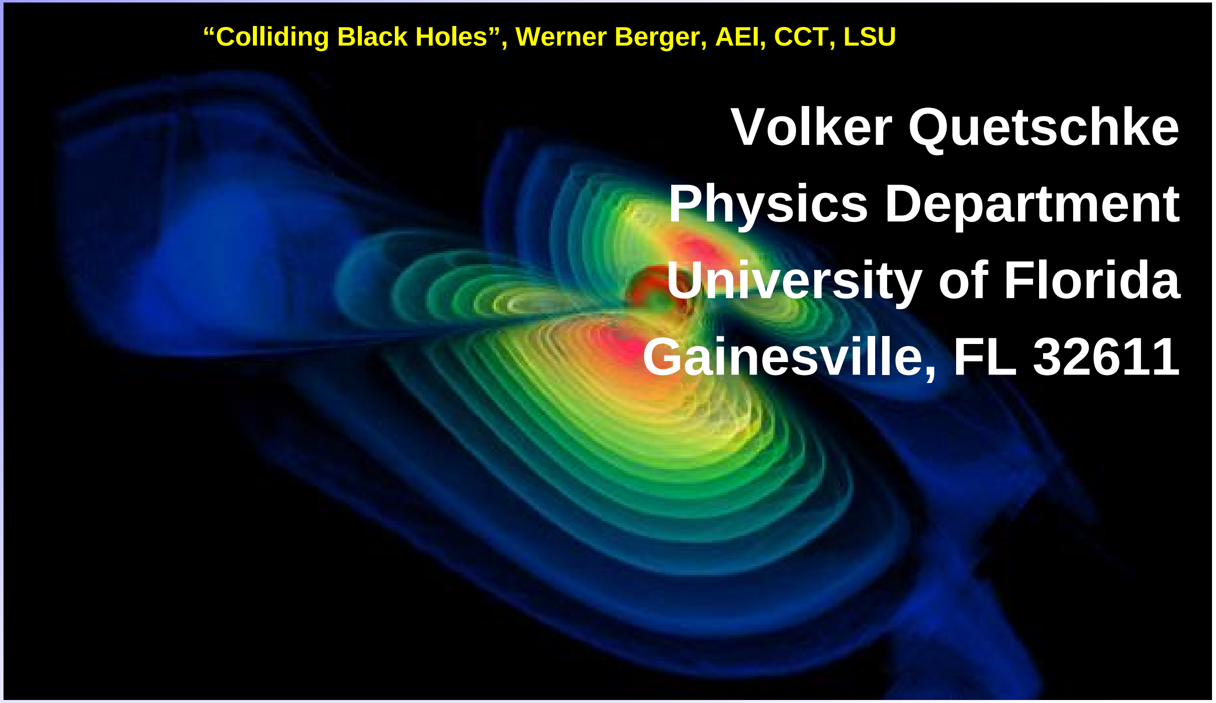
LIGO

LIGO and the Role of Phase Modulation in Controlling Interferometric GW detectors



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

Volker Quetschke
Physics Department
University of Florida
Gainesville, FL 32611

Center for Gravitational Wave Astronomy (CGWA)
University of Texas at Brownsville (UTB)
Seminar 10/31/2008

UF UNIVERSITY of FLORIDA

LSC

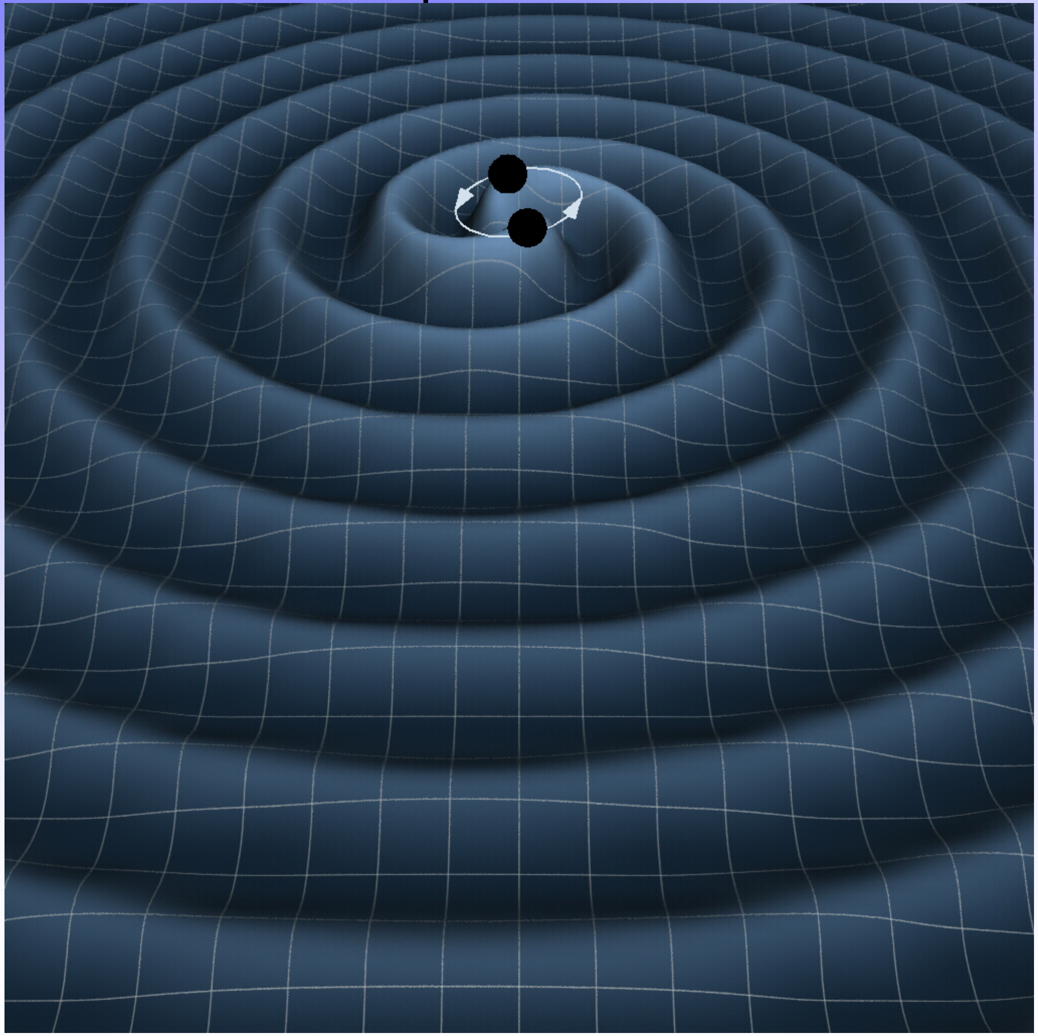
Support: NSF

Outline

- Gravitational waves
  - What are they / How to measure them
- Interferometric gravity wave detectors
  - especially LIGO
- LIGO – the instrument
- Phase modulation
  - how to lock cavities and interferometers
- Phase modulators for LIGO/eLIGO/aLIGO

Gravitational waves

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



K. Thorne (Caltech) , T. Carnahan (NASA GSFC)

- 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:

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

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

Do the math…

A wave's strength is characterized by its *strain*

$$h = \Delta L / L$$

We can calculate the expected strain at Earth for, say, an orbiting binary system:

$$|h| \approx \frac{4\pi^2 G M R^2 f_{orbit}^2}{c^4 r} \approx 10^{-21} \left(\frac{R}{20\text{km}}\right)^2 \left(\frac{M}{M_\Theta}\right) \left(\frac{f_{orbit}}{400\text{Hz}}\right)^2 \left(\frac{10\text{Mpc}}{r}\right)$$

If we make our interferometer very big, say 4,000 meters long, then

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

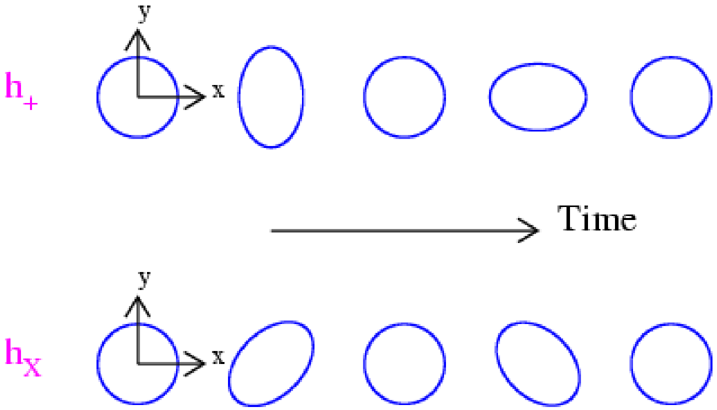
What is the observable effect?

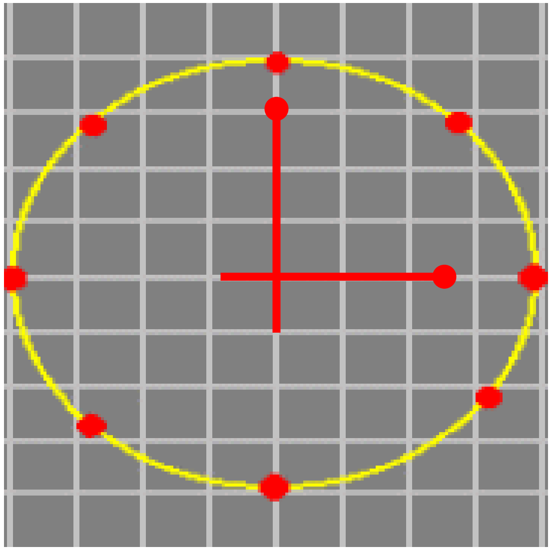
Example:

Ring of test masses

responding to wave

propagating along z





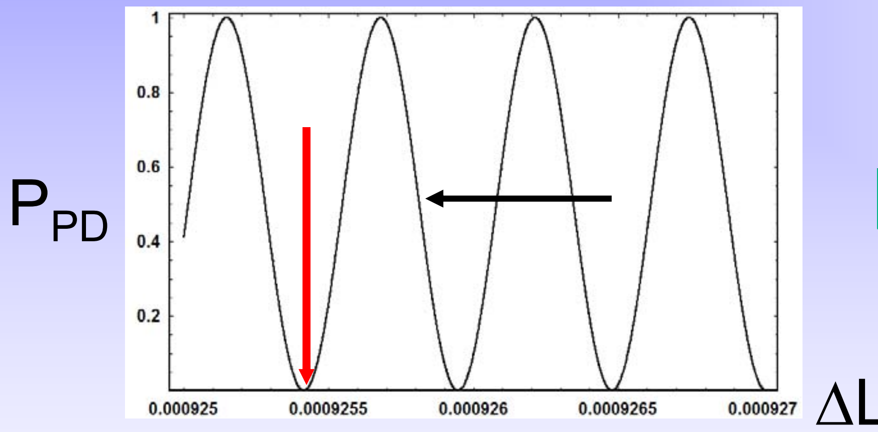
Amplitude parameterized by (tiny) dimensionless strain h:

