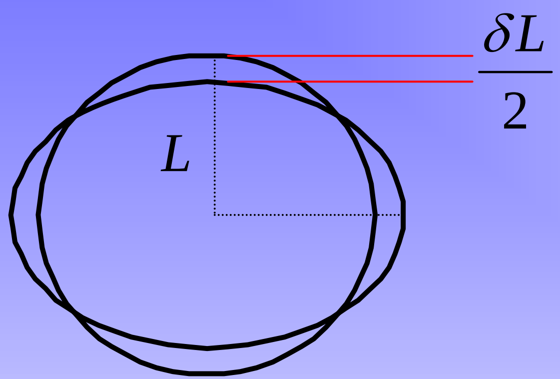
$$\Rightarrow \quad h_{\mu\nu}(\omega,t) = \frac{2G}{r\,c^4}\ddot{I}_{\mu\nu}(\omega,t)$$

$$\Rightarrow \quad h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

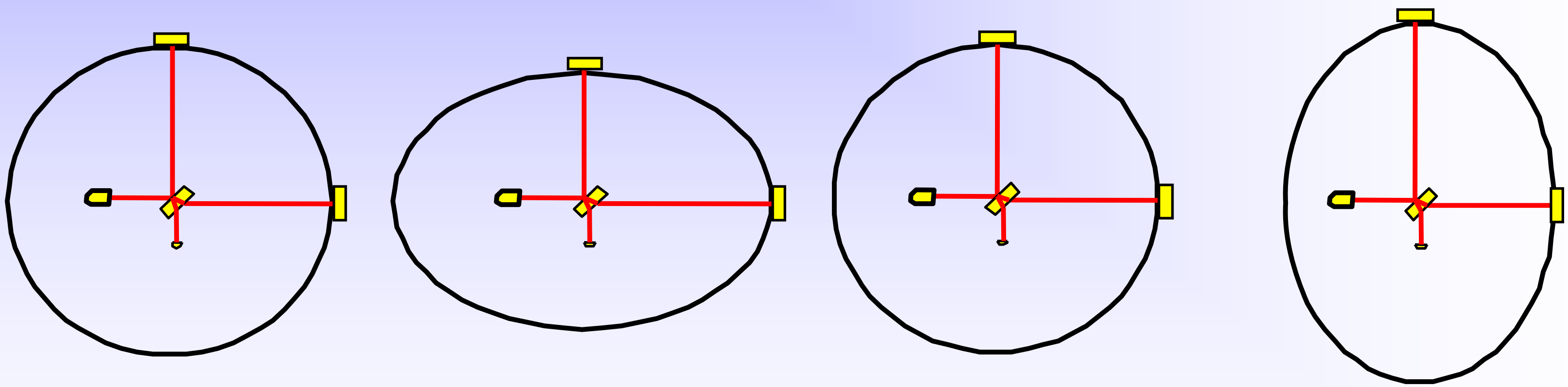
- Estimated length change for a binary neutron star system (10Mpc / 4000m long arm)

$$\Delta L = h \times L \approx 10^{-21} \times 4{,}000\,m \approx 10^{-18}\,m$$

How to Measure Gravitational Waves ?



Effect on a ring of free falling masses: Gravitational waves shrink space along one axis perpendicular to the wave direction as they stretch space along another axis perpendicular both to the shrink axis and to the wave direction.



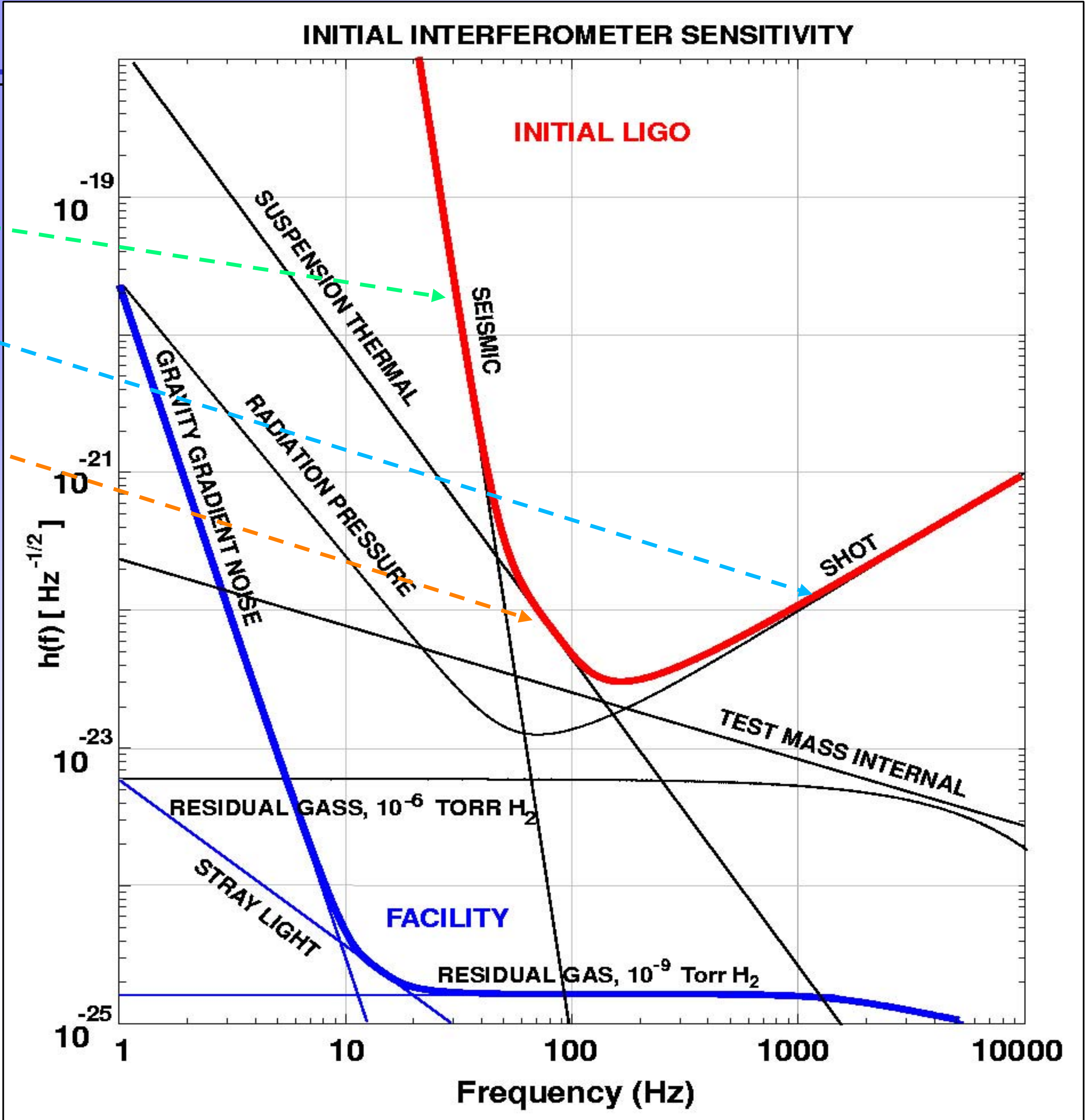
$t = 0$ $\quad$ $t = \frac{\tau}{4}$ $\quad$ $t = \frac{\tau}{2}$ $\quad$ $t = \frac{3\tau}{4}$

rvatory Sites
riangulation possible
O)
MIT
0 ms
Caltech
➢Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.g
➢NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds)
and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosp
USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Sa

Design Noise Limits

- Initial sensitivity limits
  - **seismic noise** at the lowest frequencies
  - **shot noise** at high frequencies
  - **thermal noise** at intermediate frequencies

- Based on conservative extrapolation of prototype technologies (circa ~'97)



Vacuum Chambers provide housing for the optics

View inside Corner Station

Standing at vertex beam splitter

LIGO

Beam Tubes and Enclosures

Precast concrete enclosure: *bulletproof*

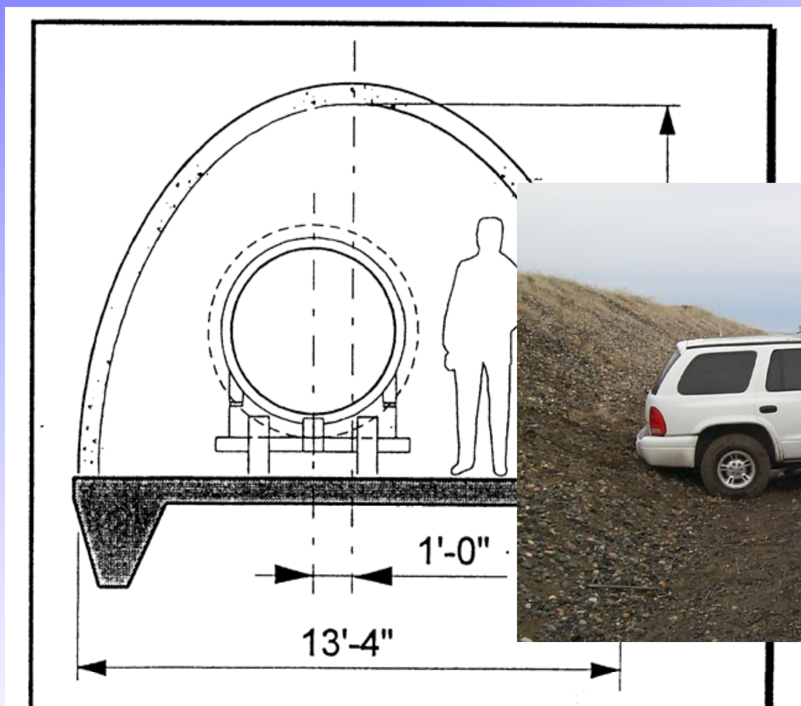


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

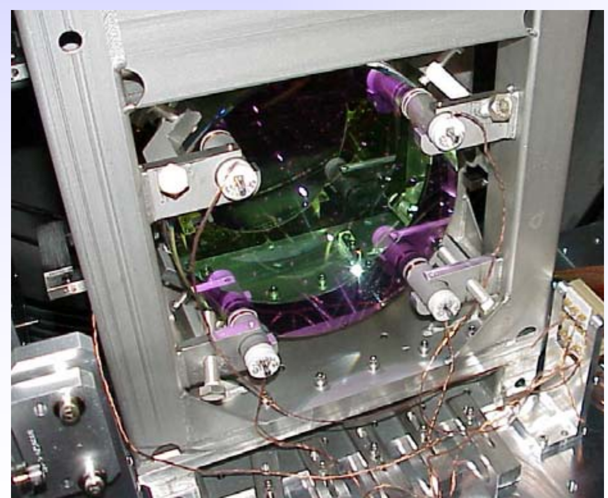
…be

- **…am; 3 mm stainless**
  - **[illegible] low-hydrogen steel process**
  - **65 ft spiral weld sections**
  - **50 km of weld (NO LEAKS!)**
  - **20,000 m³ @ 10^{-8} torr; earth's largest high vacuum system**

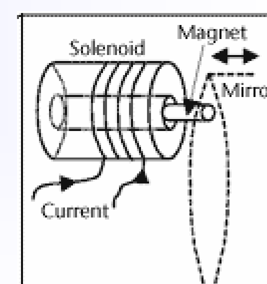
Mirror Suspensions

Pendulum design

- provide 10^2 suppression above 1 Hz
- provide ultraprecise control of optics displacement (< 1 pm)

