Simulation as a crucial tool for GW experiments

Hiro Yamamoto, Caltech / LIGO Project

- Time domain simulation
  - Fast, time series data, but only simple optics
  - Lock acquisition
  - Alignment control study
  - Noise hunting tool
- Static optics system simulation
  - Accurate for any optics configuration, but slow
  - Fields in degenerate and unstable cavity
  - Simulation with optics aberrations
  - Thermal lensing

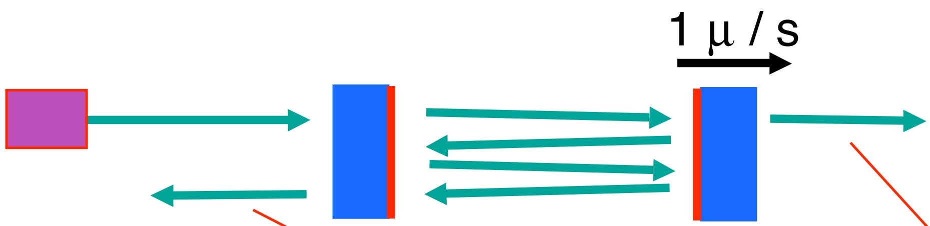
G040452-E

LIGO Time domain simulation
- e2e -

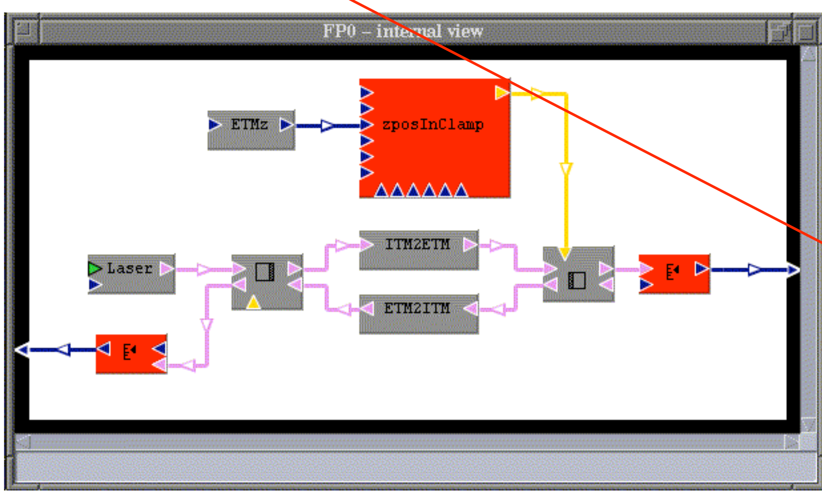
- Time domain simulation written in C++
- Like MATLAB with Interferometer toolbox
- Major physics components and tools relevant for GW interferometer experiments
  - » fields & optics, radiation pressure, shot noise, thermal lensing, mechanics, digital and analog electronics, measured noise, state space model using ABCD matrix, etc
- Flexible to apply for wide varieties of systems
  - » from a simple pendulum to full LIGO I to adv.LIGO
  - » from fast prototyping of subsystems to entire interferometer simulation
- Easy development and maintenance
  - » use of graphical front end for e2e programming
  - » object orient design for easy addition of new physics