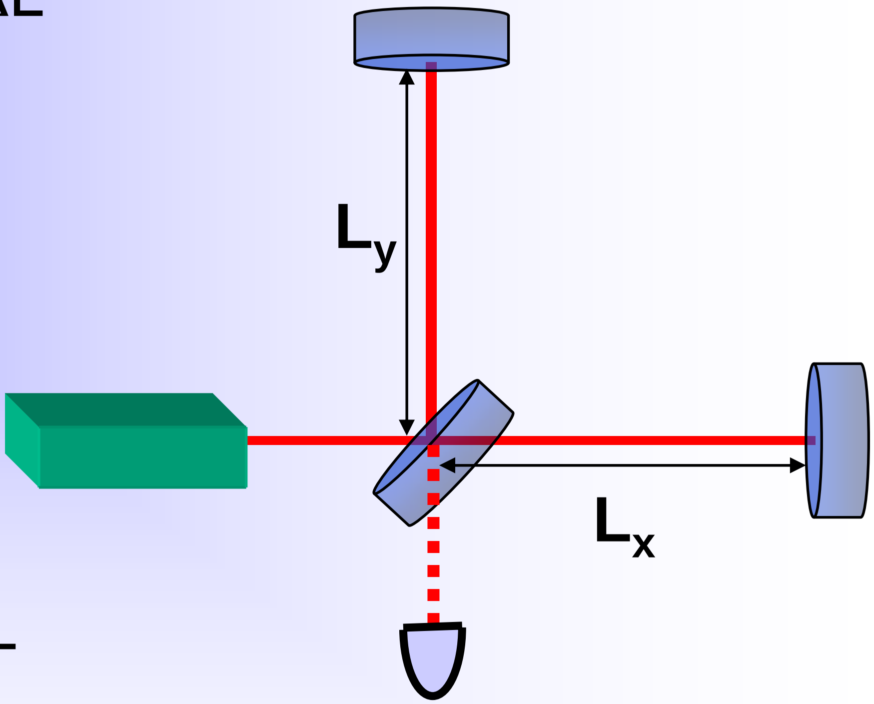
$$h(t) = \frac{\delta L(t)}{L}$$

Interferometric gravity wave detectors

Interferometry: the basics

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



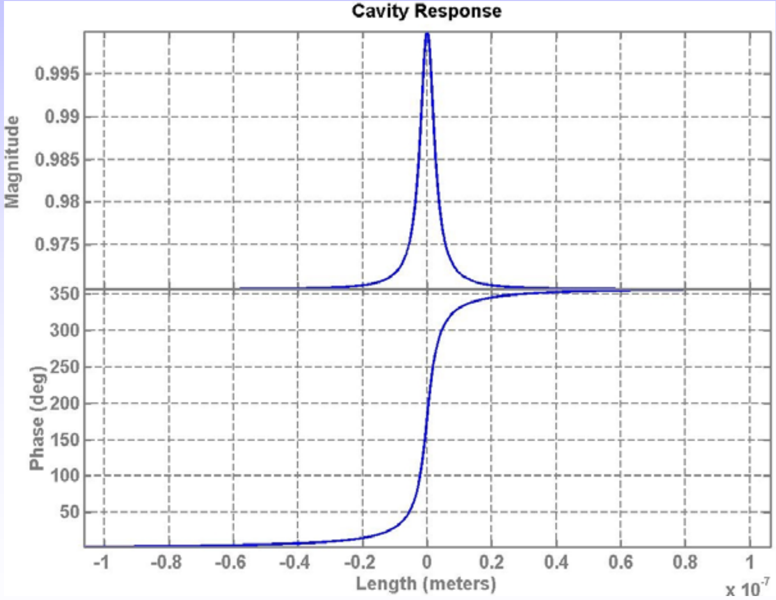


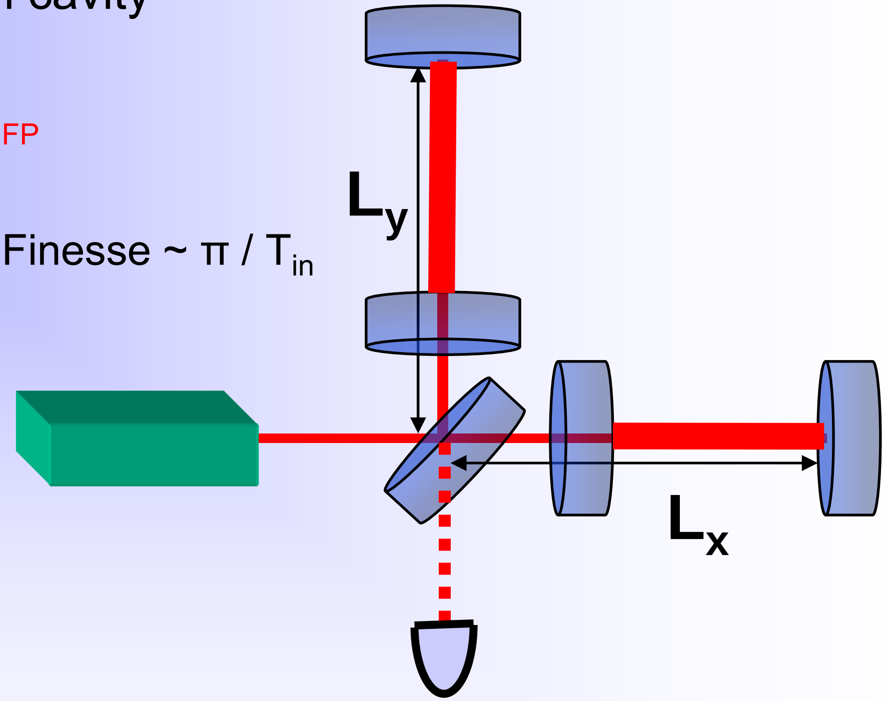
  - Strain: $h = \Delta L/L$
    - Increase sensitivity by using longer arms

$d\varphi/dh \sim L$

Advanced Interferometry I
Fabry-Perot Arm Cavities

- Fabry-Perot cavity
  - Enhances storage time of light in cavity
    - Phase shift on resonance
    - Effectively ‘lengthens’ arms ~ G_{FP}
  - Increases power in arms
    - Overcoupled cavity gain: G_{FP} ~ Finesse ~ π / T_{in}





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

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

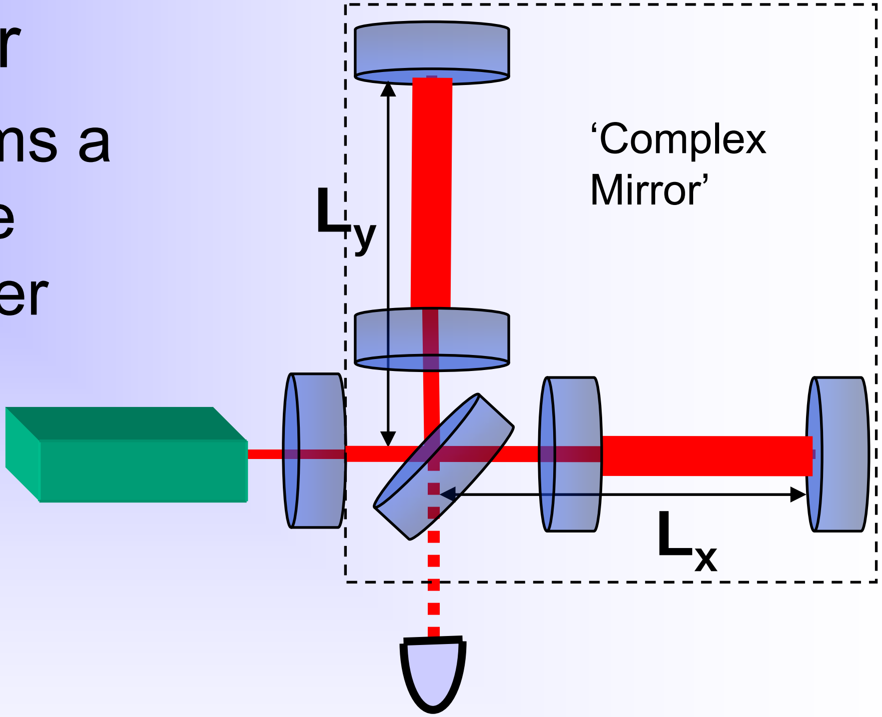
$$\boxed{P_{BS} = G_{RC}\, P_{input}}$$

$$+$$

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

=>

Enhanced Phase Sensitivity!



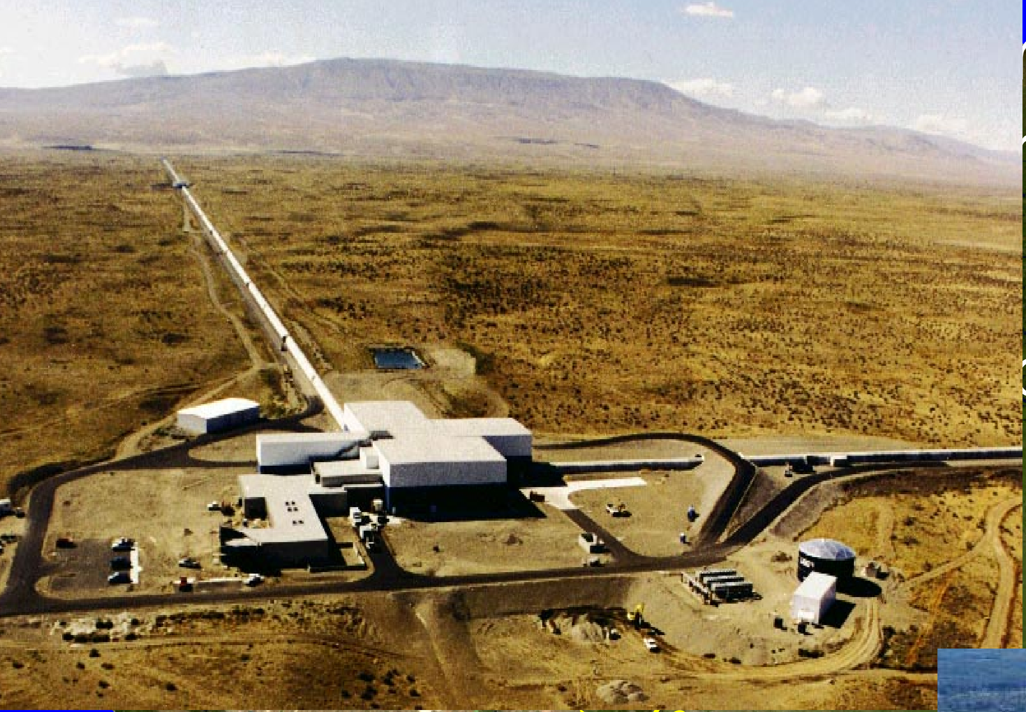
$$\boxed{G_{RC} \sim 50,\ G_{FP} \sim 80}$$

LIGO

rvatory Sites

riangulation possible

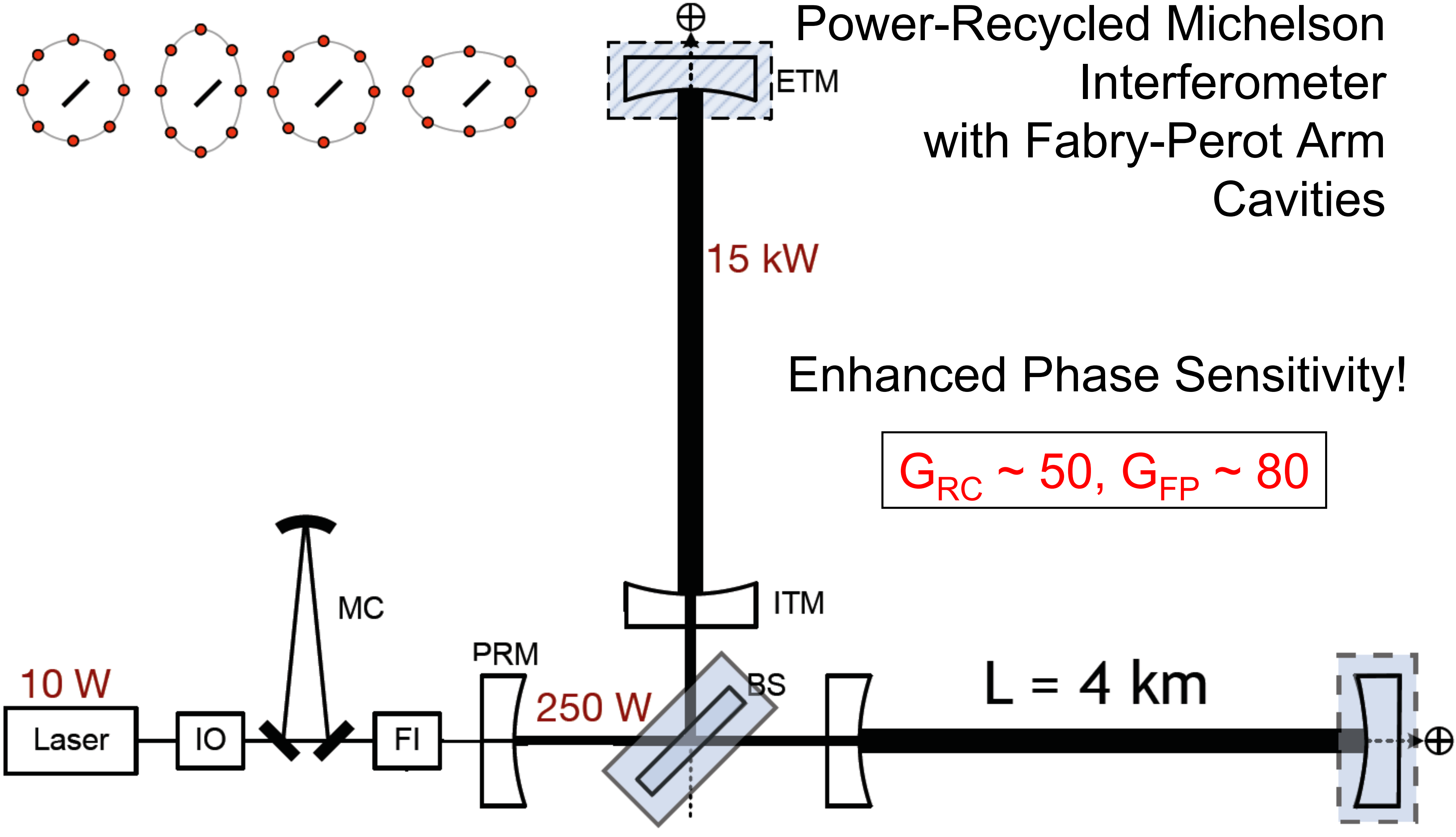
O)