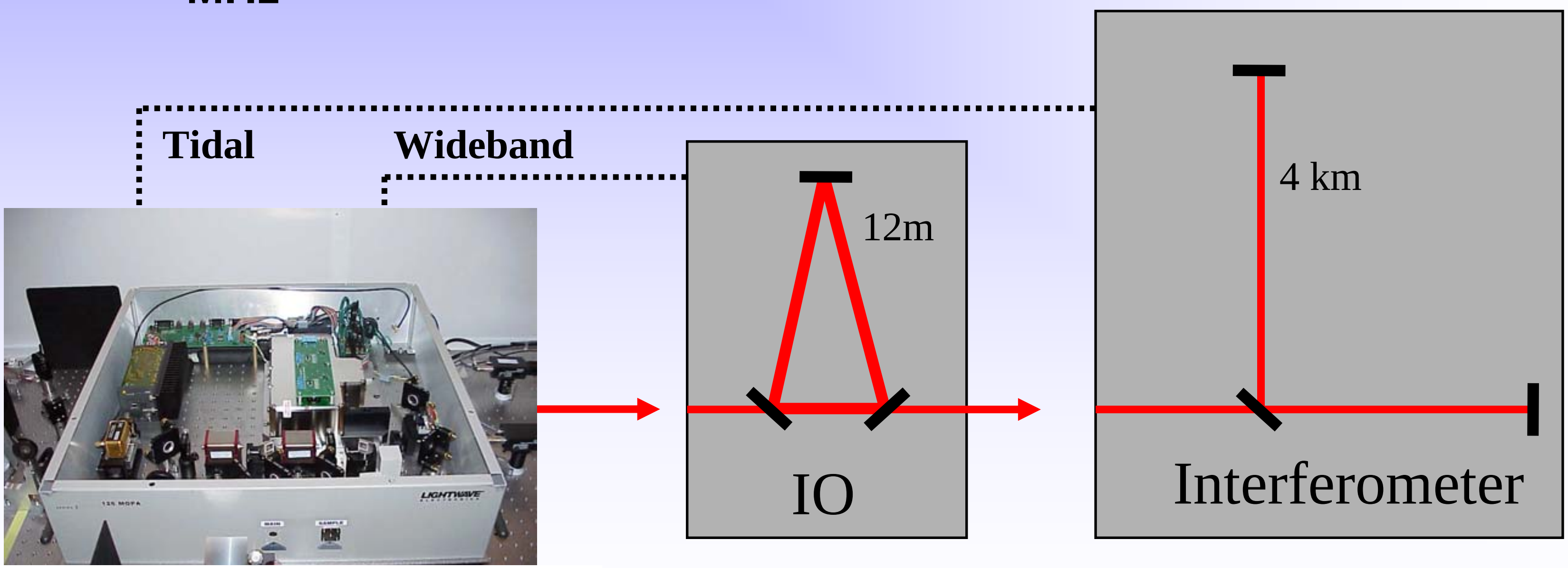


OSEM

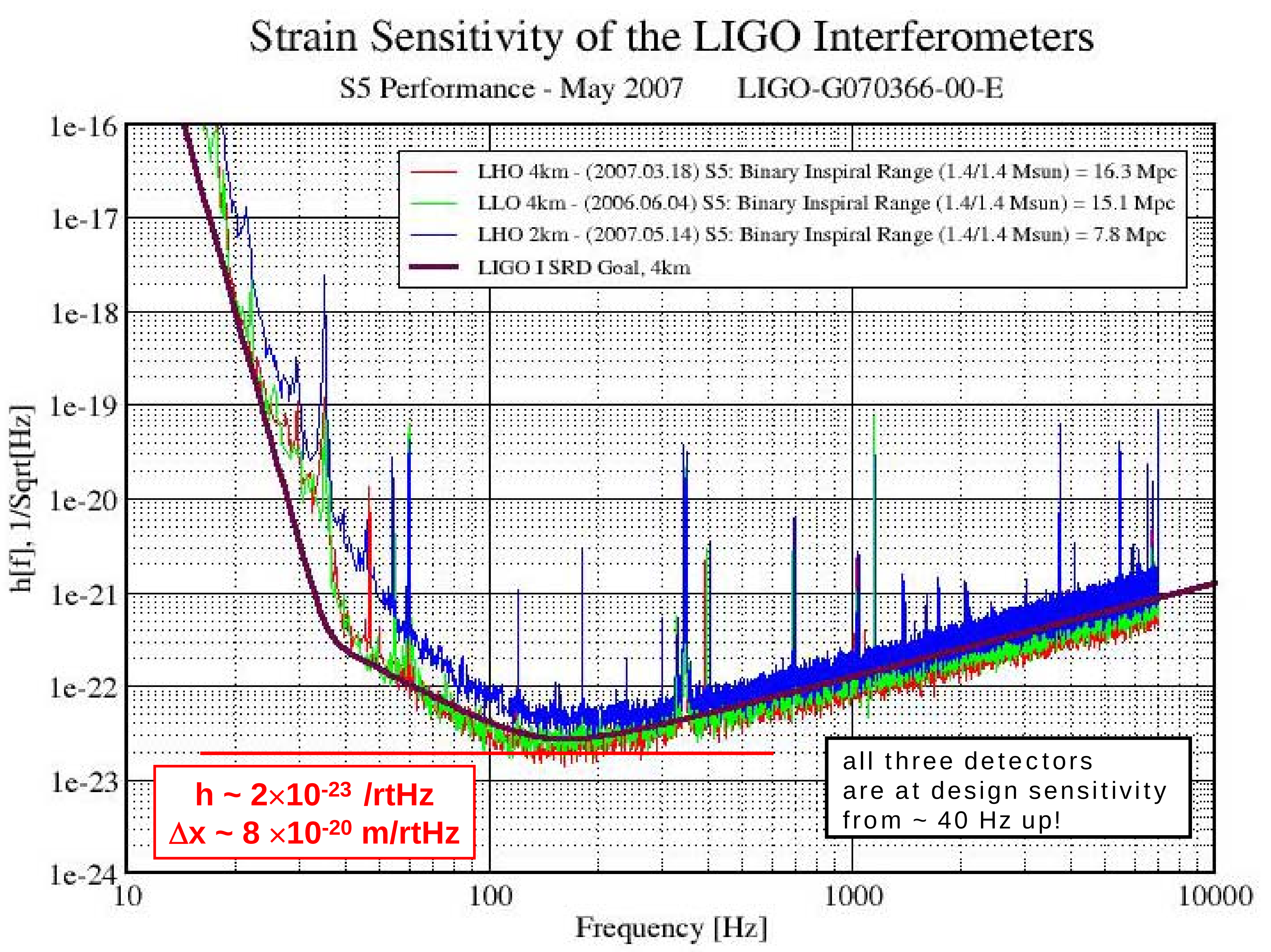


The pre-stabilized Laser System

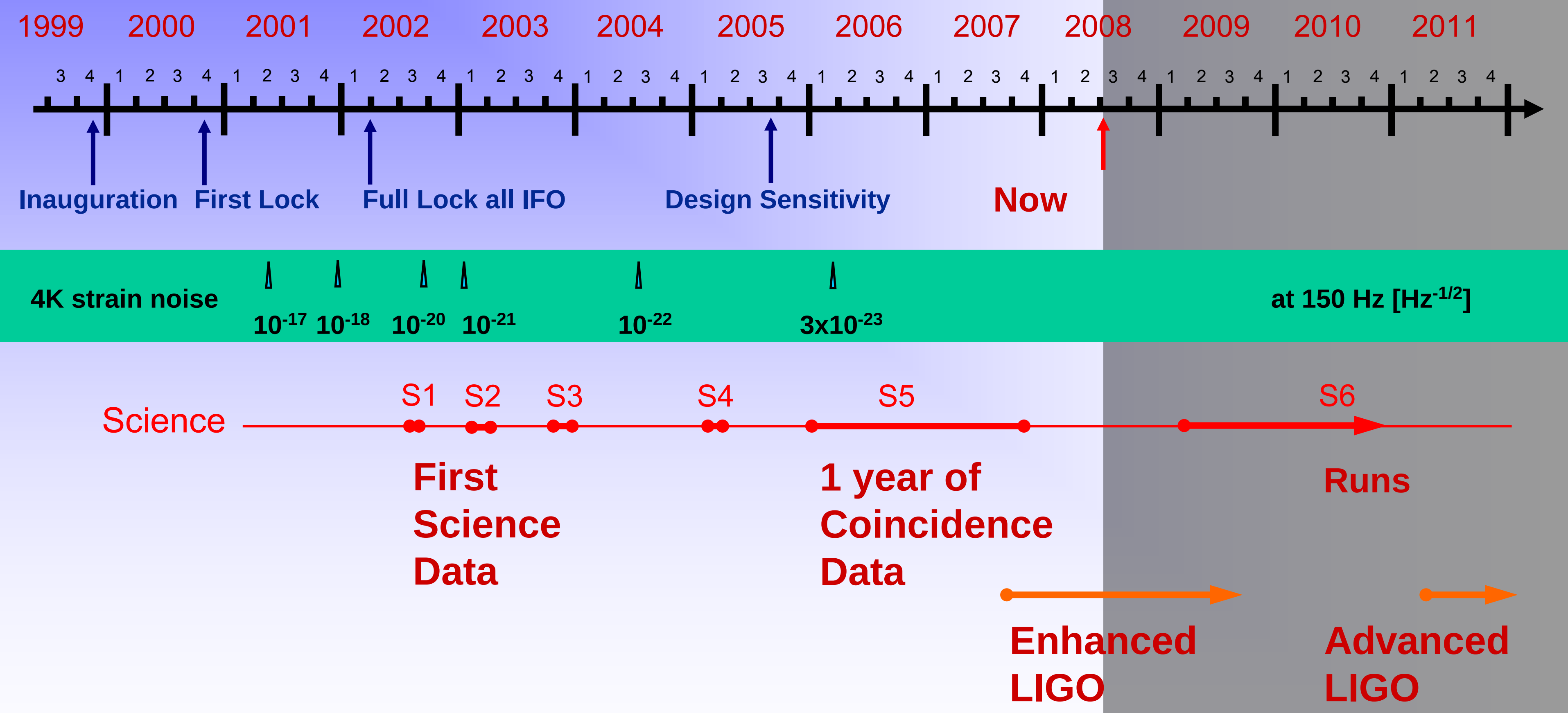
- Deliver pre-stabilized laser light to the long mode cleaner
  - **Frequency fluctuations**
  - **In-band power fluctuations**
  - **Power fluctuations at 25 MHz**
- Provide actuator inputs for further stabilization
  - **Wideband** $10^{-4} \mathrm{Hz}/\sqrt{\mathrm{Hz}}$
  - **Tidal** $10^{-7} \mathrm{Hz}/\sqrt{\mathrm{Hz}}$



10 W Nd:YAG Laser, joint development with Lightwave Electronics


Strain Sensitivity of the LIGO Interferometers
S5 Performance - May 2007
LIGO-G070366-00-E
LHO 4km - (2007.03.18) S5: Binary Inspiral Range (1.4/1.4 Msun) = 16.3 Mpc
LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
LHO 2km - (2007.05.14) S5: Binary Inspiral Range (1.4/1.4 Msun) = 7.8 Mpc
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]
h ~ 2×10^-23 /rtHz
Δx ~ 8 ×10^-20 m/rtHz
all three detectors
are at design sensitivity
from ~ 40 Hz up!

LIGO Upgrades

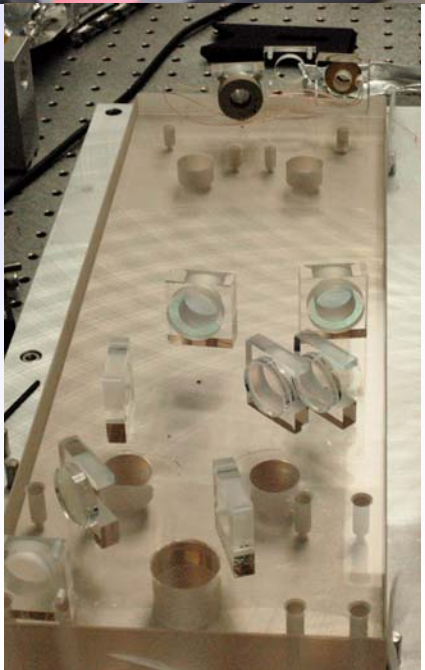


Enhanced LIGO

- Factor of ~2 improvement in strain sensitivity of the two 4km instruments (nearly order-of-magnitude improvement in rate)
- All upgrades make use of Advanced LIGO technology: retire risk
- Work was started before S5 was finished, installation begun after S5 finished, projected completion date is 02/2009
- Projected date to start S6 is 03/2009