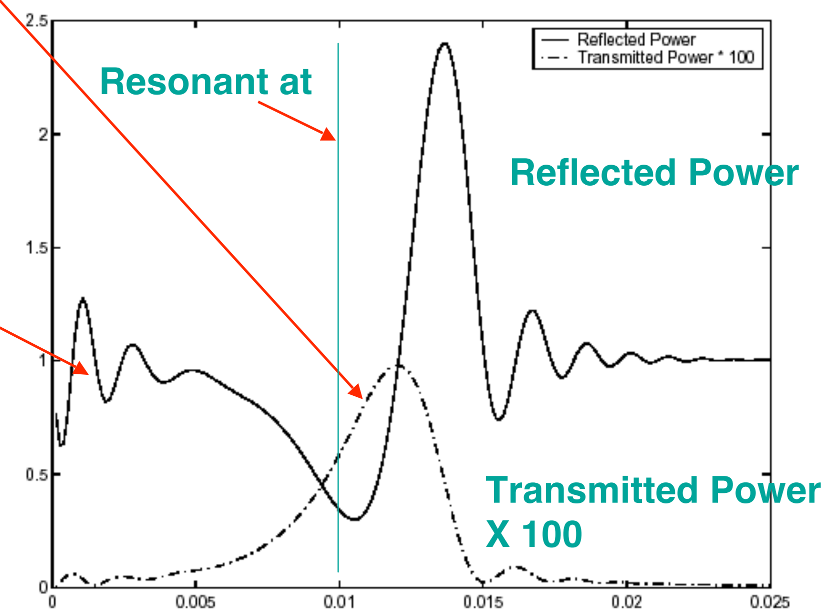
e2e example

Fabry-Perot cavity dynamics



ETMz = $-10^{-8} + 10^{-6}$ t





Power = 1 W, T_{ITM}=0.03, T_{ETM}=100ppm, L_{cavity} = 4000m

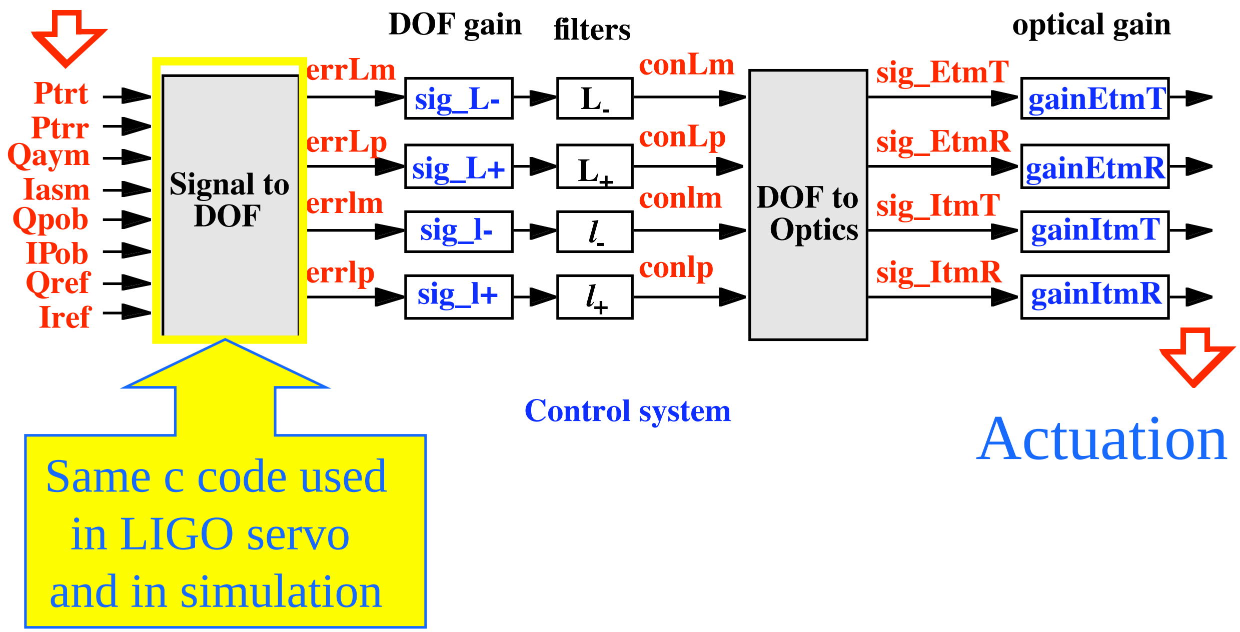
LIGO e2e usage

- LIGO I
  - » Lock acquisition design, original and improvements
  - » In-lock statue sensitivity
  - » Robust alignment control study
  - » Cross checks
    - – ASC matrix miscalculation found
    - – LIGO I 4k Schnupp asymmetry misplacement identified
  - » Effect of radiation pressures
  - » Noises due to bilinear couplings
  - » Effect of seismic noise on lock and sensitivity at LLO
  - » Detailed study of input beam (mode cleaner and mode matching telescope)
- Adv.LIGO
  - » Lock acquisition
  - » Effect of noise of input beam
  - » Radiation pressure and alignment control