➢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

Power-Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



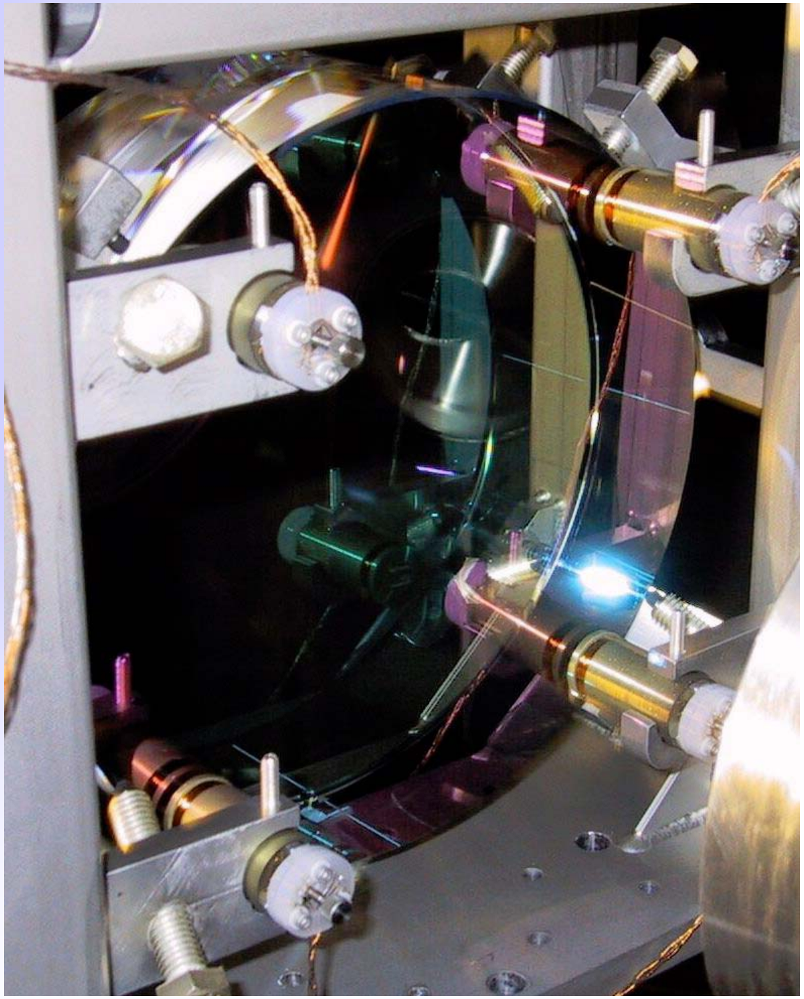
Enhanced Phase Sensitivity!

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

$1\mathrm{x}10^{-12}\ \lambda = 1\mathrm{x}10^{-18}$ m

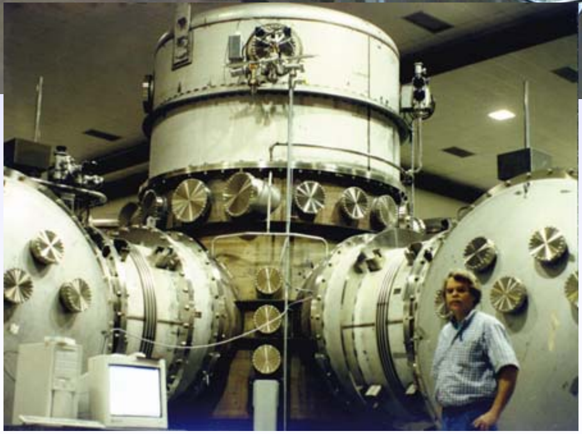
Main Features

- 4 km vacuum envelope 10^{-9} torr
- Seismic isolation stack
- Suspended masses
- 10W Nd:YAG laser, 1064 nm
- Suspended mode cleaner
- Feedback controls for length and alignment
- Physical environment monitor



Vacuum Chambers provide housing for the optics

View inside Corner Station



Standing at vertex
beam splitter

Beam Tubes and Enclosures

Precast concrete enclosure: *bulletproof*

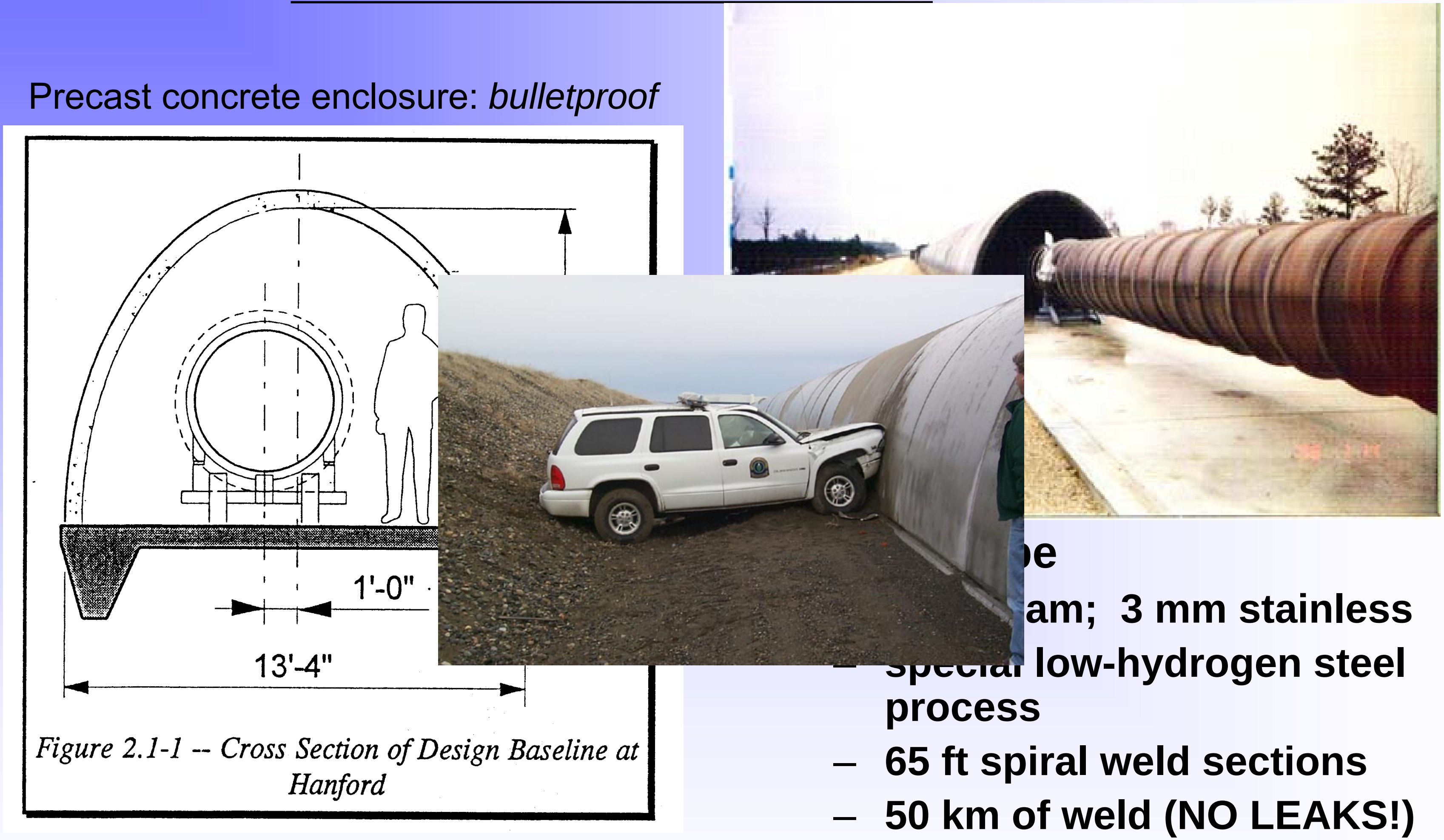


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

pe

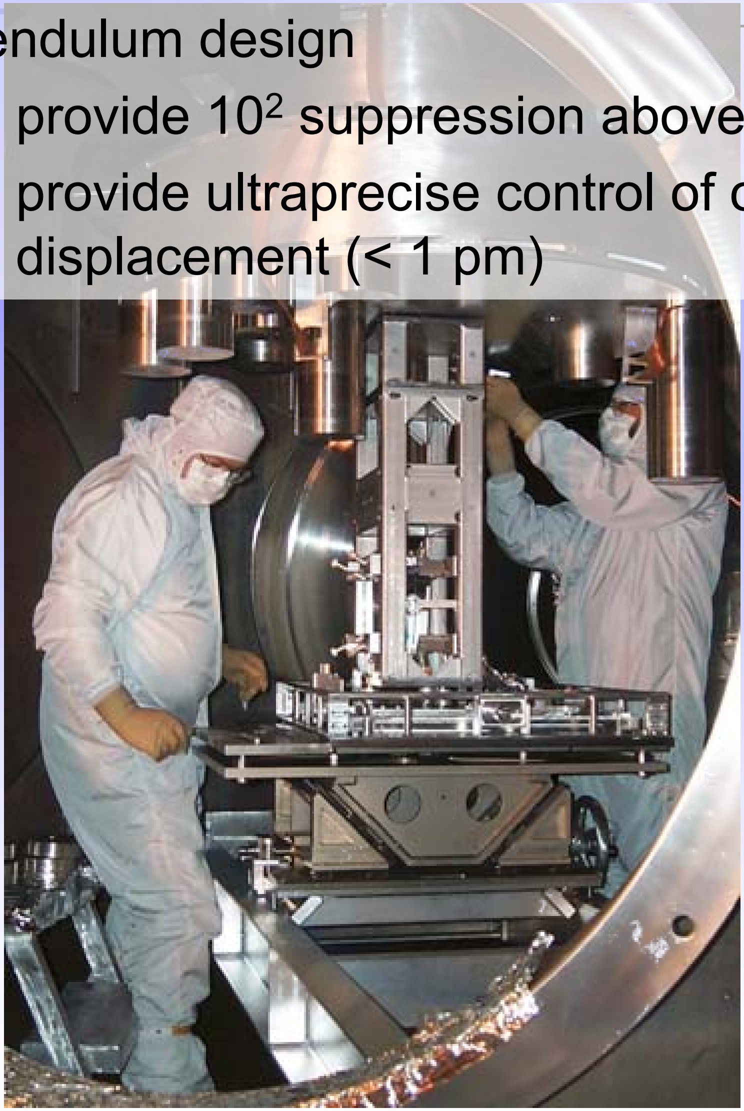
am; 3 mm stainless

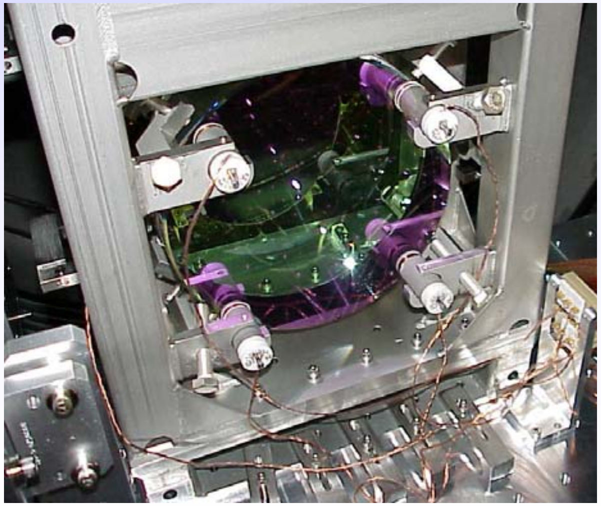
– low-hydrogen steel process
– 65 ft spiral weld sections
– 50 km of weld (NO LEAKS!)
– 20,000 m^3 @ 10^{-8} torr; earth's largest high vacuum system