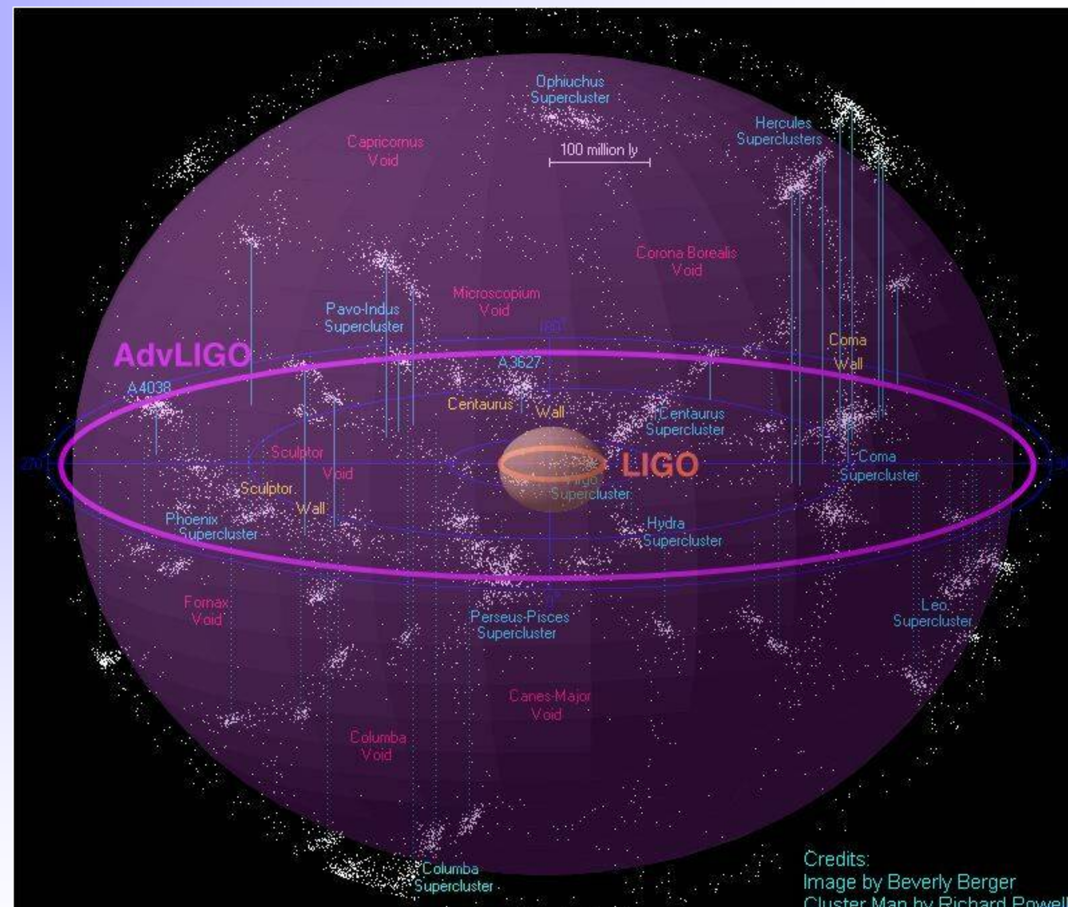
Enhanced LIGO

- **35 W Laser**
  - **4x increase in power**
  - **The "front-end" of the AdL laser**
  - **Supplied by LZH/AEI as part of Adv. LIGO**
- **High Power Input Optics**
  - **AdL electroptic Modulators (UF)**
  - **AdL Faraday Isolators (UF & IAP, Russia)**
- **AS detection in vacuum**
  - **AdL active seismic system in HAM6**
  - **Output mode cleaner**
  - **In-vacuum AdL photodetectors**
- **DC Readout of GW Strain**
  - **AdL readout scheme (DC instead of RF)**
  - **AdL Output Mode Cleaner cavity**
- **Thermal Compensation**
  - **Upgraded power & beam shaping**

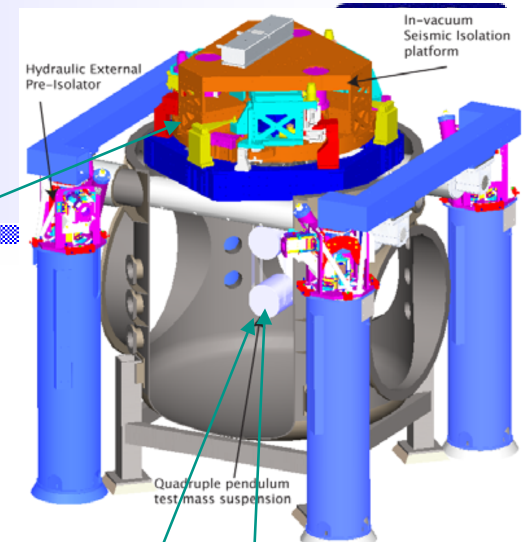


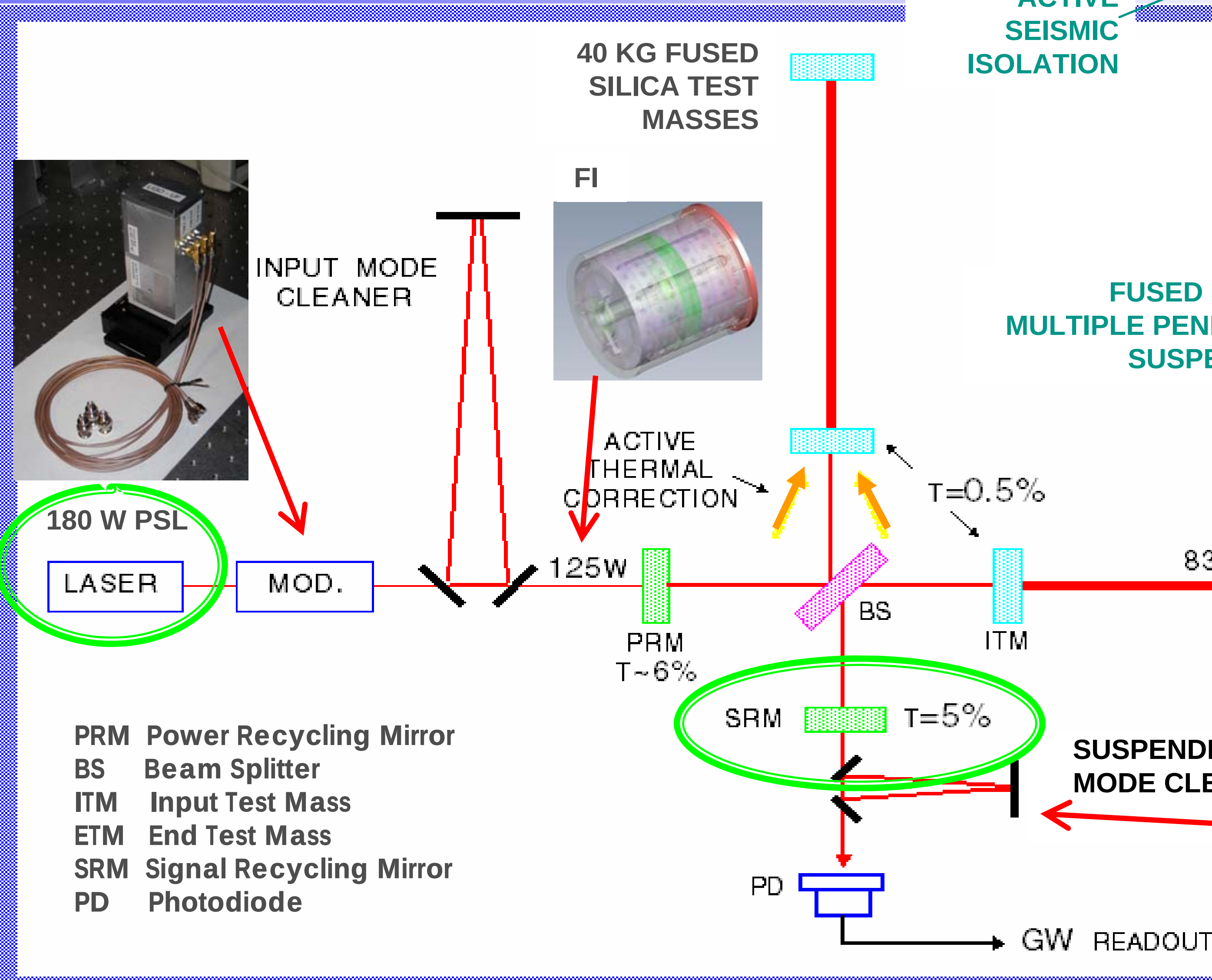
Advanced LIGO

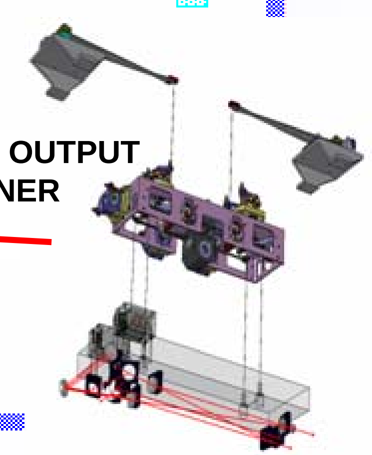
- At current sensitivity, LIGO detectors are rate-limited (NS/NS inspirals)
  - ~ 0.01 event per year
- Advanced LIGO will increase sensitivity (hence rate) over initial LIGO
  - range *r* ~ *1/h*
  - Event rate ~ r^3
- Most probable NS/NS event rate in Advanced LIGO is
  - ~ 40 per year
- Funding to started in 2008, construction to begin in 2011



LIGO Advanced LIGO Design Features

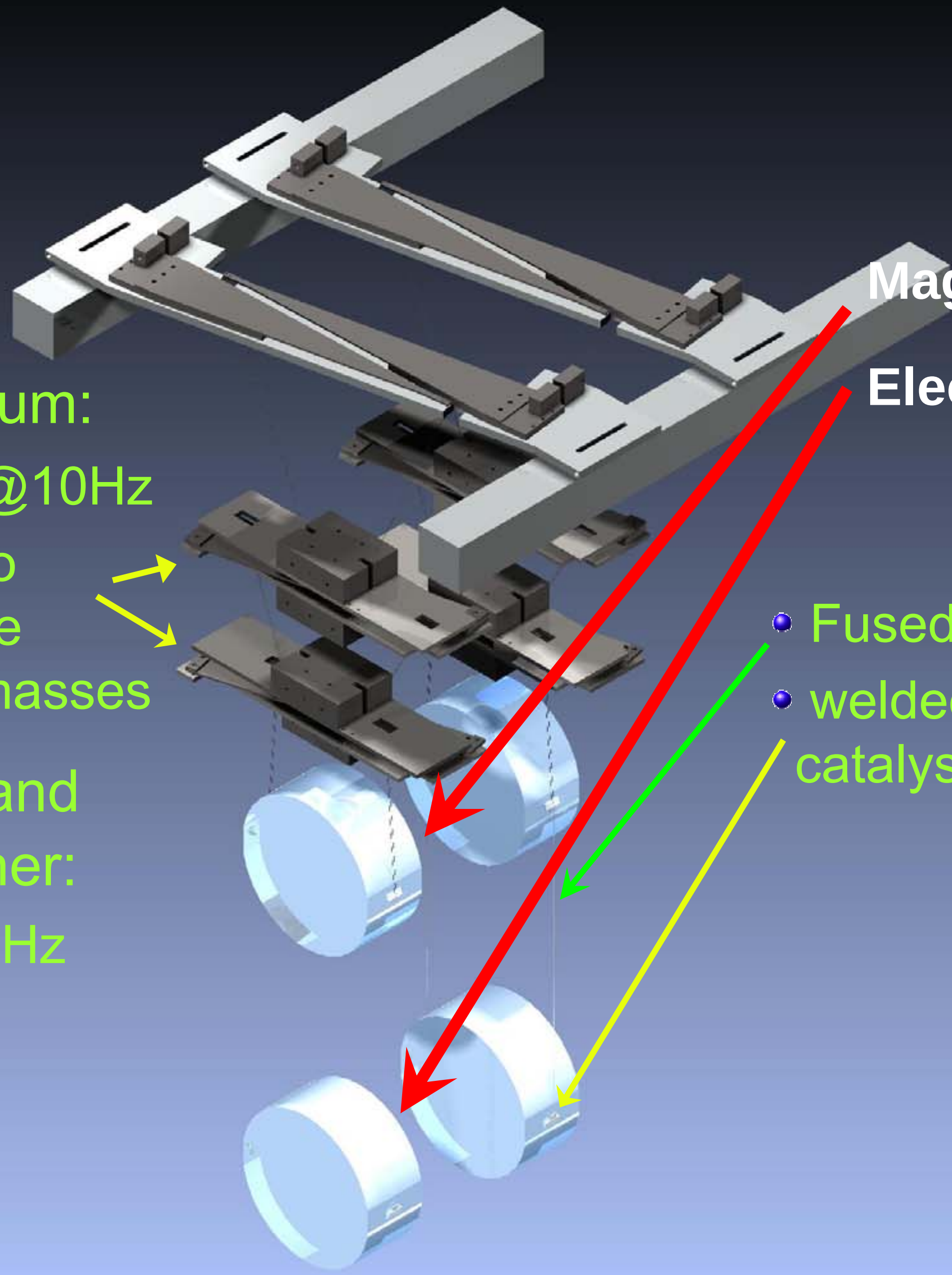






Quad Suspensions

- Quadruple pendulum:
  - ~10^7 attenuation @10Hz
  - Controls applied to upper layers; noise filtered from test masses
- Seismic isolation and suspension together:
  - 10^{-19} m/rtHz at 10 Hz