Automated Control Matrix System

First lock design - LIGO T000105 Matt Evans

Field signal

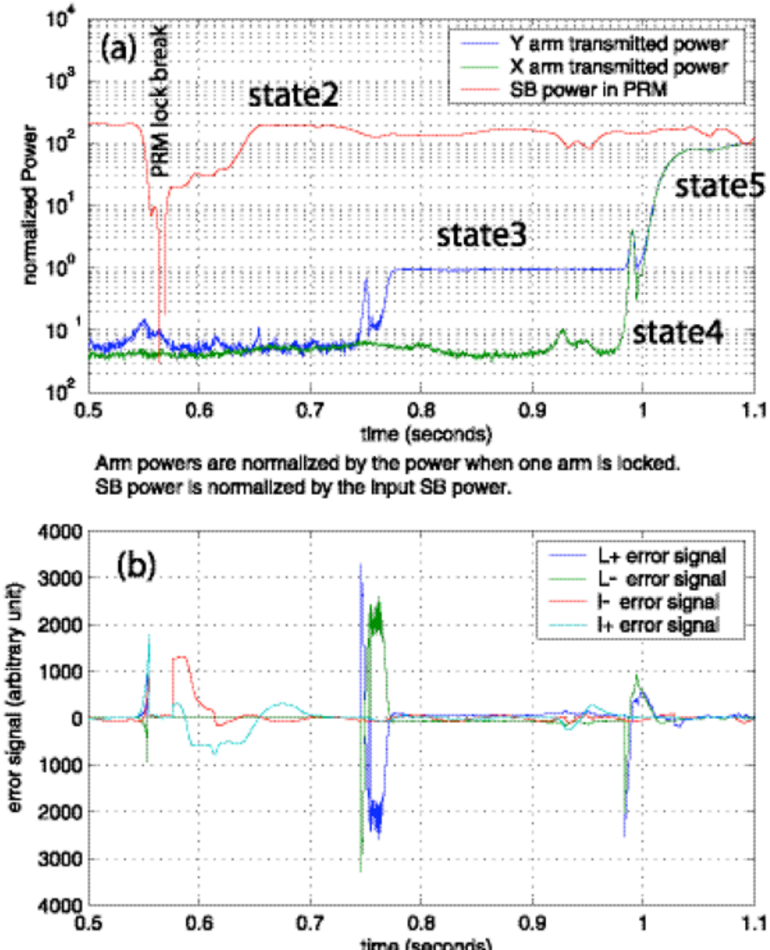


Actuation of mass

Lock acquisition

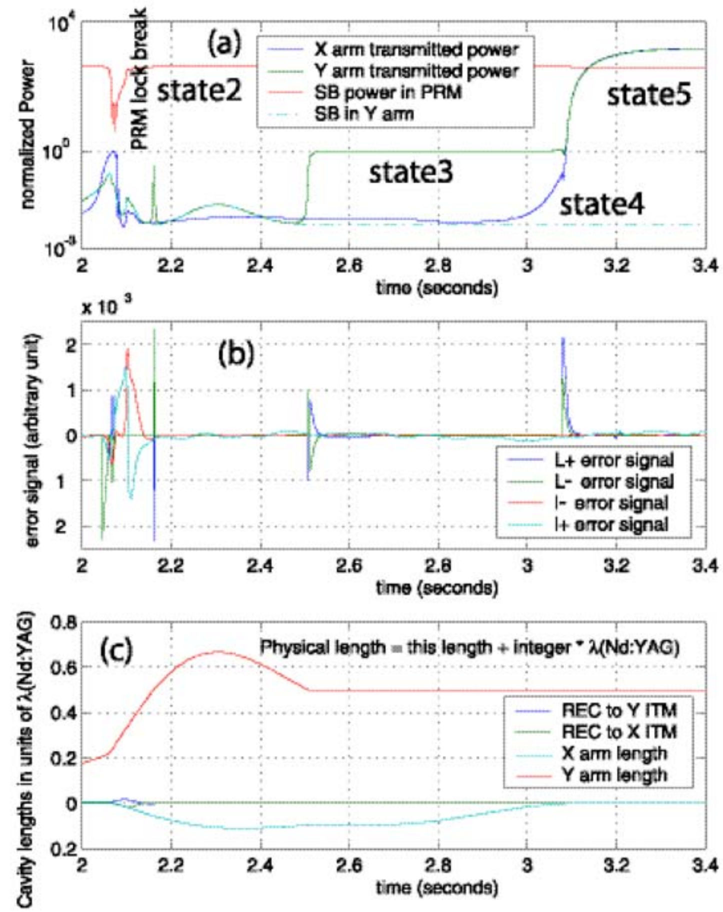
real and simulated

Figure 1. LHO 2k IFO data



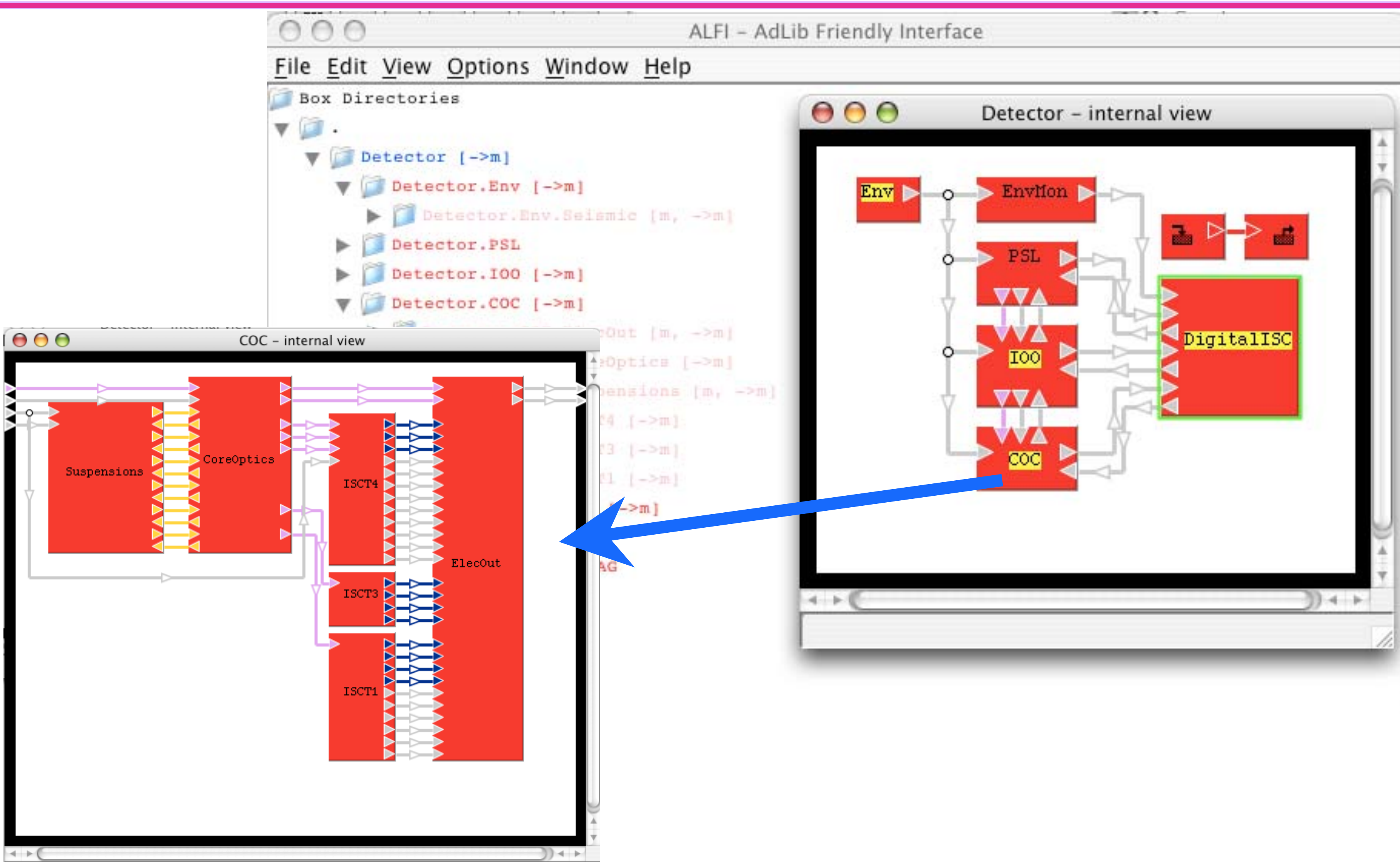
observable

Figure 2. Simulated signal

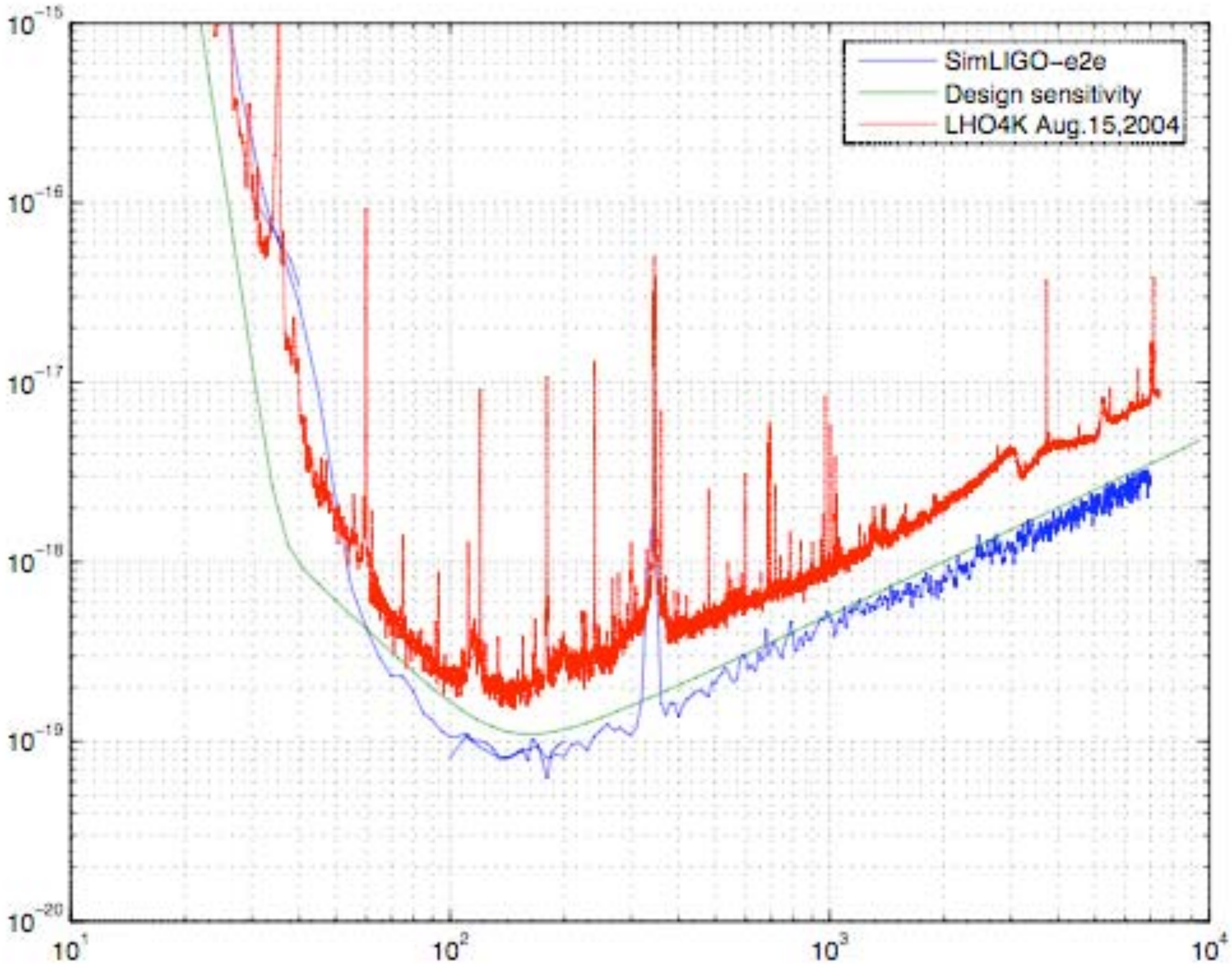


Not experimentally observable

SimLIGO
full LIGO I simulation



Sensitivity curve



Summary of e2e

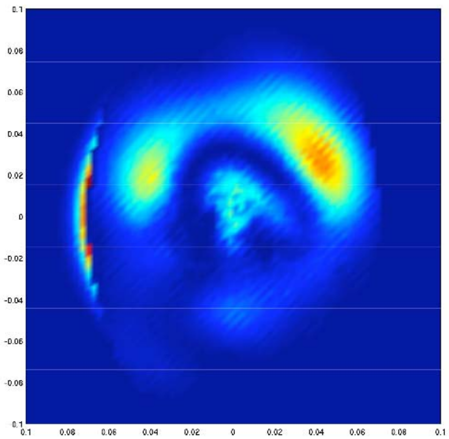
- LIGO I simulation is ready