Mirror Suspensions

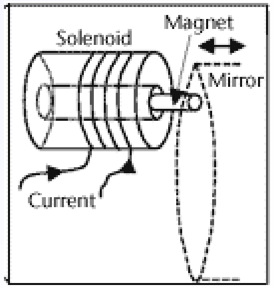
Pendulum design

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



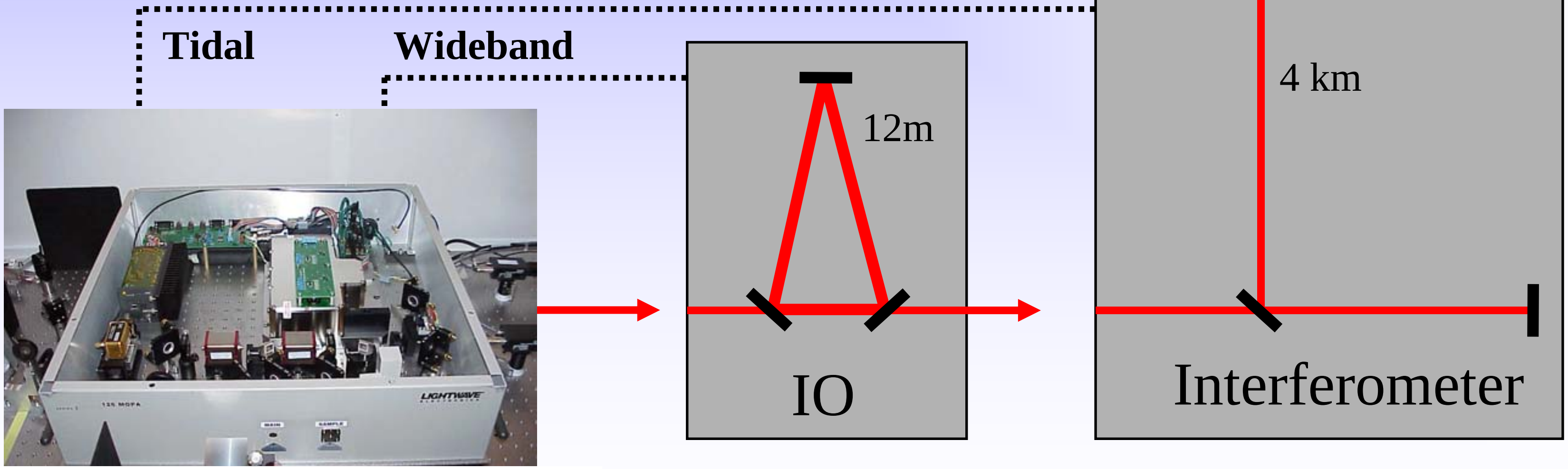


OSEM



The pre-stabilized Laser System

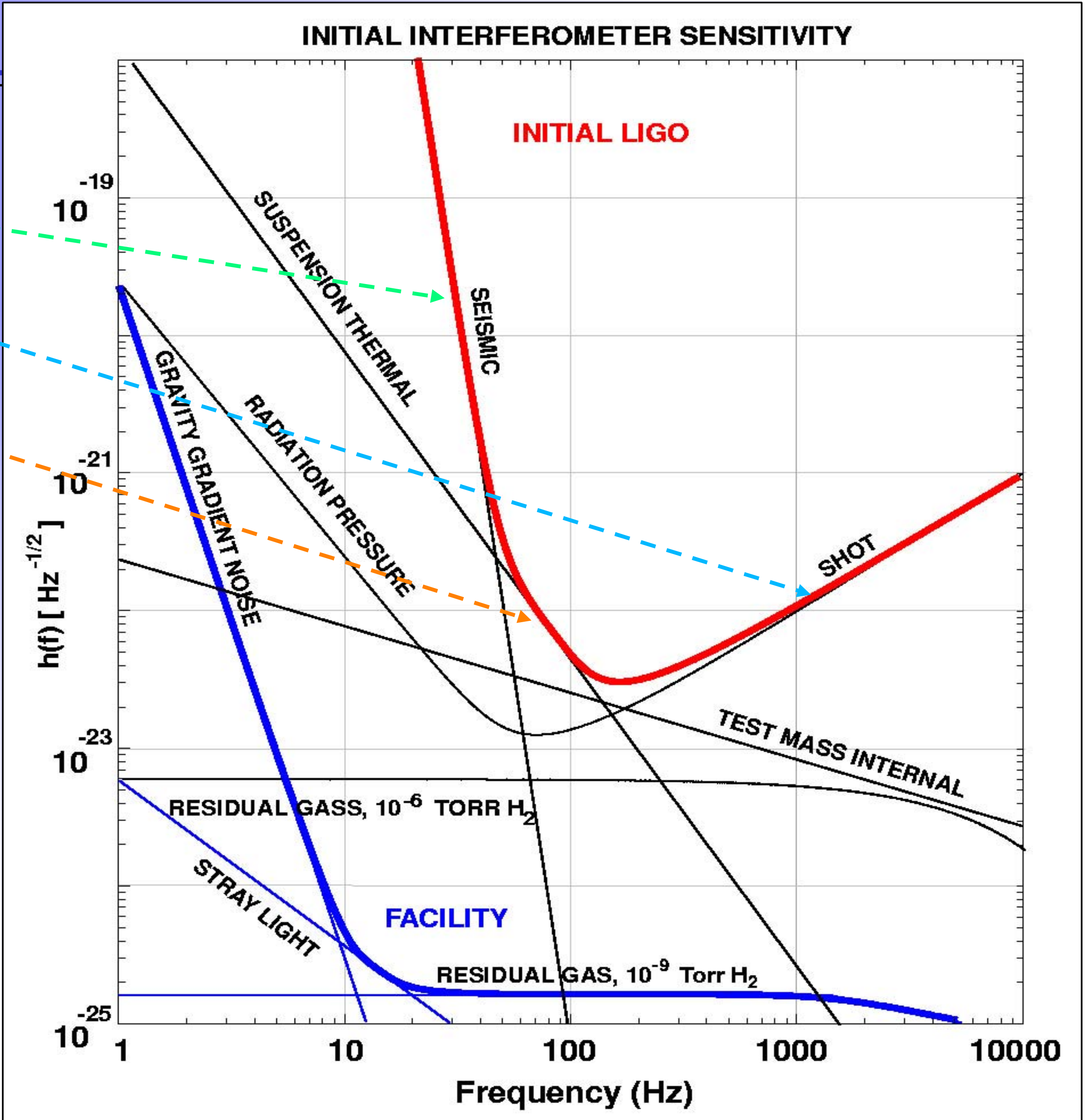
- Deliver pre-stabilized laser light to the long mode cleaner
  - **Frequency fluctuations**
  - **In-band power fluctuations**
  - **Power fluctuations at 25 MHz**
- Provide actuator inputs for further stabilization
  - **Wideband** $10^{-4}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$
  - **Tidal** $10^{-7}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$



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

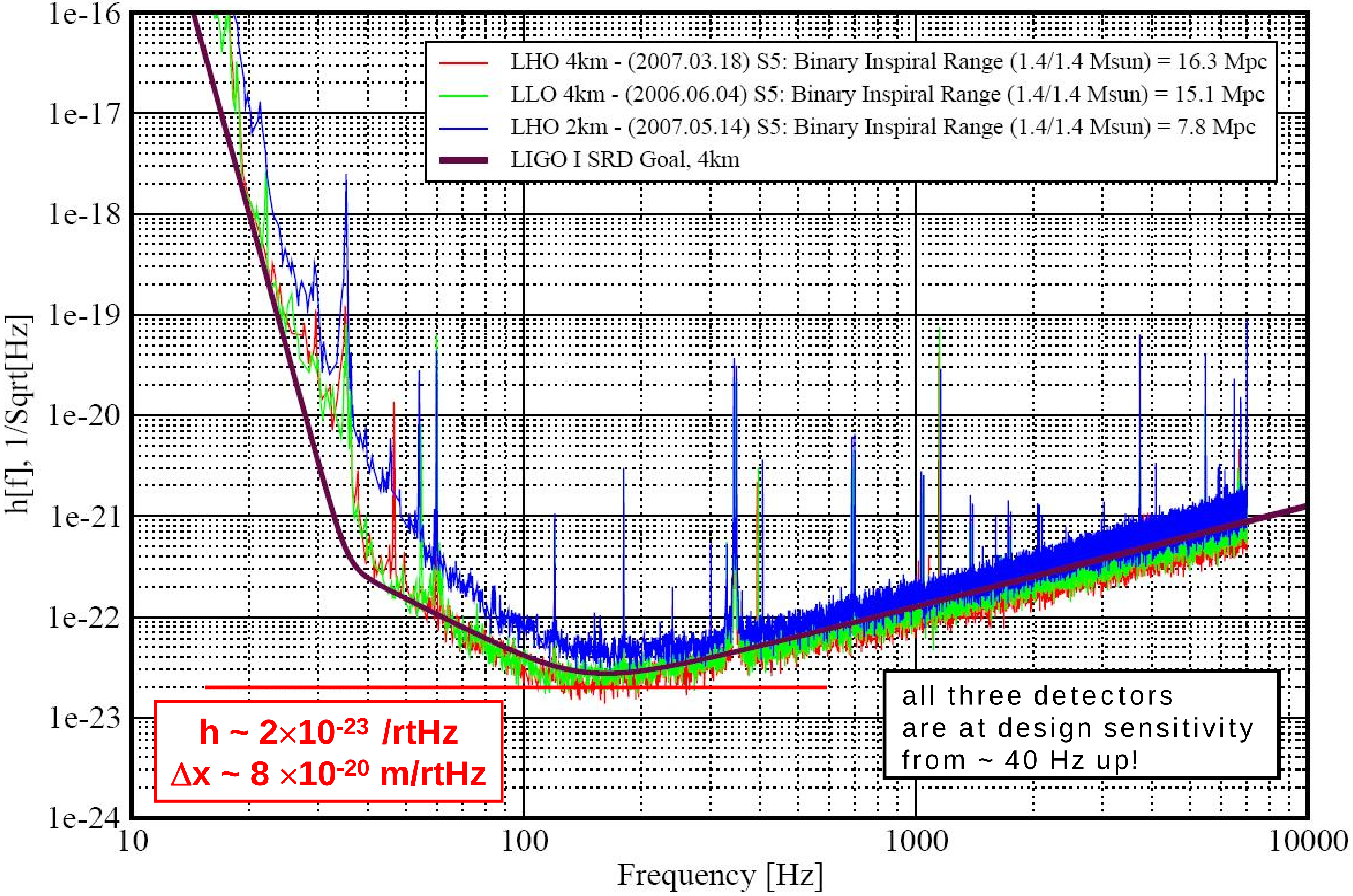
Design Noise Limits

- 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)



Strain Sensitivity of the LIGO Interferometers

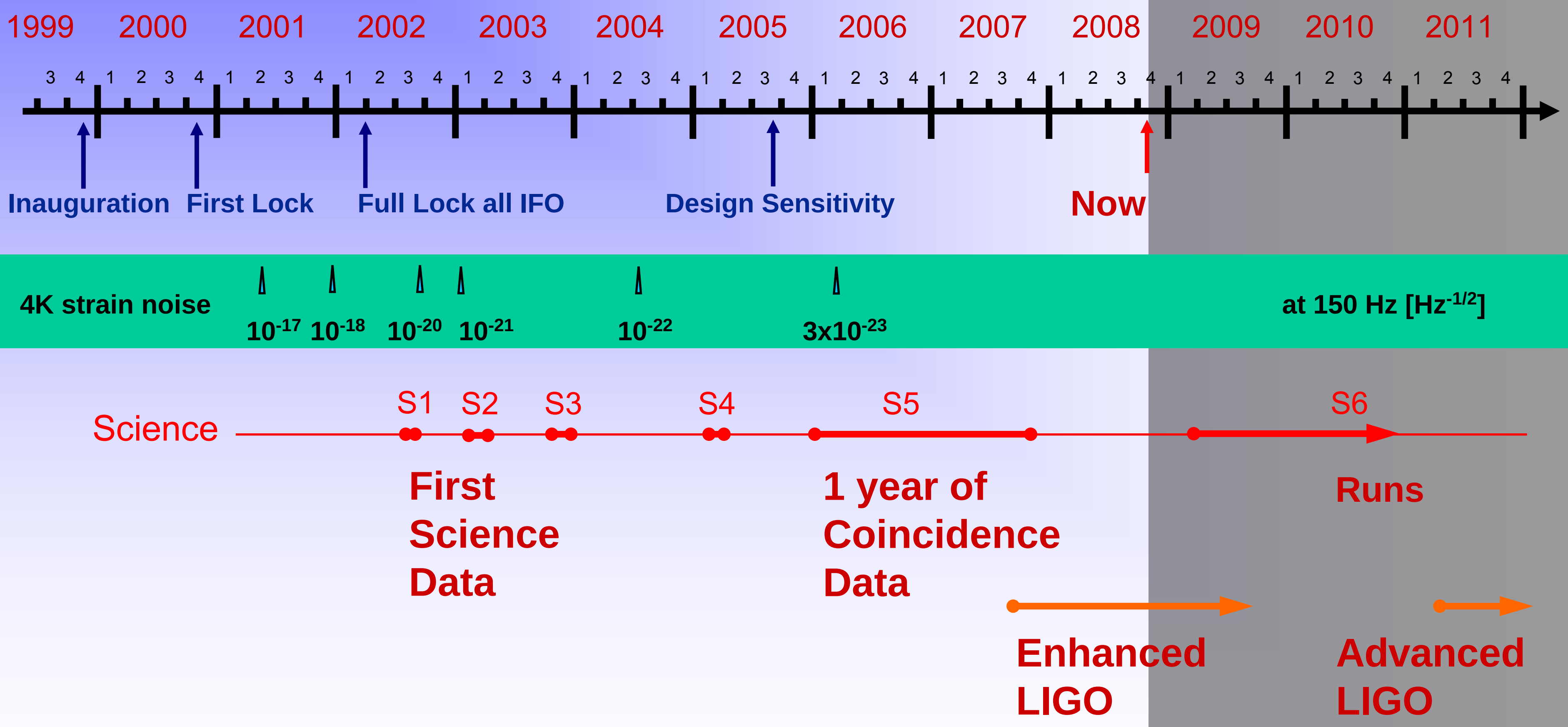
S5 Performance - May 2007 LIGO-G070366-00-E



$h \sim 2\times10^{-23}$ /rtHz
$\Delta x \sim 8 \times10^{-20}$ m/rtHz

all three detectors
are at design sensitivity
from ~ 40 Hz up!