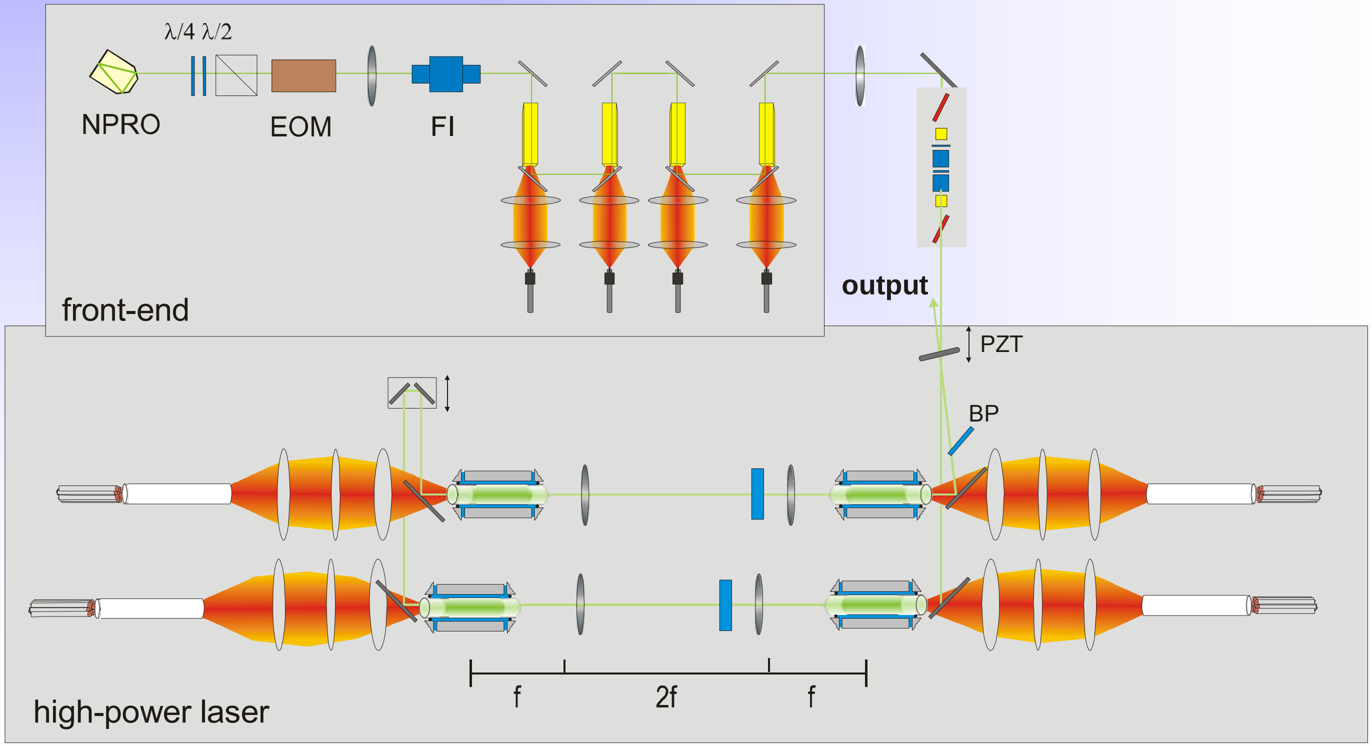


- Fused silica fiber
- welded to hydroxy-catalysis bonded ‘ears’

Advanced LIGO Pre-stabilized Laser

LIGO

- 180 W amplitude and frequency stabilized Nd:YAG laser
- Two stage amplification
  - First stage: MOPA (NPRO + single pass amplifier)
  - Second stage: injection-locked ring cavity
- Developed by Laser Zentrum Hannover (and MPI at Hannover)



Status of Advanced LIGO

- Baseline Review in June 2006, plus follow-on reviews in June 2007 and November 2008…project ready

- R&D is well underway
- Breach vacuum in 2010
- Start commissioning 1st interferometer for Advanced LIGO in 2013

high-power phase modulator

- LIGO is currently being upgraded to eLIGO
- Laser power is increased to 30 W
- Electro-optic modulators (EOMs) are replaced.
  - $LiNbO_3$ modulators would suffer from severe thermal lensing or might even break

- eLIGO devices (techniques) will be used in AdvLIGO

Overview eLIGO EOMs

- eLIGO EOMs
  - Lithium niobate ($LiNb0_3$), used in initial LIGO, not satisfactory
    - Thermal lensing / Damage / Residual absorption
  - Choose RTP (rubidium titanyl phosphate - $RbTiOPO_4$) as EO material
    - RTP has significantly lower absorption and therefore thermal lensing.
  - Use custom made housing to separate the crystal housing from the housing for the resonant circuit.
    Advantage: Resonant frequencies can be changed without disturbing the optical alignment.
  - Use wedged crystals to reduce spurious amplitude modulation
    Additional advantage: EOM acts as polarizer

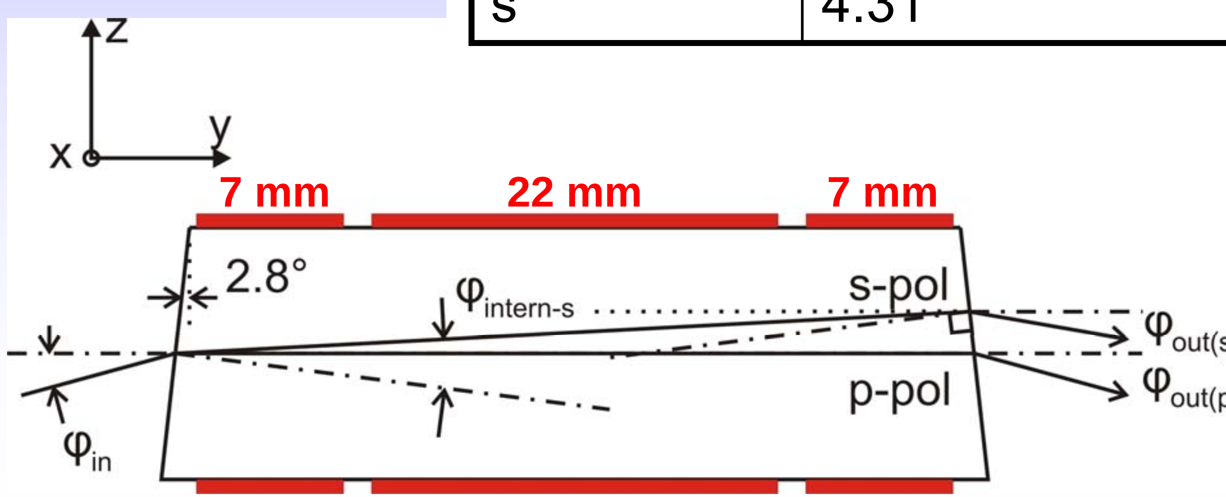
LIGO

Wedged RTP crystal

- Wedged crystal separates the polarizations and acts as a polarizer.
  - This avoids cavity effects and reduces amplitude modulation.

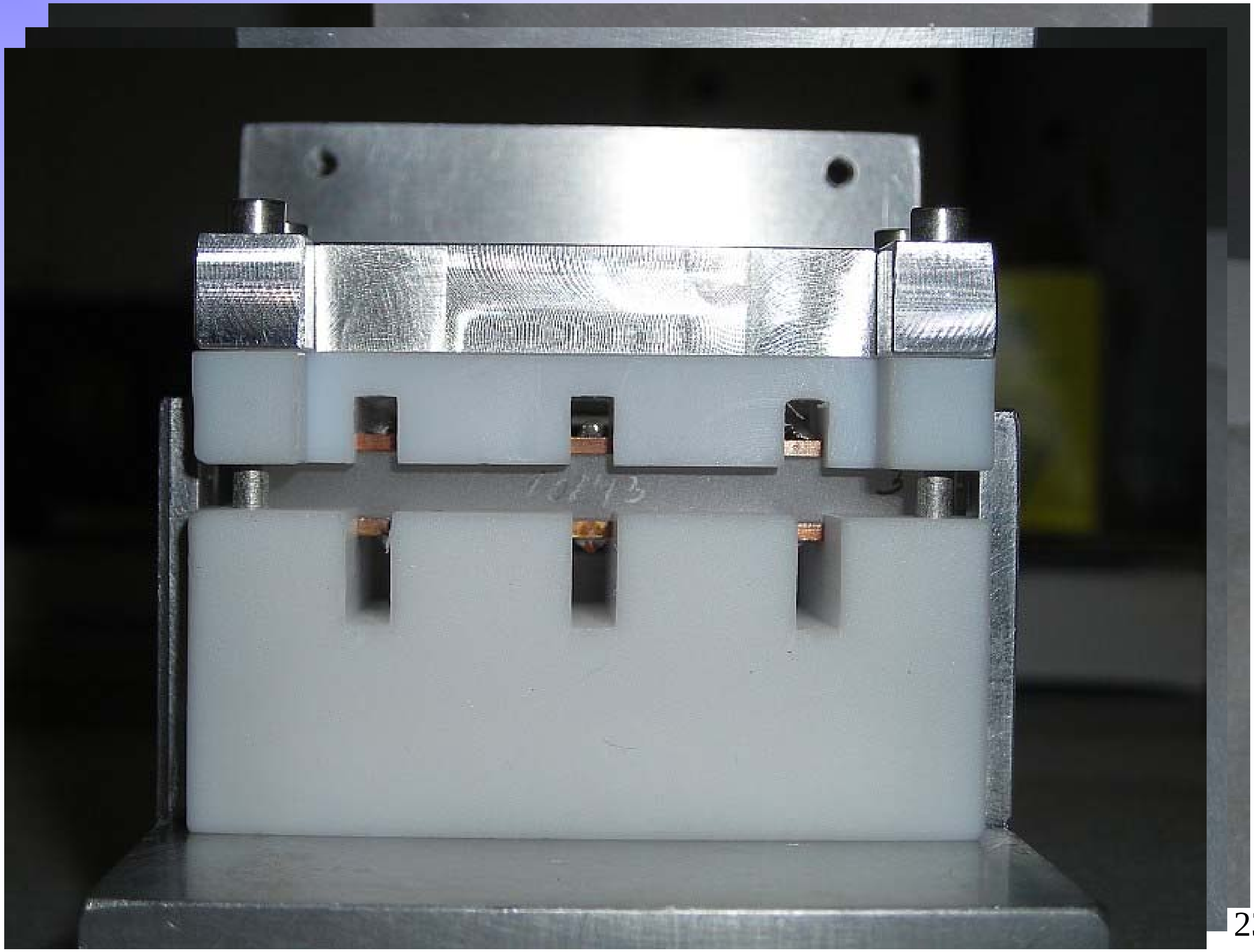
Polarization	Angle [degrees]
p	4.81
s	4.31

- AR coatings (< 0.1%) on crystal faces.



Three Modulations / Single Crystal design

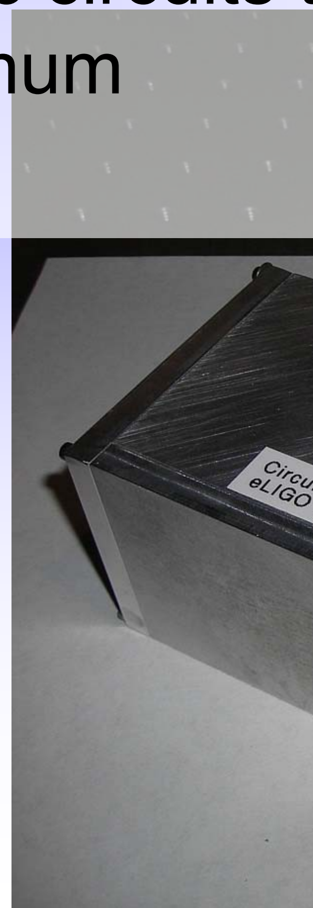
- Use one crystal but three separate pairs of electrodes to apply three different modulation frequencies at once.