  - » Good playground for length and alignment control study
  - » Sensitivity curve properly simulated
  - » Assist to improve another factor of 2
  - » Bilinear coupling
  - » more noise, more reality
    - – scattering noise, acoustic coupling, beam clipping
- adv.LIGO simulation demands more
  - » physics (dual recycling cavity, better Modal Model or faster FFT)
  - » Speed (thread)
  - » Accuracy (quadruple precision by hardware !?)

Static optics system simulation using FFT-based software

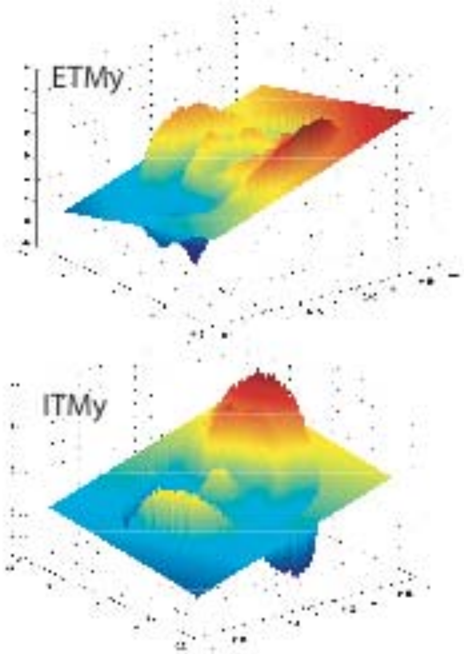
- Detailed calculation of static fields in Core Optics system
  - » Orsay -> MIT/LIGO
  - » Extensive use of FFT to handle optics system with details
- Physics motivation
  - » Effect of core optics phase map or mirror surface aberration
  - » Effect of beam splitter curvature
  - » Imbalance of upper and lower sidebands
  - » Thermal lensing effect
    - – When LIGO thermal compensation system (TCS) is used to heat input test masses (ITM), somehow the interferometer works better when the offline ITM is heated more than inline ITM