LIGO Time Line



1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011

3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4

Inauguration **First Lock** **Full Lock all IFO** **Design Sensitivity** **Now**

4K strain noise **10^{-17}** **10^{-18}** **10^{-20}** **10^{-21}** **10^{-22}** **3×10^{-23}** **at 150 Hz [$\mathrm{Hz}^{-1/2}$]**

Science S1 S2 S3 S4 S5 S6

First Science Data

1 year of Coincidence Data

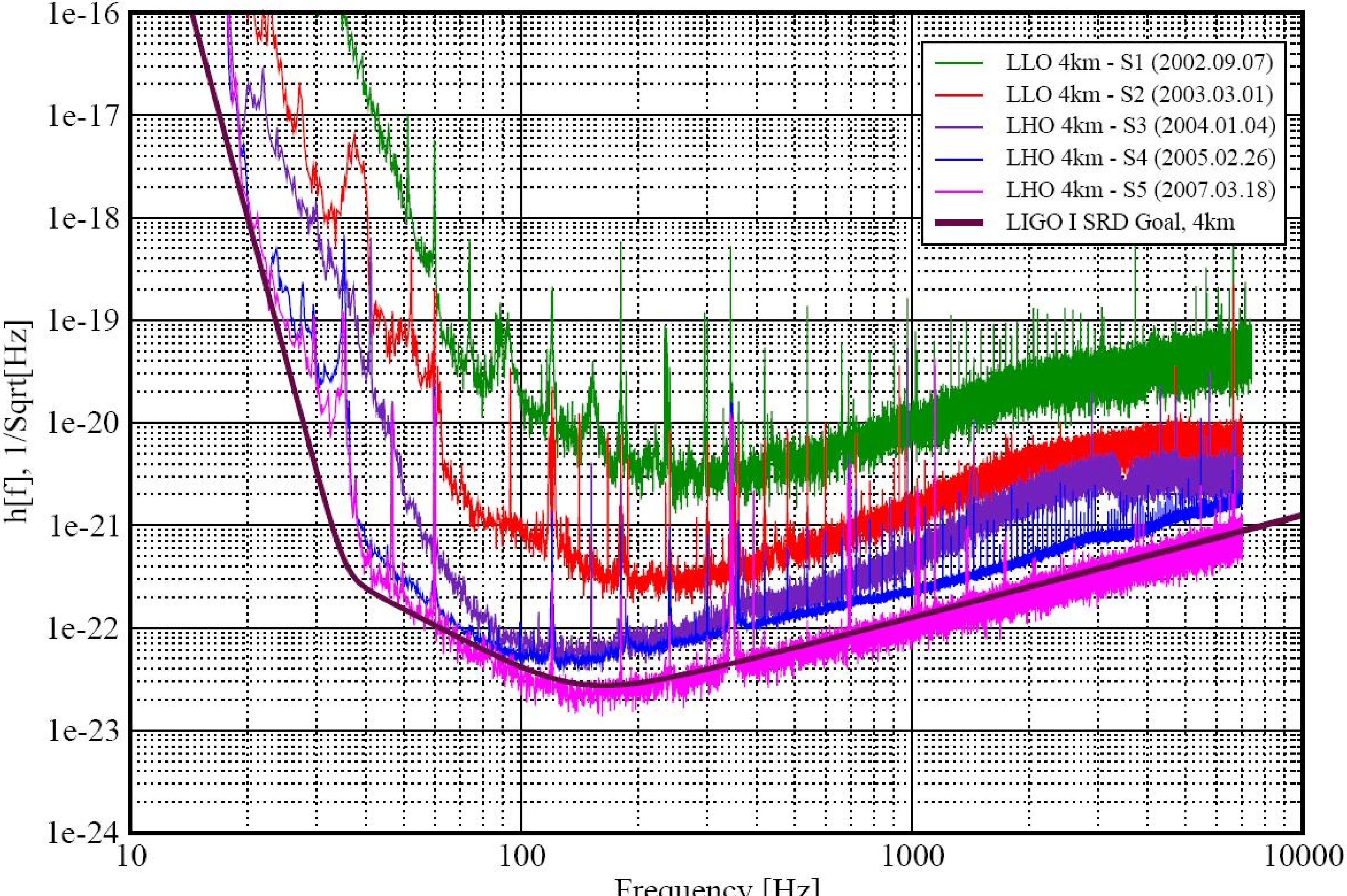
Runs

Enhanced LIGO

Advanced LIGO

LIGO sensitivity improvement over time

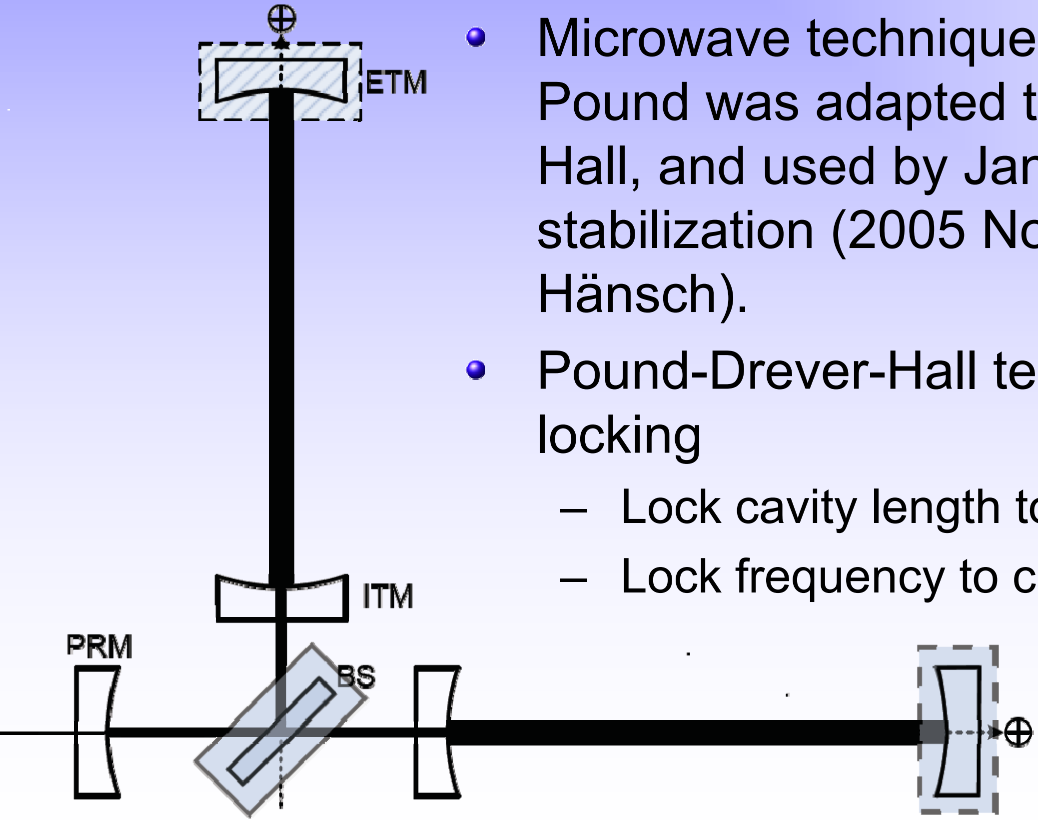
Comparisons among S1 - S5 Runs   LIGO-G060009-03-Z



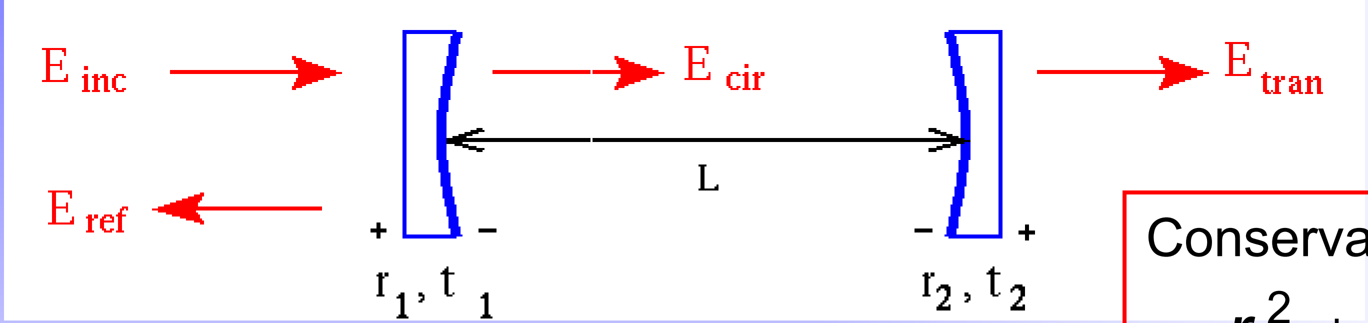
Phase Modulation

and why it is needed to operate an interferometric detector

- Laser field must resonate in the cavities for interferometer to operate as intended
- External disturbances cause cavity length and laser frequency to fluctuate, thus active sensing and control is required to keep laser resonant in the cavities
- Microwave technique for locking cavities developed by Pound was adapted to optical cavities by Drever and Hall, and used by Jan Hall for advances in laser stabilization (2005 Nobel price in Physics for Hall and Hänsch).
- Pound-Drever-Hall technique is widely used for cavity locking
  - Lock cavity length to laser frequency or,
  - Lock frequency to cavity length (frequency stabilization)



Fabry-Perot Optical Resonator Cavities



Conservation of energy:

$$r_i^2 + t_i^2 + L_i = 1$$

$$R_i + T_i + L_i = 1$$

$$E_{cir} = t_1 E_{inc} + r_1 r_2 e^{-2ikL} E_{cir} = \frac{t_1}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{ref} = r_1 E_{inc} - t_1 r_2 e^{-2ikL} E_{cir} = \underbrace{\frac{r_1 - r_2(1-L)e^{-2ikL}}{1 - r_1 r_2 e^{-2ikL}}}_{r_{cav}} E_{inc}$$