LIGO

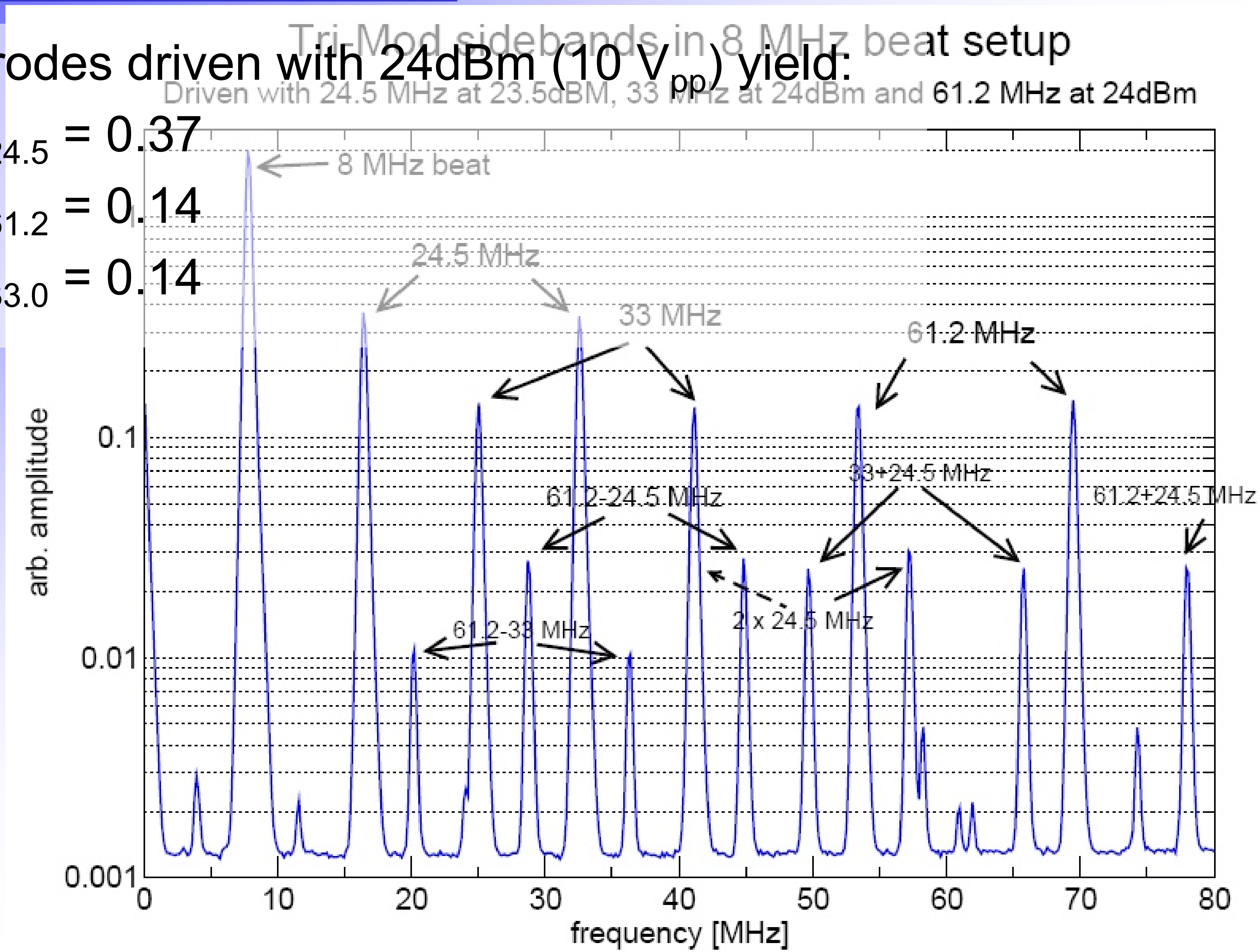
Industry-quality housing

- Separate the crystal housing from the housing of the electronic circuits t maintain maximum flexibility.



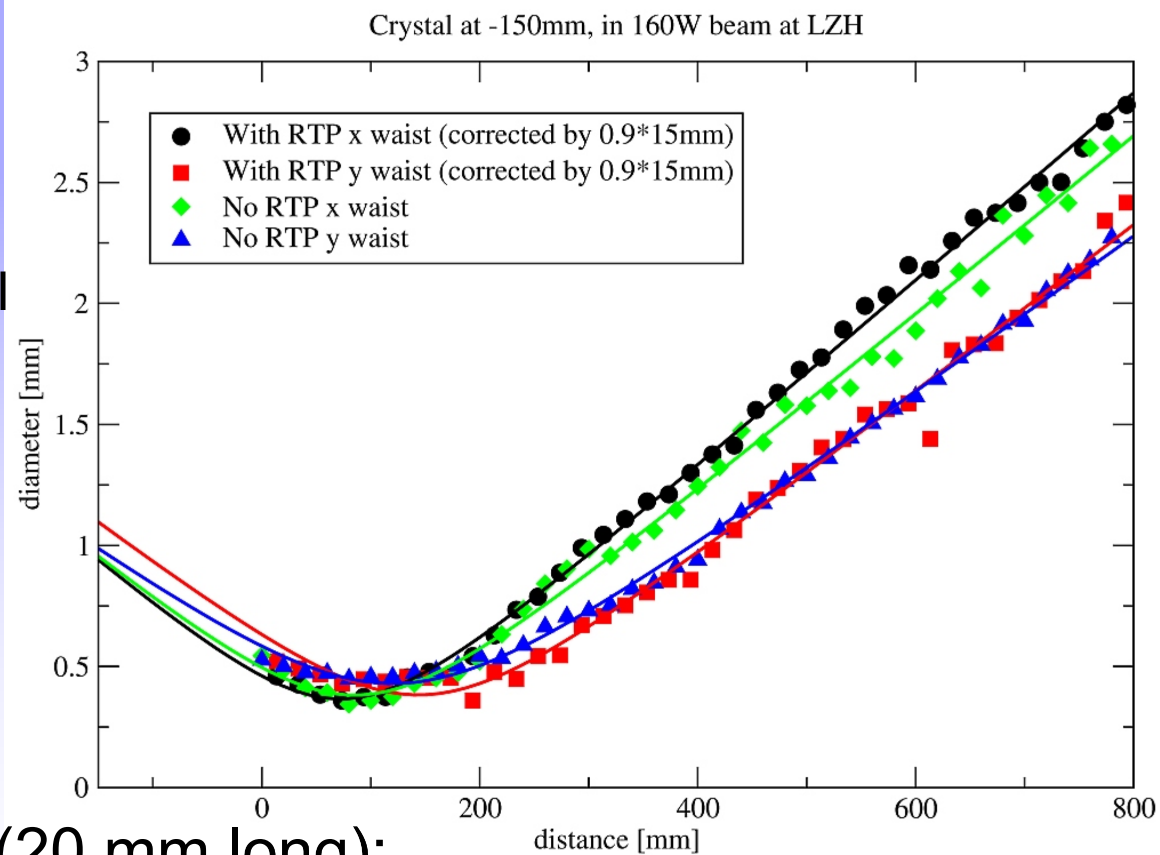
Modulation index measurement

- Electrodes driven with 24dBm (10 V_{pp}) yield:
  - $m_{24.5} = 0.37$
  - $m_{61.2} = 0.14$
  - $m_{33.0} = 0.14$



Thermal properties

- The AdvLIGO laser prototype was used to measure the thermal lensing.
  - Full Power = 160 W
  - Beam Waist = 950 µm diameter at crystal
  - 4x4x15 mm RTP crystal
  - Thermal lenses:
    $f_X > 4$ m
    f_Y = much longer



- compare with LiNbO3 (20 mm long):
  $f_{thermal} \sim 3.3$ m @ 10 W

RFAM

- Wedged geometry suppresses amplitude modulation. (No polarisation rotation possible)
  - Measured AM:
    $\Delta I/I < 10^{-5}$ at $\Omega_{mod} = 25.4$ MHz / m = 0.17

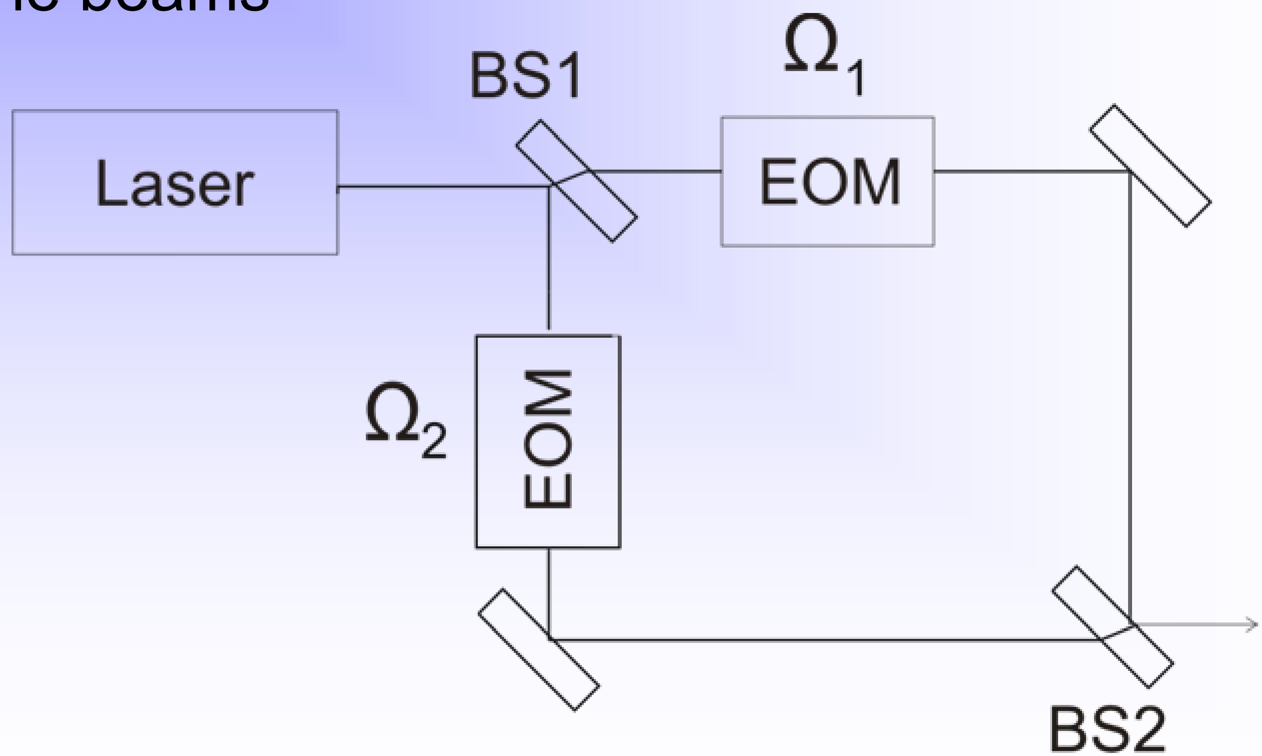
- Piezo effects in can lead to standing waves (AOM) and pointing (RF-pointing) at the modulation frequency

AdvLIGO Mach-Zehnder (parallel) modulation

- Not a high power issue, but related to advanced modulation configurations.
- Objective:
  - Solve the sidebands on sidebands problem by using parallel modulation.
  - Currently used in the 40m prototype
- Problems:
  - Sideband power reduced by a factor of 4
  - Additional intensity noise at modulation and mixing (sum/difference) frequencies
  - Excess intensity, frequency and sideband noise is possible depending on the stability of the MZ and the corner frequencies of the MZ stabilization loop.
- Only address the last point for now ..