Effect of mirror aberration

Dark port CR

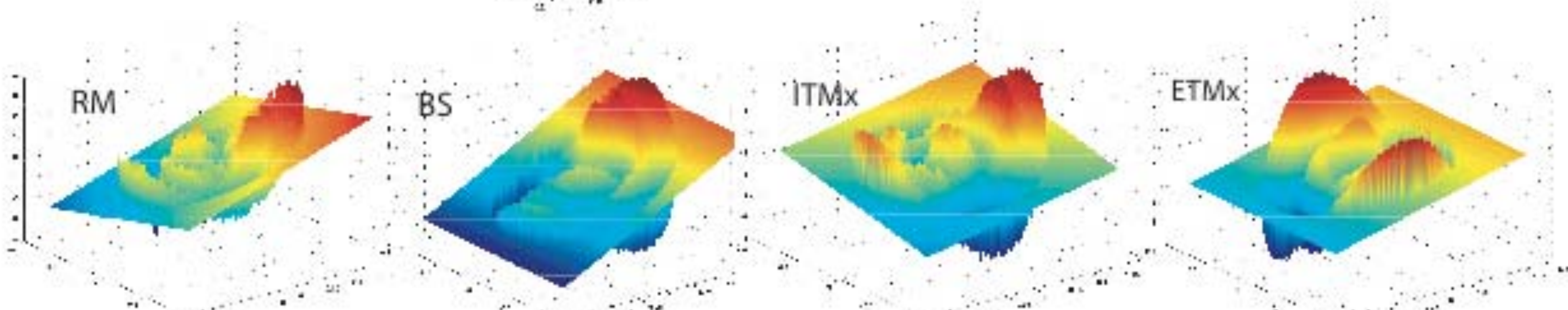


P(CR)=3.2kW -> 2.5kW



Contrast defect

Mode matched, identical arms	5.5e-7
+ as-built arms	6.8e-5
+ BS curvature	1.2e-4
+ Mirror phase maps	2.3e-4
+ Differential heating	2.5e-4