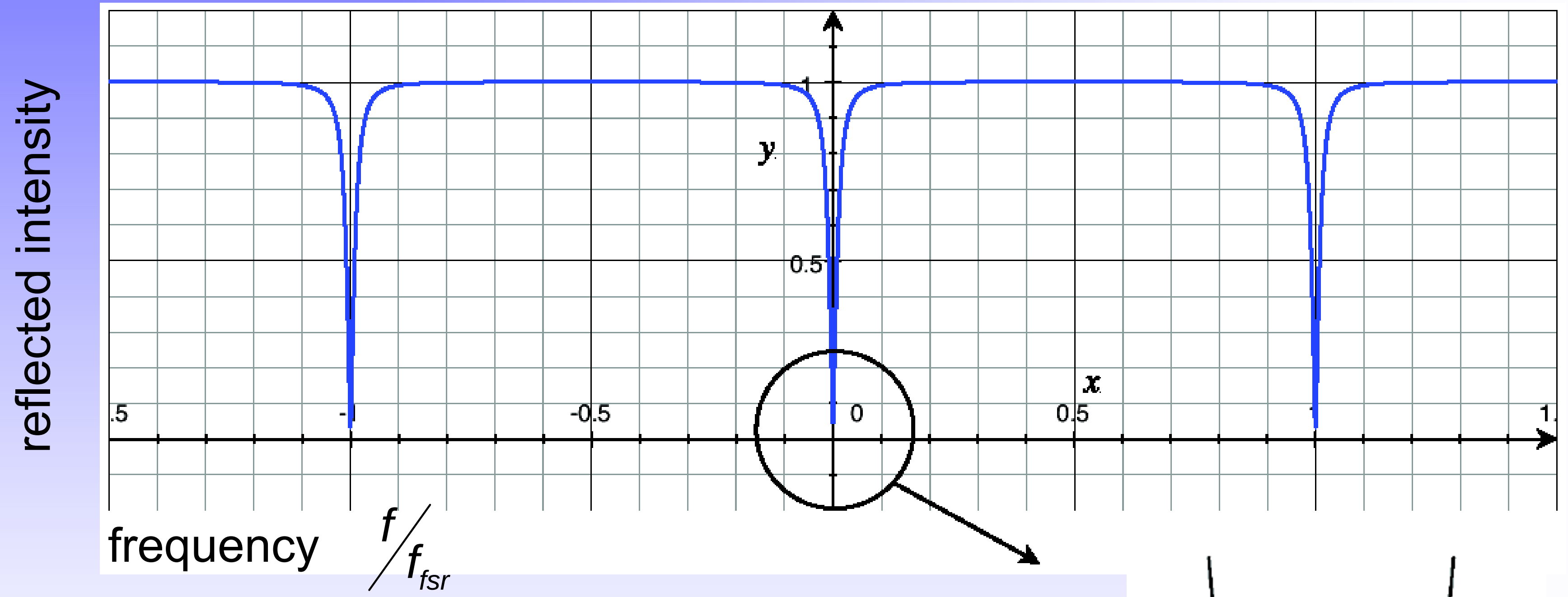
$$E_{tran} = t_2\, e^{-ikL} E_{cir} = \frac{t_1 t_2 e^{-ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

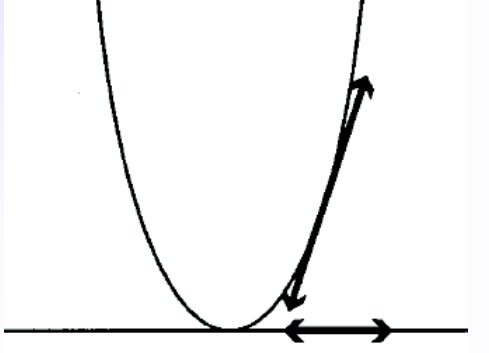
with $E_{inc} = E_0 e^{i\omega t} + c.c.$

When *2kL = n(2p), (ie, L=nl/2),*

E_{cir} , E_{tran} maximized ⇒ resonance!

Cavity Reflectance

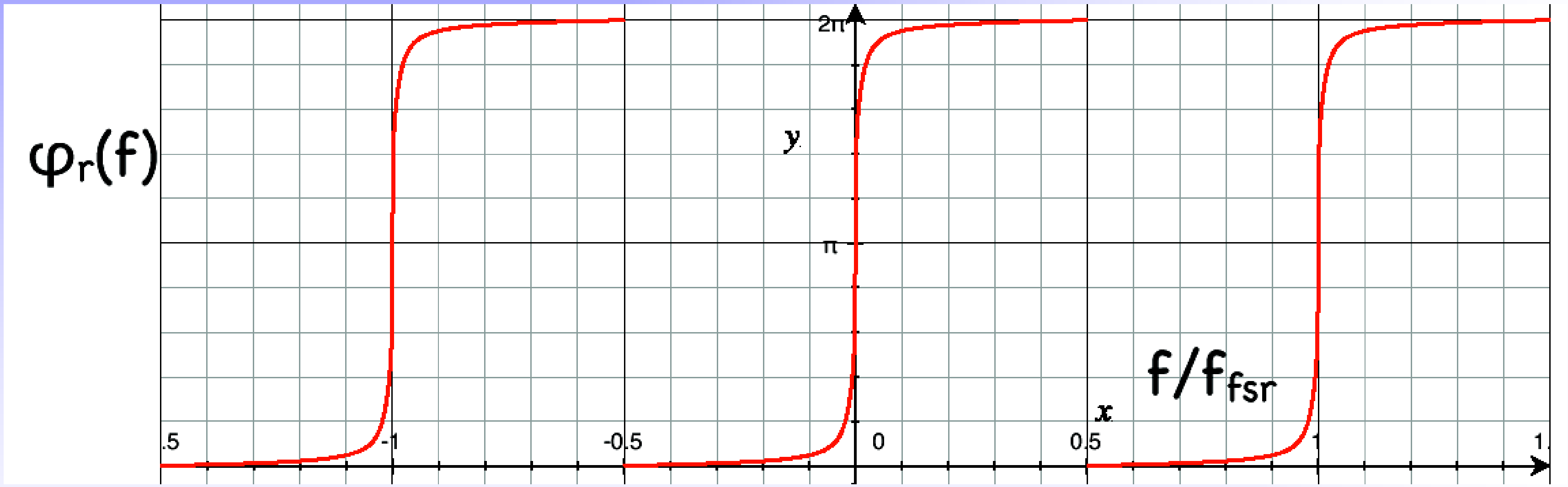




Modulation of the round trip phase (laser frequency or cavity length) at a frequency f_m generates a modulation on the reflected power at f_m if the cavity is off-resonance.

Phase shift for reflected light

- The reflected light not only changes in magnitude, it also experiences a phase shift

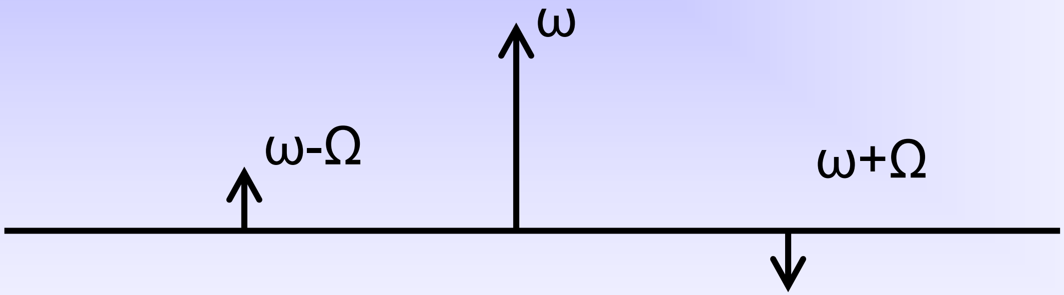


Phase modulation

- Phase modulation can be described as:

$$E_{in} \approx E_0 e^{i\omega t}\left(J_0(m) + J_1(m)e^{-i\Omega t} + J_1(m)e^{i\Omega t}\right) + c.c.$$

- where m is the modulation depth, $\Omega=2\pi f_m$ is the modulation frequency and $\omega=2\pi f$ the carrier
- or in the phasor picture as:



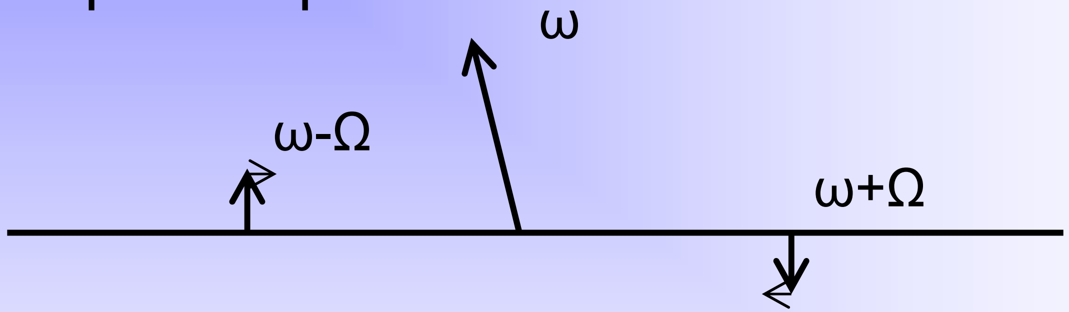
- As long as Ω is not near to $\frac{n \cdot f_{fsr}}{2\pi}$ sidebands are not resonant even when the carrier is near or on the resonance.

Phase modulated light reflected from cavity

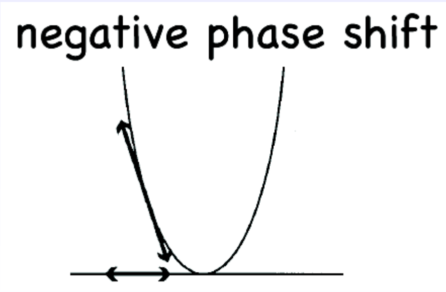
- The reflected light is described like this:

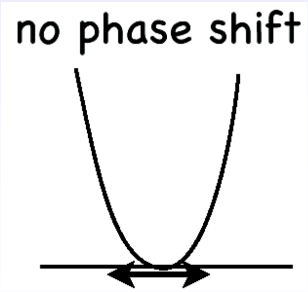
$$E_r \approx E_0 e^{i\omega t}\left(J_0(m)\cdot r_{cav}(\omega) + J_1(m)\cdot r_{cav}(-\Omega)e^{-i\Omega t} + J_1(m)\cdot r_{cav}(\Omega)e^{i\Omega t}\right) + c.c.$$

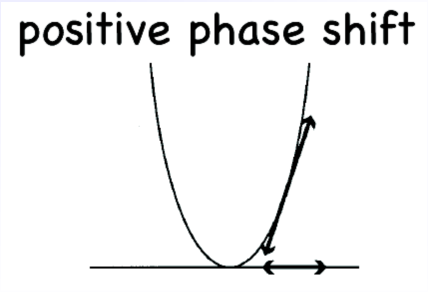
- Or in the phasor picture



- The resonance transforms phase modulated light into amplitude modulated light







Generating an error signal

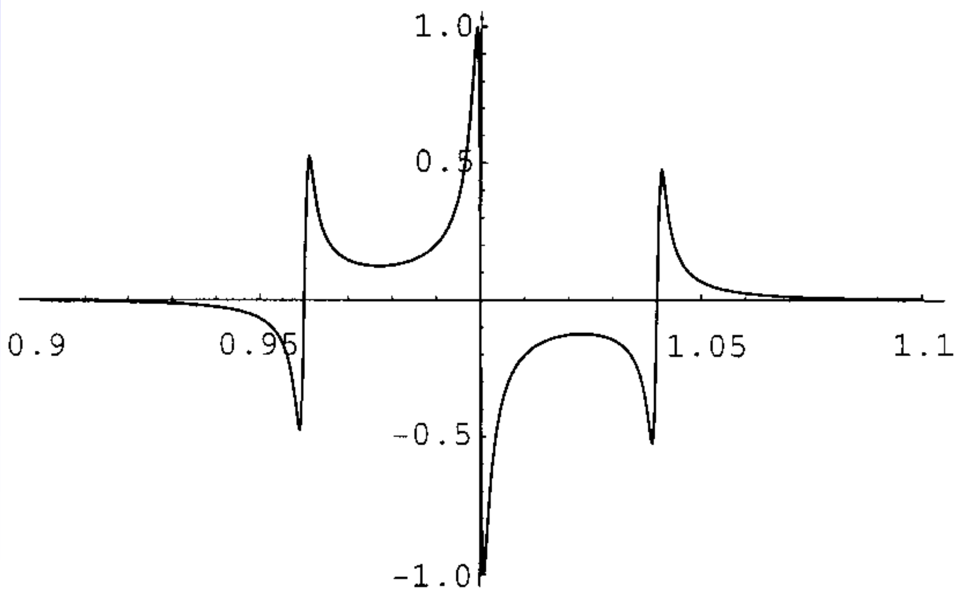
- From the electric field

$$E_r \approx E_0 e^{i\omega t}\left(J_0(m)\cdot r_{cav}(\omega) + J_1(m)\cdot r_{cav}(-\Omega)e^{-i\Omega t} + J_1(m)\cdot r_{cav}(\Omega)e^{i\Omega t}\right) + c.c.$$

the intensity can be calculated:

$$I(\partial f) = DC\,terms + 2\Omega\ terms + 4E_0^2 r_0 J_0(m)J_1(m)\sin\left(2\pi\frac{\partial f}{FWHM}\right)\cos(\Omega t)$$