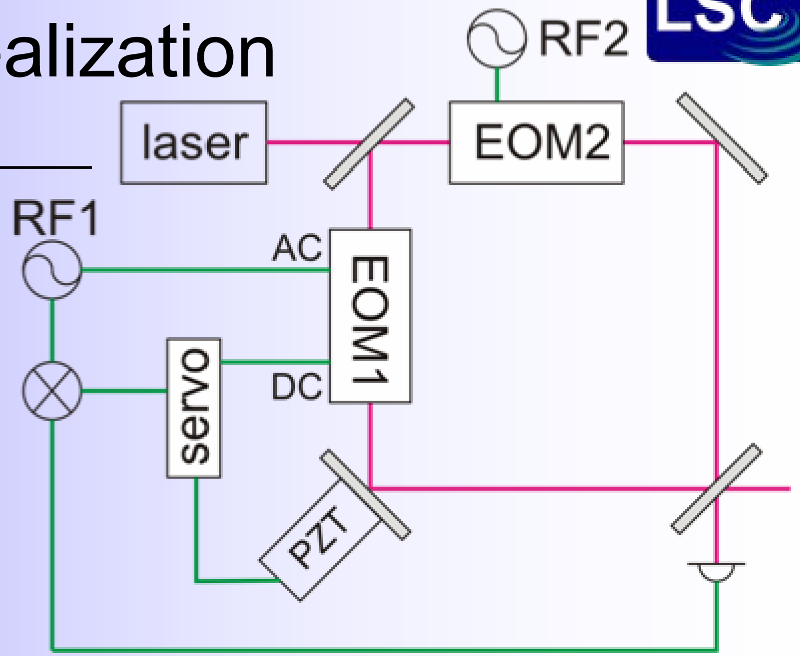
MZ modulation scheme

- Parallel modulation with two modulation frequencies
- Avoid the sideband-on-sideband problem by separating the beams

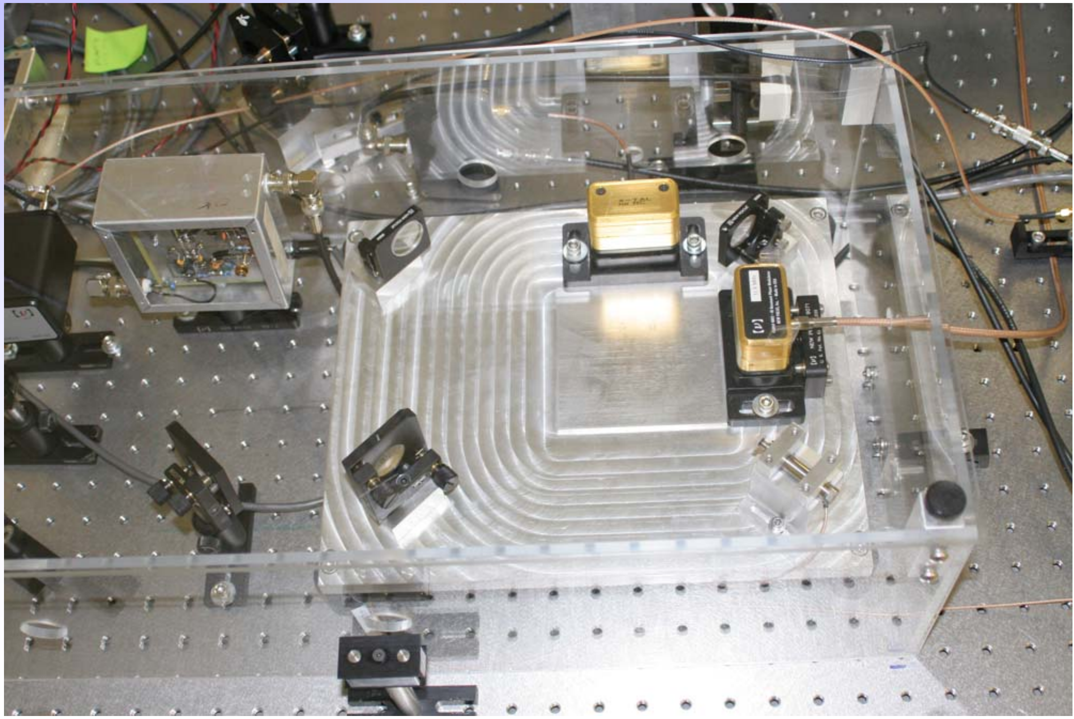


LIGO

Experimental realization



- Slow length control with big dynamic range with PZT
- Fast phase control with phase correcting EOM
- Stable mechanical "quasi-monolithic" design
- Reduce environmental effects with a Plexiglas enclosure.
- Modulation at 25 MHz and 31.5 MHz



- Current development:
  A stable, high power capable AdvLIGO prototype

Complex modulation

Why use complex modulation?

- Objective:
  - Solve the sidebands on sidebands problem.
  - Reduce the number of modulators to reduce the optical losses
- Idea: Simulate the effect of a MZ without physically separating the beams
- Requirements:
  - Generate AM and PM with arbitrary waveforms at very high sampling frequencies

Complex modulation

- General representation for an amplitude- and phase modulated light field:

$$E(t) = \frac{E_0}{2} \exp(i\omega t + f(t)) + c.c.$$

- with

$$f(t) = \phi(t) + i\alpha(t)$$

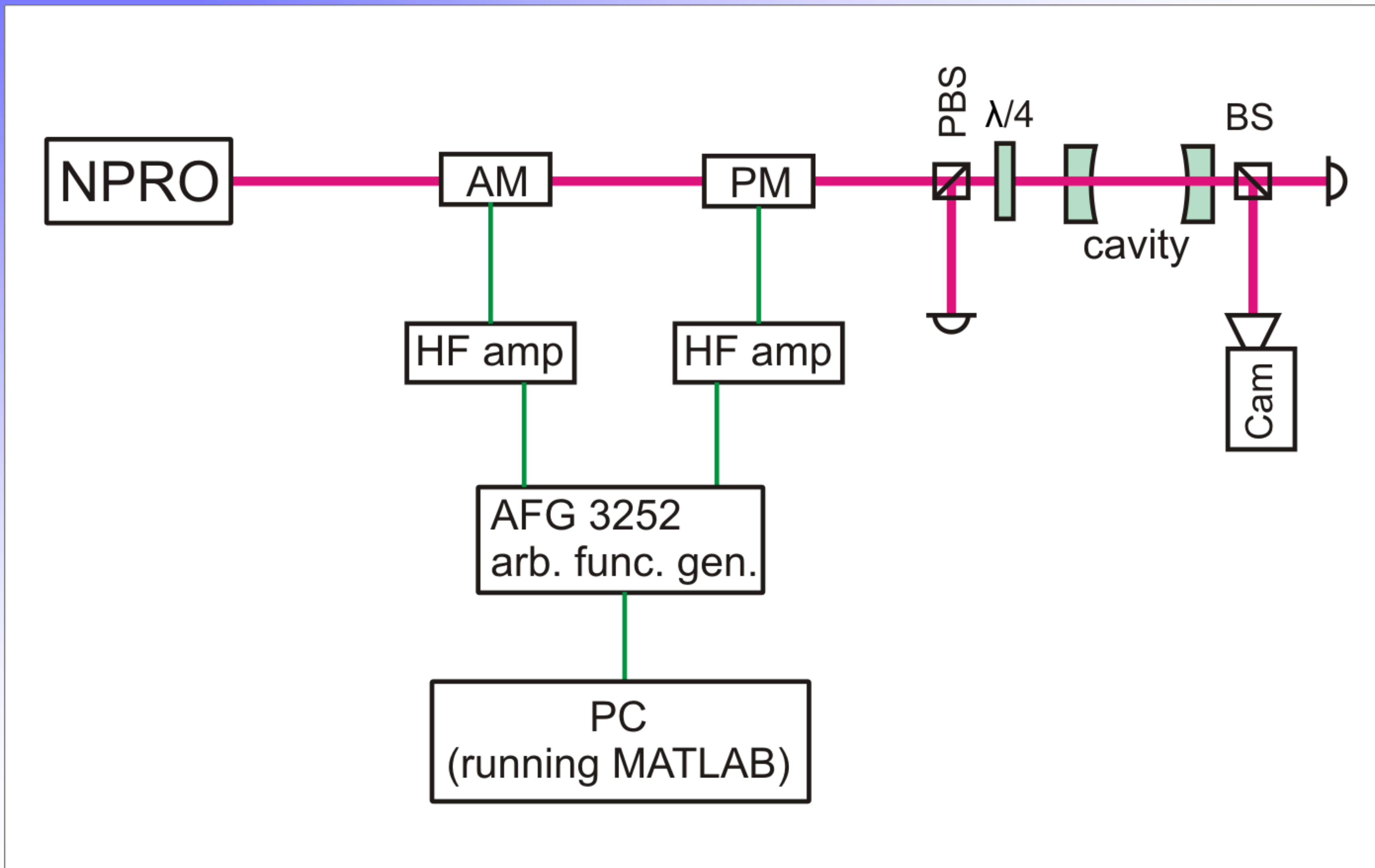
- Question: which modulation is needed to generate a certain light field?

$$E_{new}(t) = E_0(t) \cdot \exp(f(t)) + c.c.$$

- solving (easy without the + c.c.) leads to:

$$\phi(t) = \arg\left(\frac{E_{new}(t)}{E_0(t)}\right) \qquad \alpha(t) = \ln\left|\frac{E_{new}(t)}{E_0(t)}\right|$$

Experimental setup



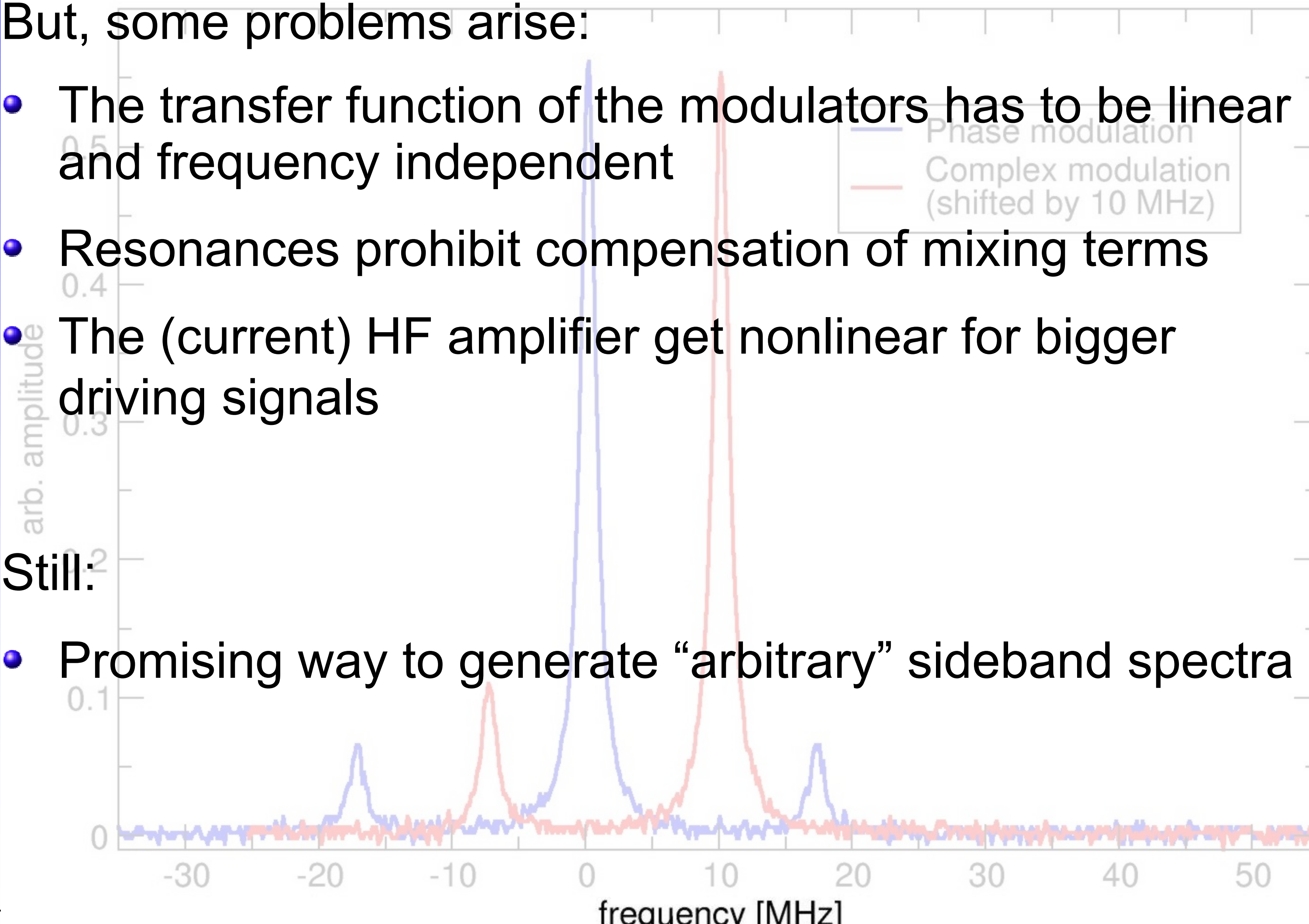
Encouraging first results

But, some problems arise:

- The transfer function of the modulators has to be linear and frequency independent
- Resonances prohibit compensation of mixing terms
- The (current) HF amplifier get nonlinear for bigger driving signals

Still:

- Promising way to generate “arbitrary” sideband spectra



Conclusions

- LIGO finished S5 Science run
- enhanced LIGO upgrade is happening
- advanced LIGO is beginning
- modulation challenges are understood/solved
- Gravitational wave detection pushes state-of-the art in CW solid state laser technology, optical fabrication and metrology, and control systems

Acknowledgments:

and the Members of the LIGO Laboratory, members of the LIGO Science Collaboration, National Science Foundation

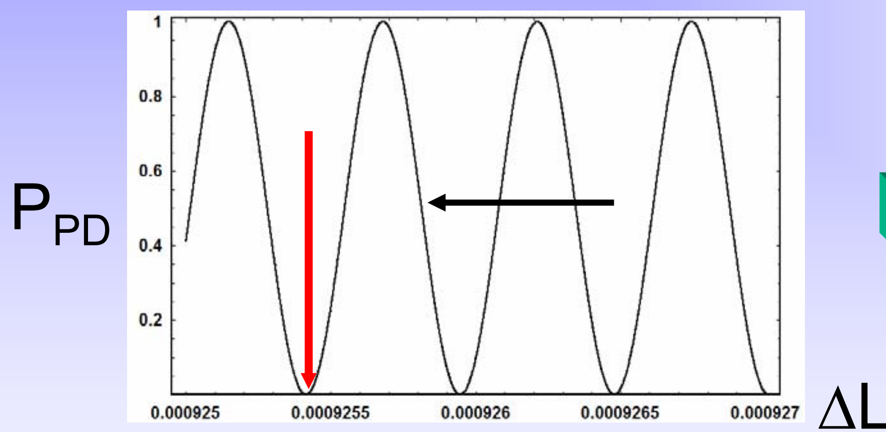
More Information:

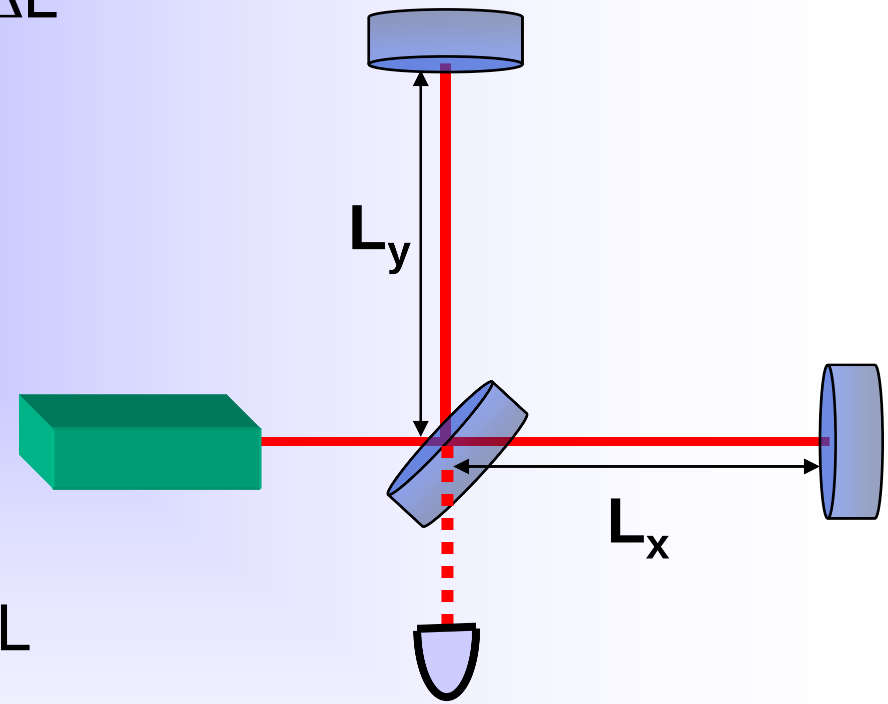
- http://www.ligo.caltech.edu; www.ligo.org

Supplementary material

Interferometry: the basics

- Simple Michelson
  - Phase: $\phi = 4\pi (L_x - L_y) / \lambda \sim \Delta L$
  - Power: $P_{PD} = P_{BS} \sin^2\phi$
    - $dP/d\phi \sim P_{BS} \sin\phi \cos\phi$



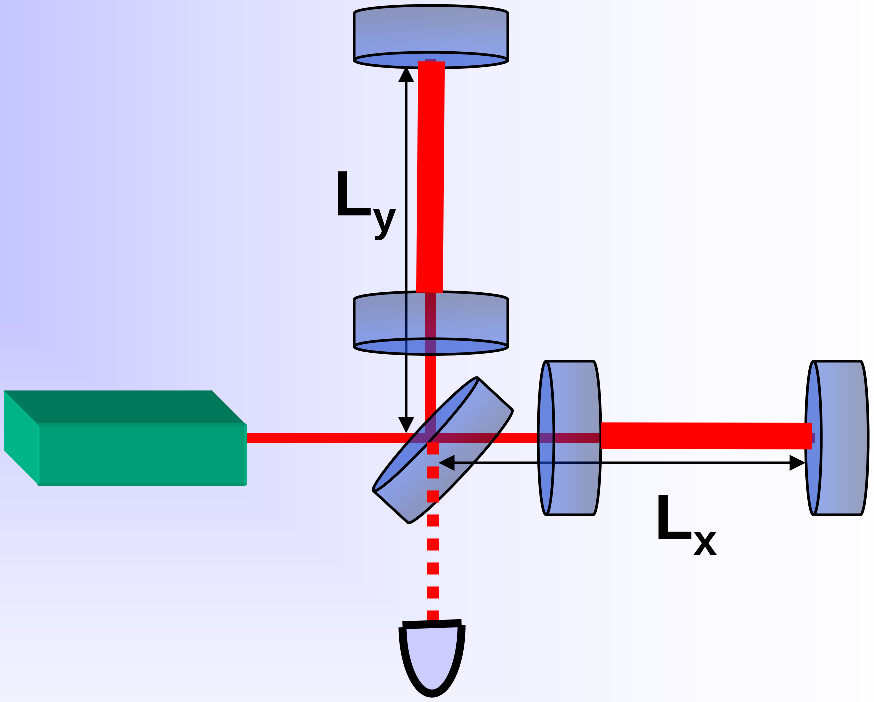


  - Strain: $h = \Delta L/L$
    - Increase sensitivity by using longer arms

$d\varphi/dh \sim L$

Advanced Interferometry I
Fabry-Perot Arm Cavities

- Fabry-Perot cavity
  - Increases power in arms
    Overcoupled cavity gain:
    $G_{FP} \sim 4 / T_{input}$
  - Enhances storage time of light in cavity
  - Effectively 'lengthens' arms
    $\sim G_{FP}$



$d\varphi/dh \sim G_{FP} \times L$

Advanced Interferometry II: Power Recycling

- 'Recycle' light coming back from beamsplitter
  - Add a mirror which forms a resonant cavity with the rest of the interferometer

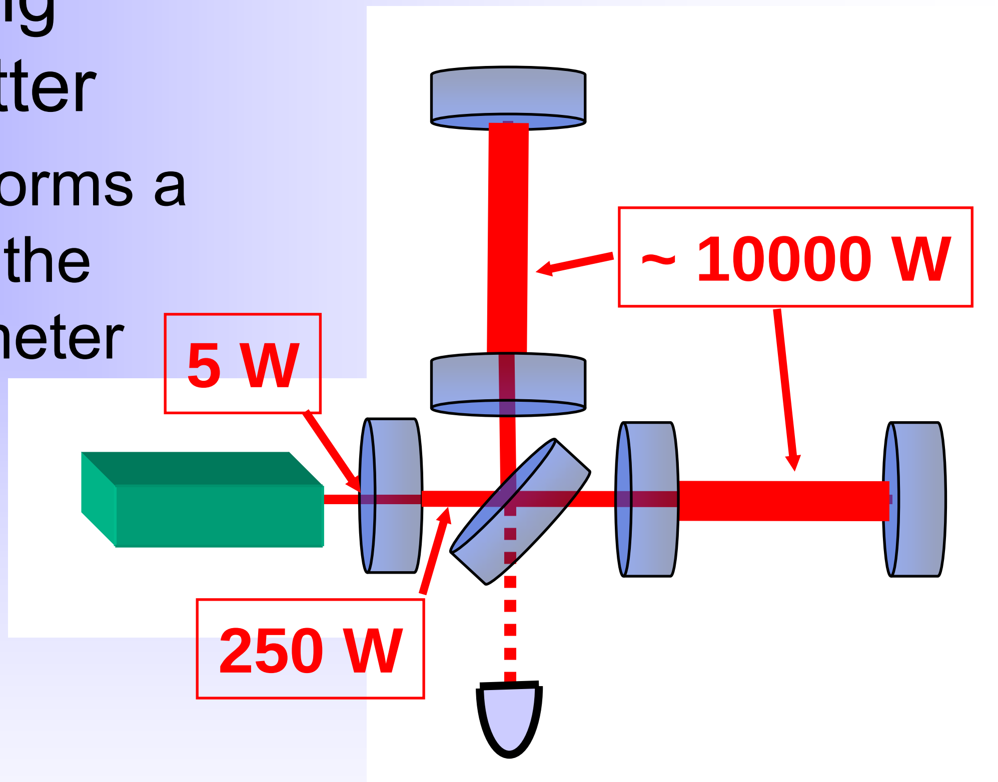
$P_{BS} = G_{RC}\, P_{input}$

+

$d\varphi/dh \sim G_{FP} \times L$

=>

Enhanced Phase Sensitivity!

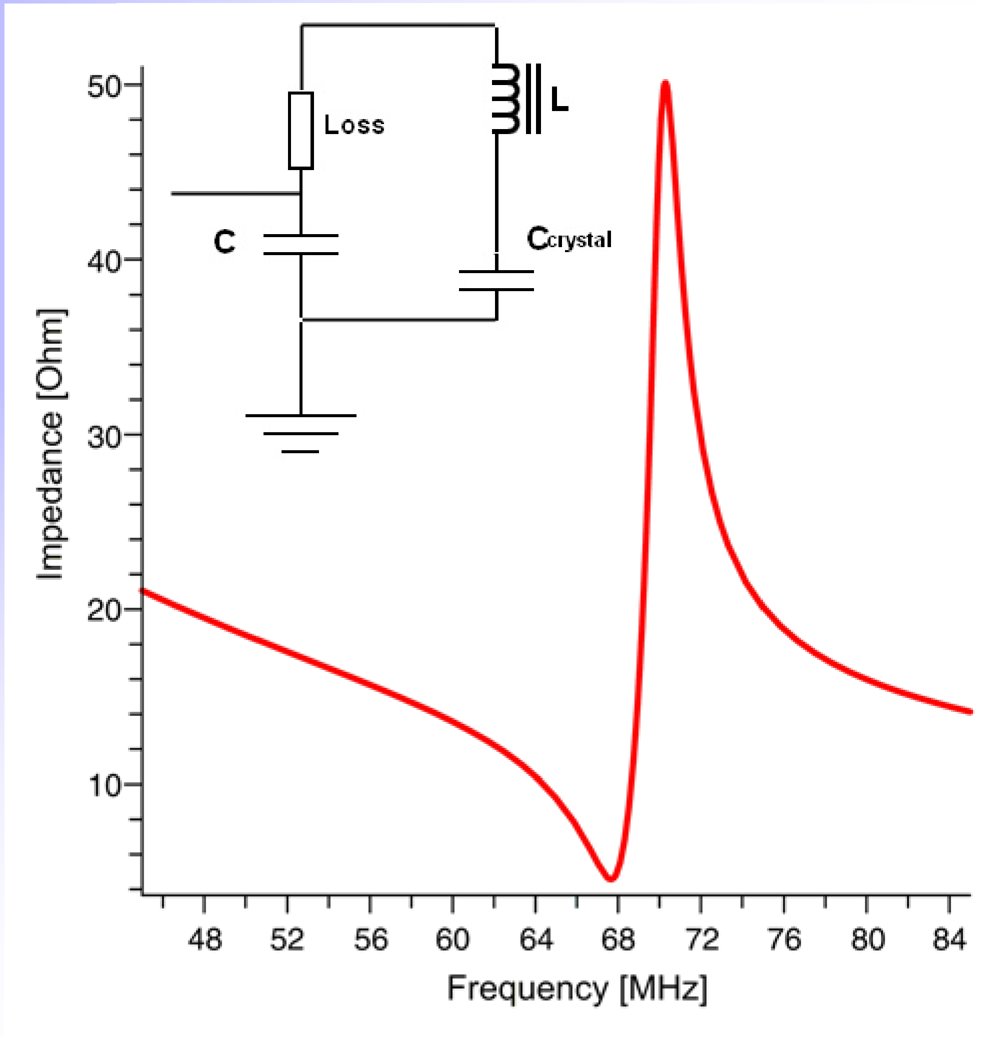


$G_{RC} \sim 50,\ G_{FP} \sim 80$

Pi-Network resonant enhancement

- Impedance matching circuit in separate housing.
- Resonant circuit with 50 Ω input impedance.