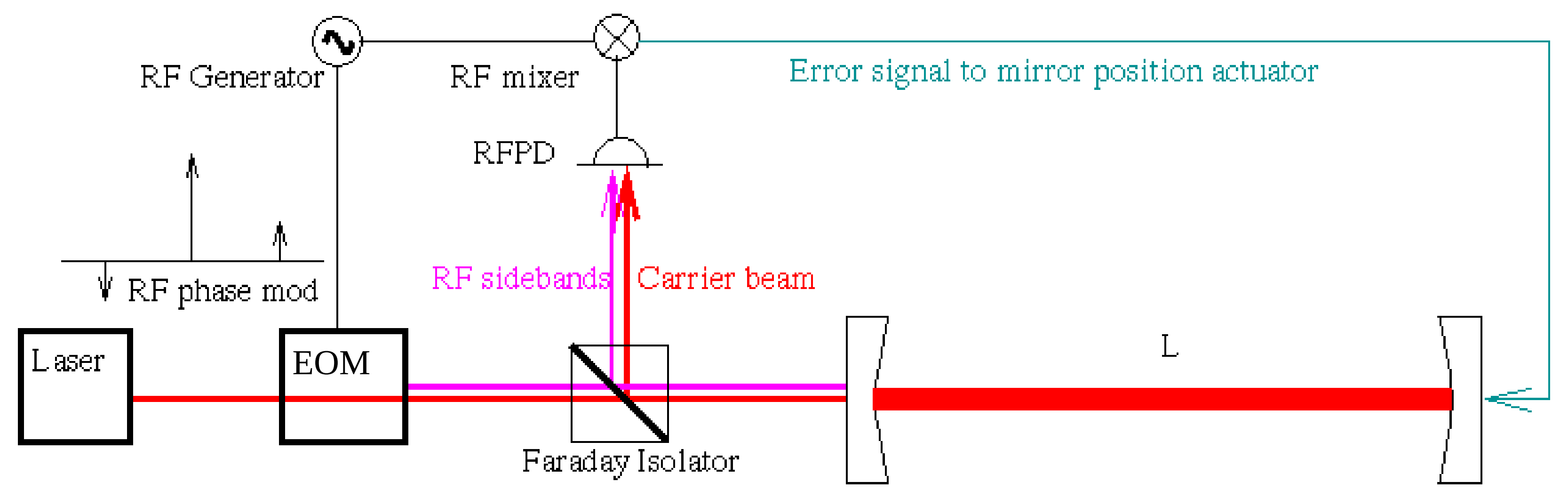
- The cos(Ωt) component is proportional to ∂f. After demodulation with a “mixer” or “lock-in amplifier” an error signal can be generated (as a function of the detuning):



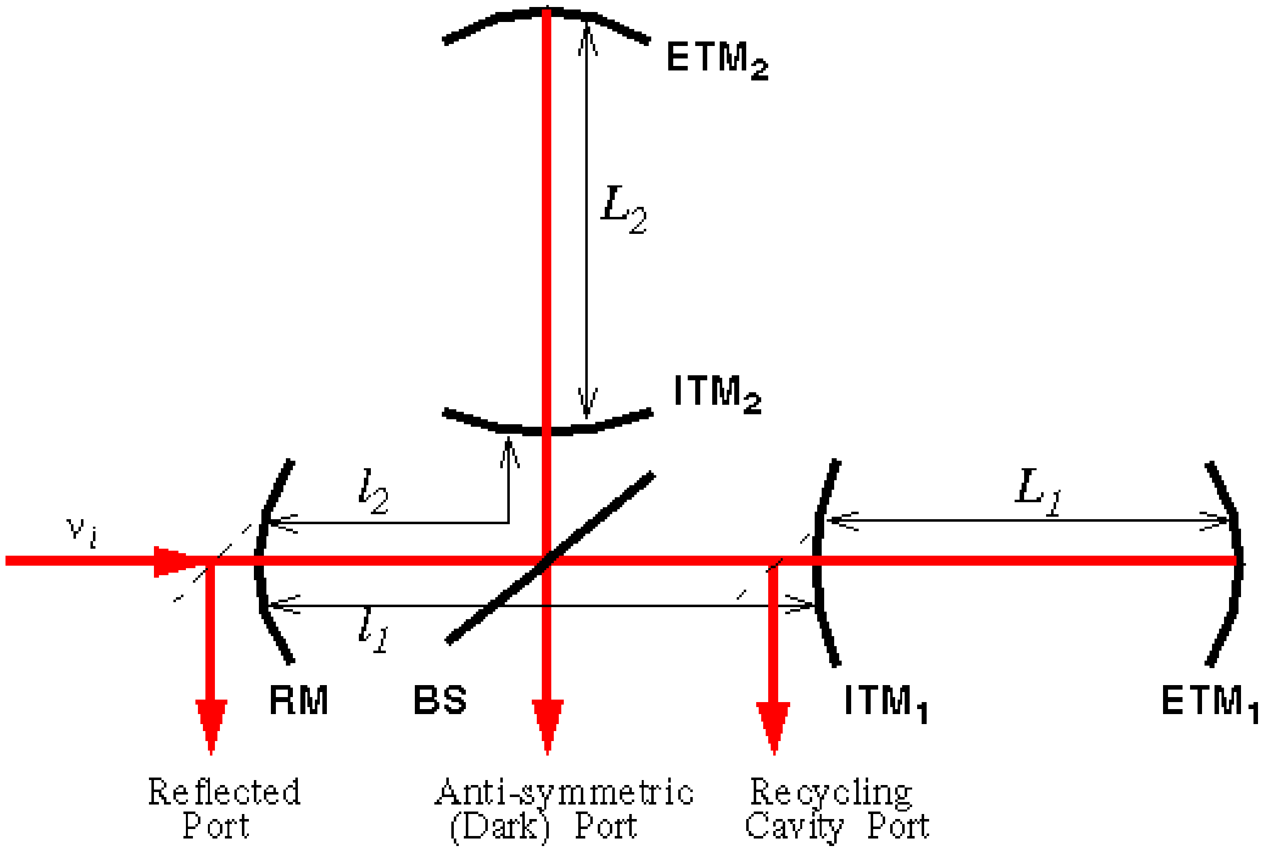
LIGO Experimental Example - Cavity control

Pound-Drever (reflection) locking used to control lengths of an optical cavity

- Phase modulate incoming laser light, producing RF sidebands
- Carrier is resonant in cavity, sidebands are not
- Beats between carrier and sidebands provide error signal for cavity length

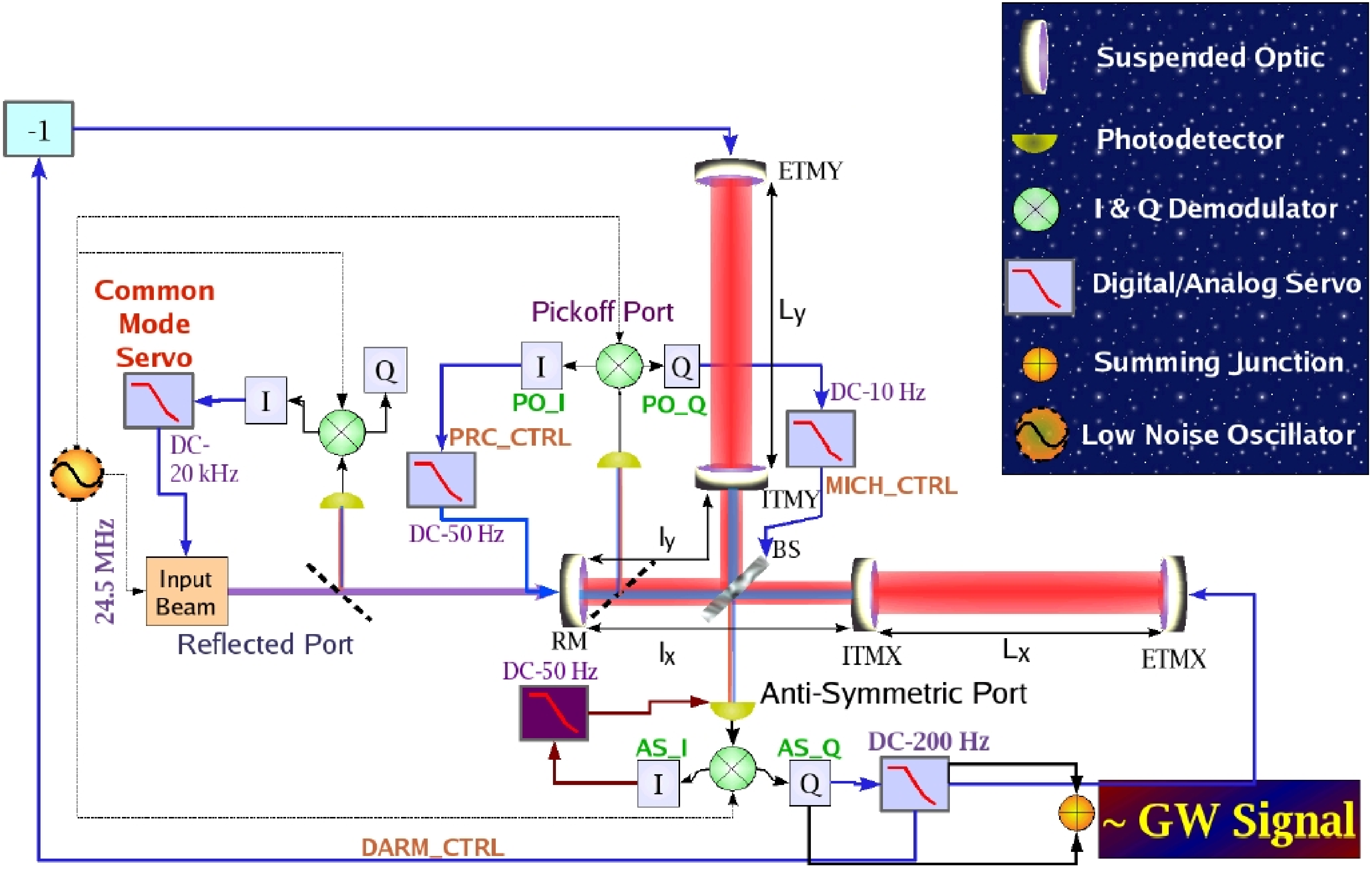


Another example
The control problem in LIGO



- Four interferometer lengths
- Ten mirror angles

Length sensing & control (LSC)



Phase modulators for eLIGO/aLIGO

- eLIGO modulator design
- eLIGO modulator commissioning
- aLIGO modulator prototype

eLIGO phase modulator

- LIGO is currently being upgraded to eLIGO
- Laser power is increased to 30 W
- iLIGO electro-optic modulators (EOMs) must be replaced
  - LiNbO3 modulators would suffer from severe thermal lensing or might even break

- eLIGO devices (techniques) serve as testbed for aLIGO

Wedged RTP crystal

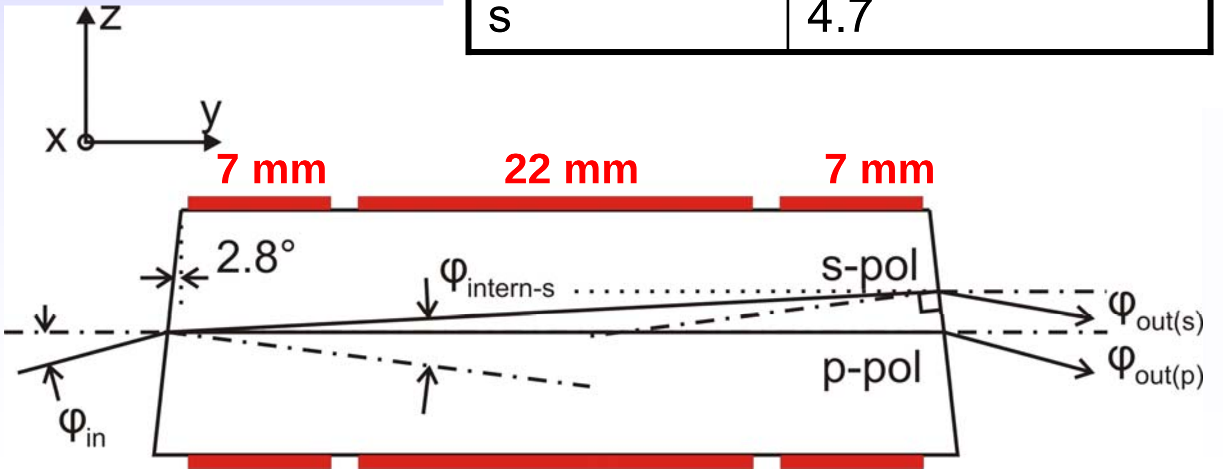
(rubidium titanyl phosphate - $RbTiOPO_4$)

- iLIGO lithium niobate ($LiNb0_3$) modulators are not satisfactory
  - Thermal lensing / Damage / Residual absorption.