- eLIGO version has three resonant circuits:
  - 24.5 / 33.0 / 61.2 MHz



RTP Thermal properties

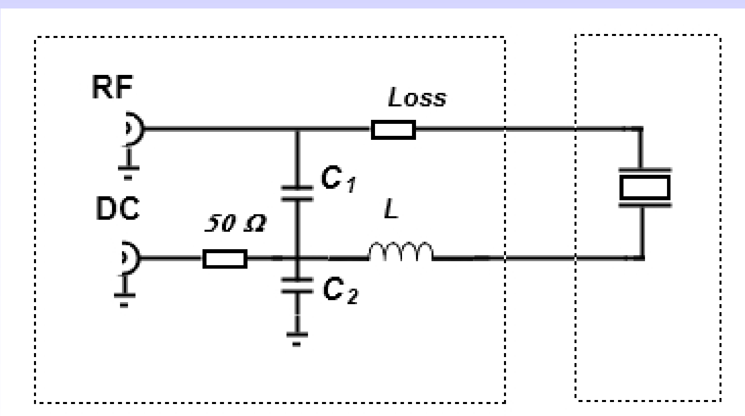
Properties	Units	RTP	RTA	KTP	$LiNb0_3$
dn_x/dT	$10^{-6}/K$	-	-	11	5.4
dn_y/dT	$10^{-6}/K$	2.79	5.66	13	5.4
dn_z/dT	$10^{-6}/K$	9.24	11.0	16	37.9
κ_x	W/Km	3		2	5.6
κ_y	W/Km	3		3	5.6
κ_z	W/Km	3		3	5.6
α	cm^{-1}	< 0.0005	< 0.005	< 0.005	< 0.05
Q_x	1/W	-	-	2.2	4.8
Q_y	1/W	0.047	0.94	2.2	4.8
Q_z	1/W	0.15	1.83	2.7	34

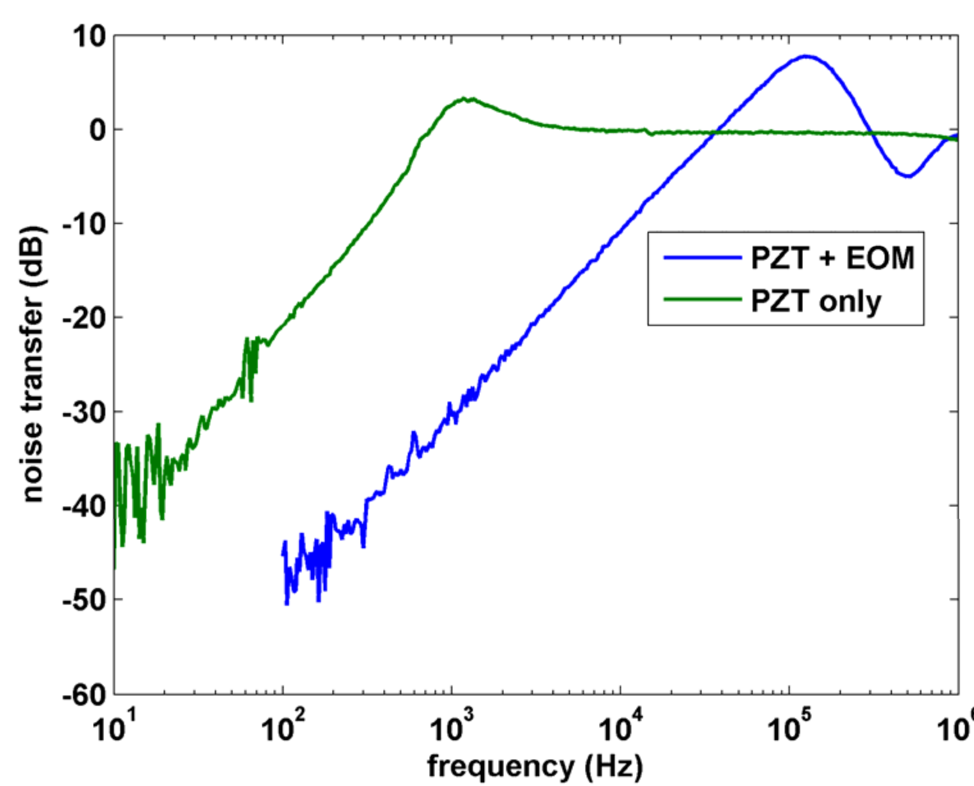
Optical and electrical properties

Properties	Units/conditions	RTP	RTA	$LiNbO_3$
Damage Threshold	MW/cm^2,	>600	400	280
n_x	1064nm	1.742	1.811	2.23
n_y	1064nm	1.751	1.815	2.23
n_z	1064nm	1.820	1.890	2.16
Absorption coeff. α	cm^{-1} (1064 nm)	< 0.0005	< 0.005	< 0.005
r_{33}	pm/V	39.6	40.5	30.8
r_{23}	pm/V	17.1	17.5	8.6
r_{13}	pm/V	12.5	13.5	8.6
r_{42}	pm/V	?	?	28
r_{51}	pm/V	?	?	28
r_{22}	pm/V			3.4
$n_z^3\, r_{33}$	pm/V	239	273	306
Dielectric const., ε_z	500 kHz, 22 ^{o}C	30	19	
Conductivity, σ_z	$\Omega^{-1}cm^{-1}$, 10 MHz	$\sim 10^{-9}$	$3x10^{-7}$	
Loss Tangent, d_z	500 kHz, 22 ^{o}C	1.18	-	

Resonant/DC EOM – high servo UGF

- To realize the fast phase correcting without using an additional EOM a slightly modified resonant circuit was used.
  - Simultaneous modulation at resonant frequency
  - DC phase changes up to 1 MHz possible

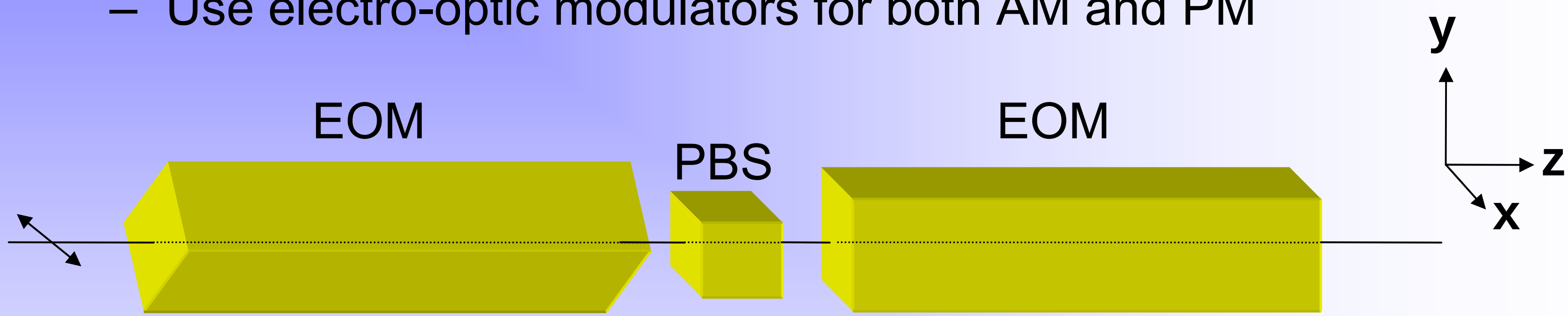




LIGO

Experimental realization I

- Sidebands at several ten MHz require fast phase and amplitude changes.
  - Use electro-optic modulators for both AM and PM



$$i\phi_a(t) + \alpha(t) \qquad\qquad i\phi_p(t)$$

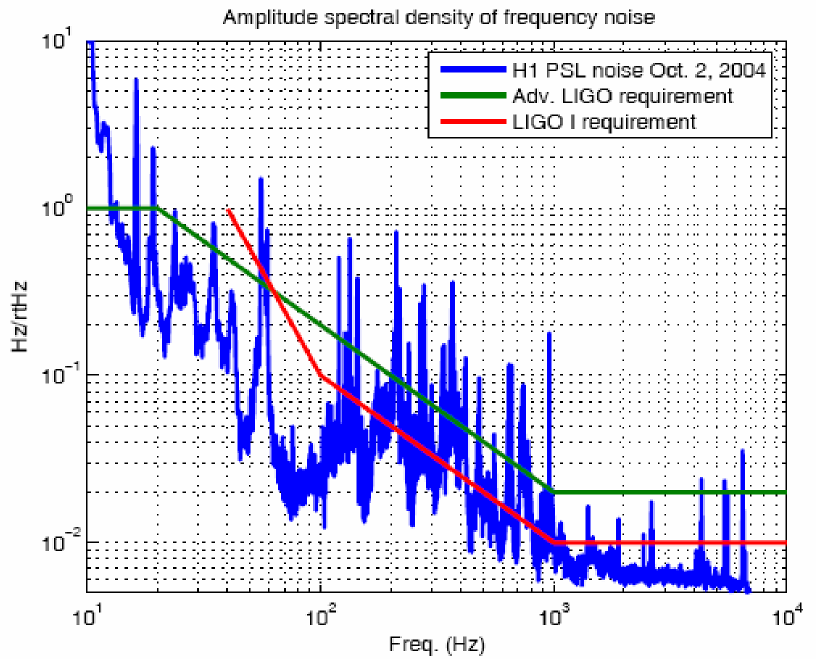
- PM - (OK)
- AM - PM between polarizers (drawback: unwanted phase modulation)

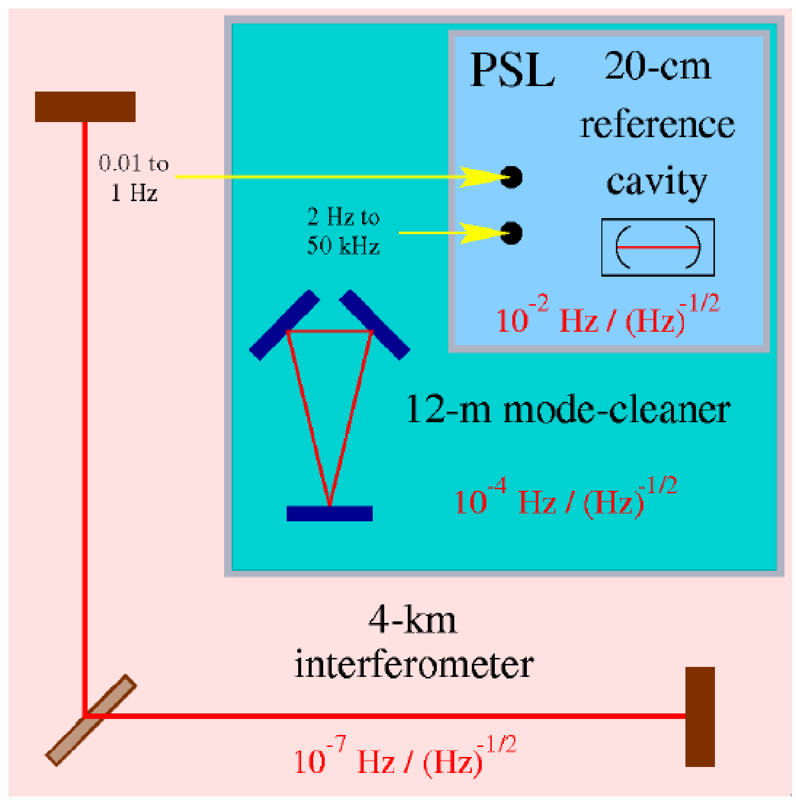
- Creation of complex modulation is possible:

$$f(t) = i\phi_a(t) + i\phi_p(t) + \alpha(t)$$

Frequency Stabilization in LIGO

- Nested control loops
  - Stage 1 – thermally-20 cm long stabilized reference cavity
  - Stage 2 – in vacuum suspended 12 or 15 m long “mode cleaner’ cavity
  - Stage 3 – Fabry Perot arm cavities





$\Delta f/f \sim 3 \times 10^{-22}$ @ 100 Hz