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

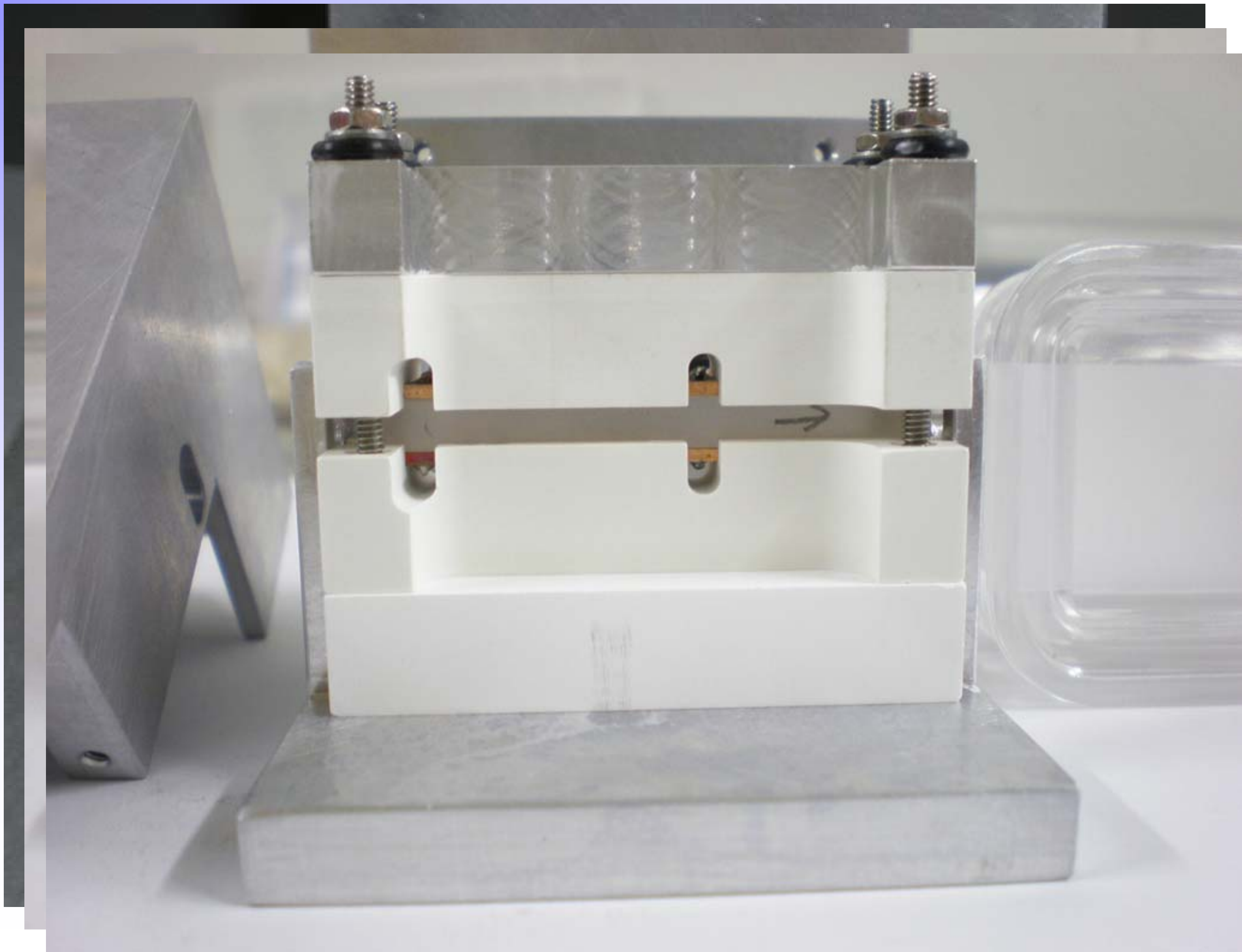
Polarization	Angle [degrees]
p	5.2
s	4.7

- AR coatings (< 0.1%)



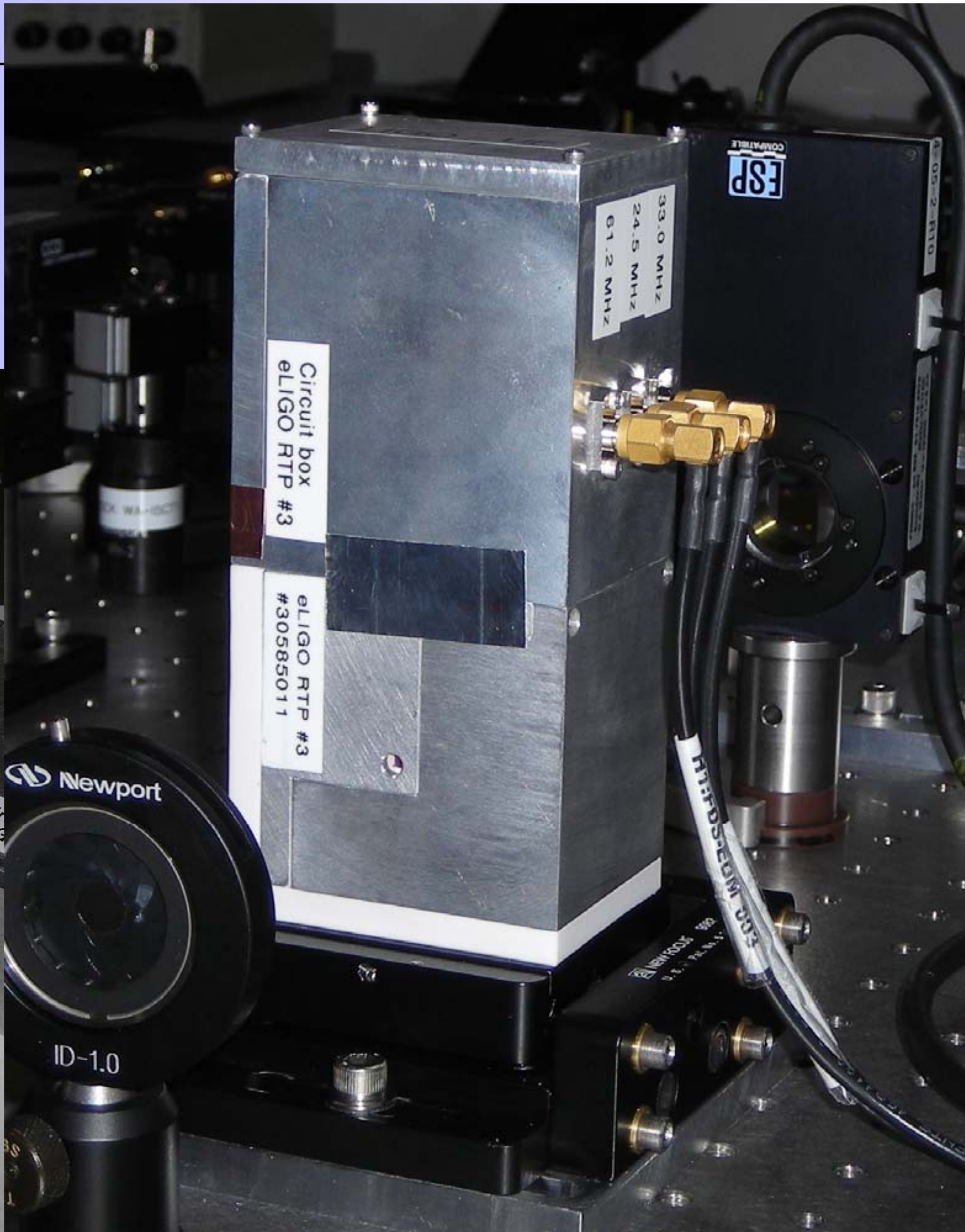
Three Modulations / Single Crystal design

- One crystal with three separate pairs of electrodes. Crystal and electrodes are held by Boron-Nitride spacer (2nd generation, replaced Teflon).
- Electrode lengths:
  - 7 mm
  - 22 mm
  - 7 mm



Separate optic and electronic cases

- The crystal housing is separated from the resonant circuits to maintain maximum flexibility while the crystal remains in the optical setup.

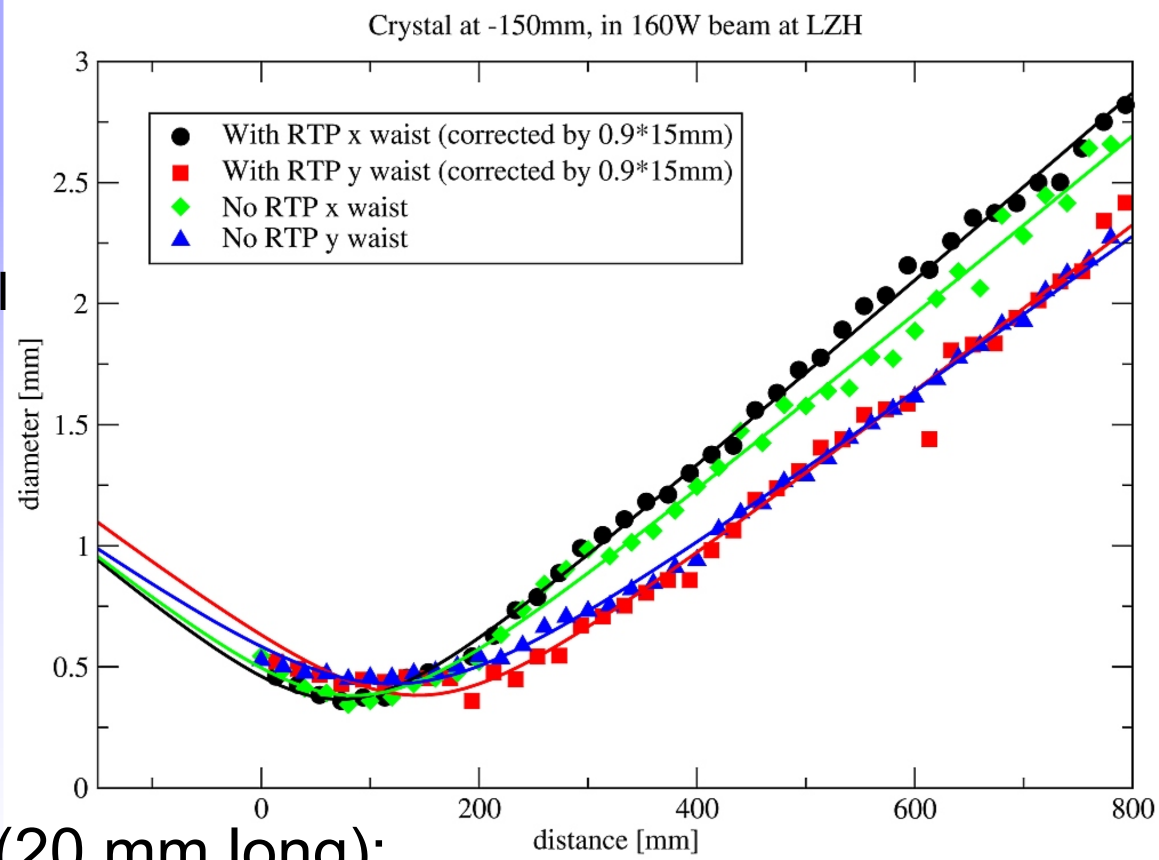


Resonant circuit

- Impedance matching circuit in separate housing.
- Pi-network resonant circuit with 50 Ω input impedance.
- Matched to eLIGO Frequencies:
  - 24.5 / 33.0 / 61.2 MHz

Thermal properties

- The aLIGO 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

eLIGO modulator commissioning

- Installed at LHO
  - drive electronics changed to output 24dBm
  - installed after PMC, before power control. EOM always sees maximum power (~28W)
  - Modulation indices
    - 24.5MHz: m=0.50 @ 12.0Vpp
    - 33.3MHz: m=0.094 @ 5.0Vpp
    - 61.2MHz: m=0.146 @ 8.6Vpp
  - MC visibility 98%
- Installation at LLO happened last week, commissioning is not yet finished.

Status of aLIGO modulator

- Prototypes are ready.
- Same internal setup as eLIGO modulators, but only two electrode pairs:
  31 mm / 7 mm
- High power testing at 140W was performed

Future work

- Investigation of EOM induced noise
  - RF-AM
  - RF pointing
  - carrier fluctuations
  - carrier pointing
  - mode distortion (thermal, maybe electrical)
- Sideband phase stability (clock noise)

Acknowledgements

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**