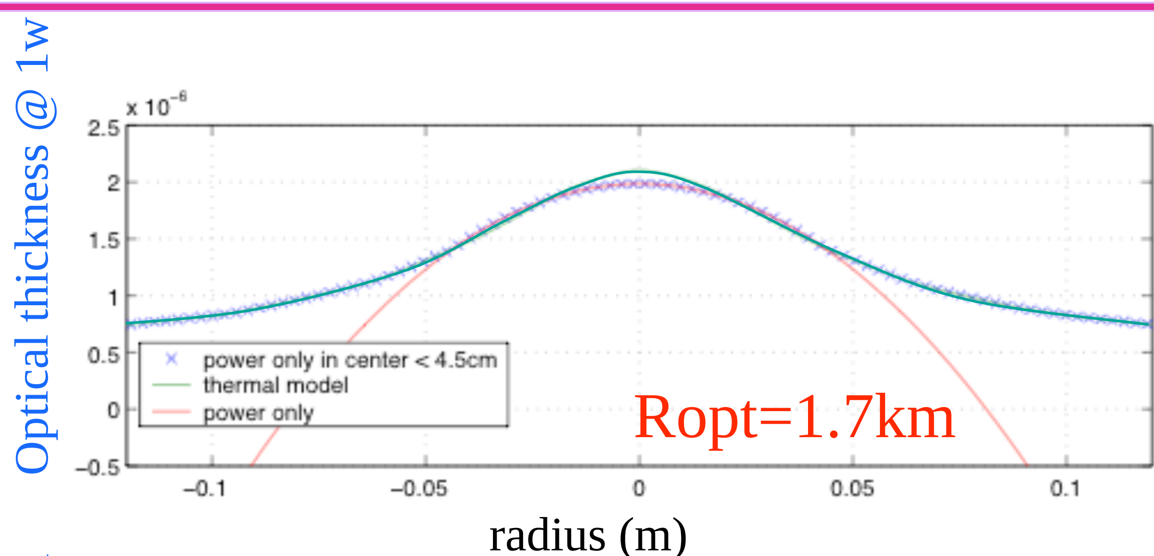


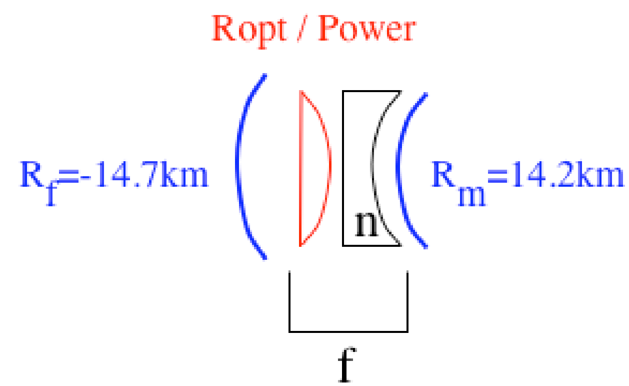
P(CR)=46W ->36 W

P(CR)=3.3kW -> 2.6kW

Thermal lensing in FFT

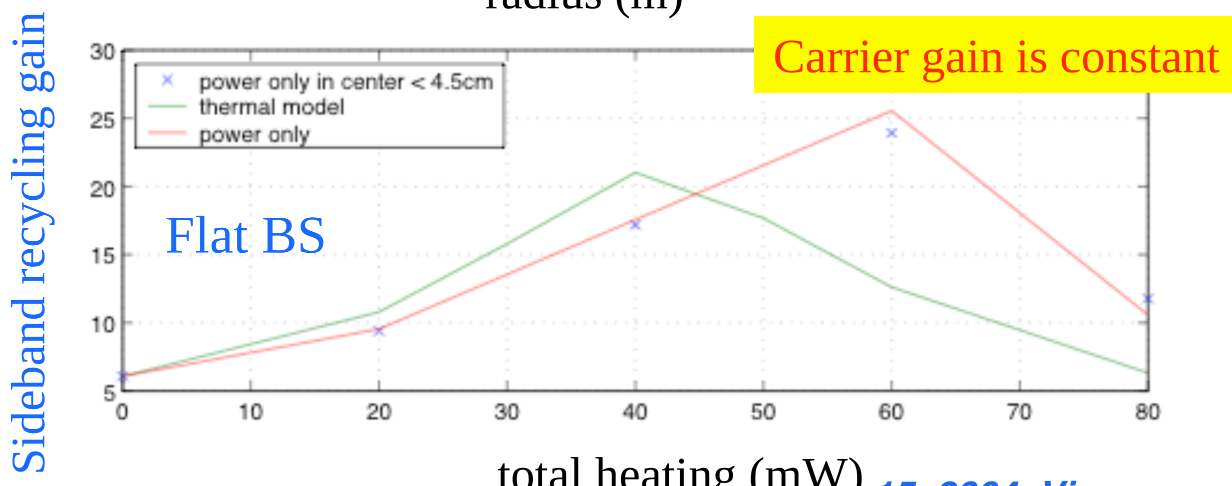
- P. Willems calculated based on MIT model -





$$\frac{1}{f} = -\frac{n-1}{Rm} + \frac{1}{Ropt} Power$$

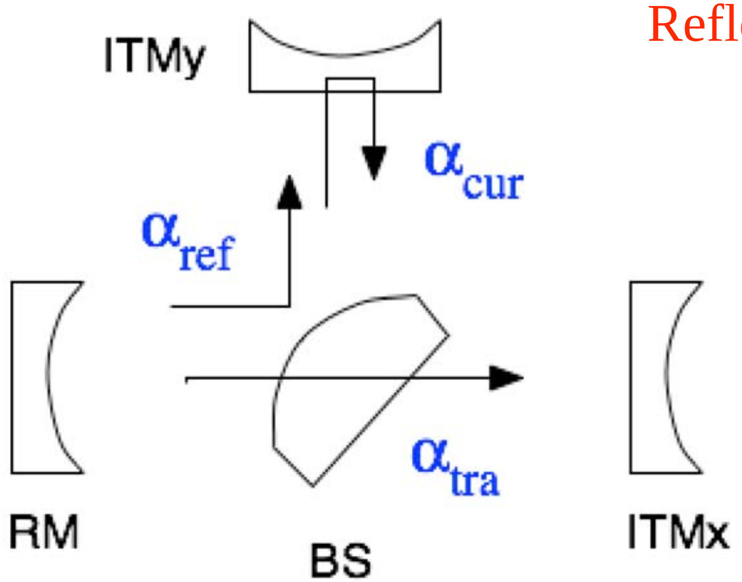
$$\frac{1}{R_f(HR)} = \frac{1}{R_f(AR)} - \frac{1}{f}$$



Power = 58mW

Mode disturbance in PRM

- BS and ITM curvature and BS lens -



Reflection and transmission change field curvature

$$\alpha_{cur} = \frac{z}{z_0}\left(1 - \frac{R_f(z)}{R_{ITM}}\right) \quad : 0.23(cold) \sim 0(hot)$$

$$\alpha_{ref}(x/y) = -\frac{z^2 + z_0^2}{z_0 \cdot R_{BS}\sqrt{2}^{\pm 1}} \quad : 0.027$$

$$\alpha_{tra} = -\frac{n-1}{2}\alpha_{ref} \quad : -0.005$$

R_{BS} = -200km

R_{ITM} = -14km

z_0(Rayleigh range) = 3.6km

z(distance to waist) = -1km

$$TEM00(out) = \frac{1}{\sqrt{(1+i\alpha_x)(1+i\alpha_y)}} TEM00(in)$$

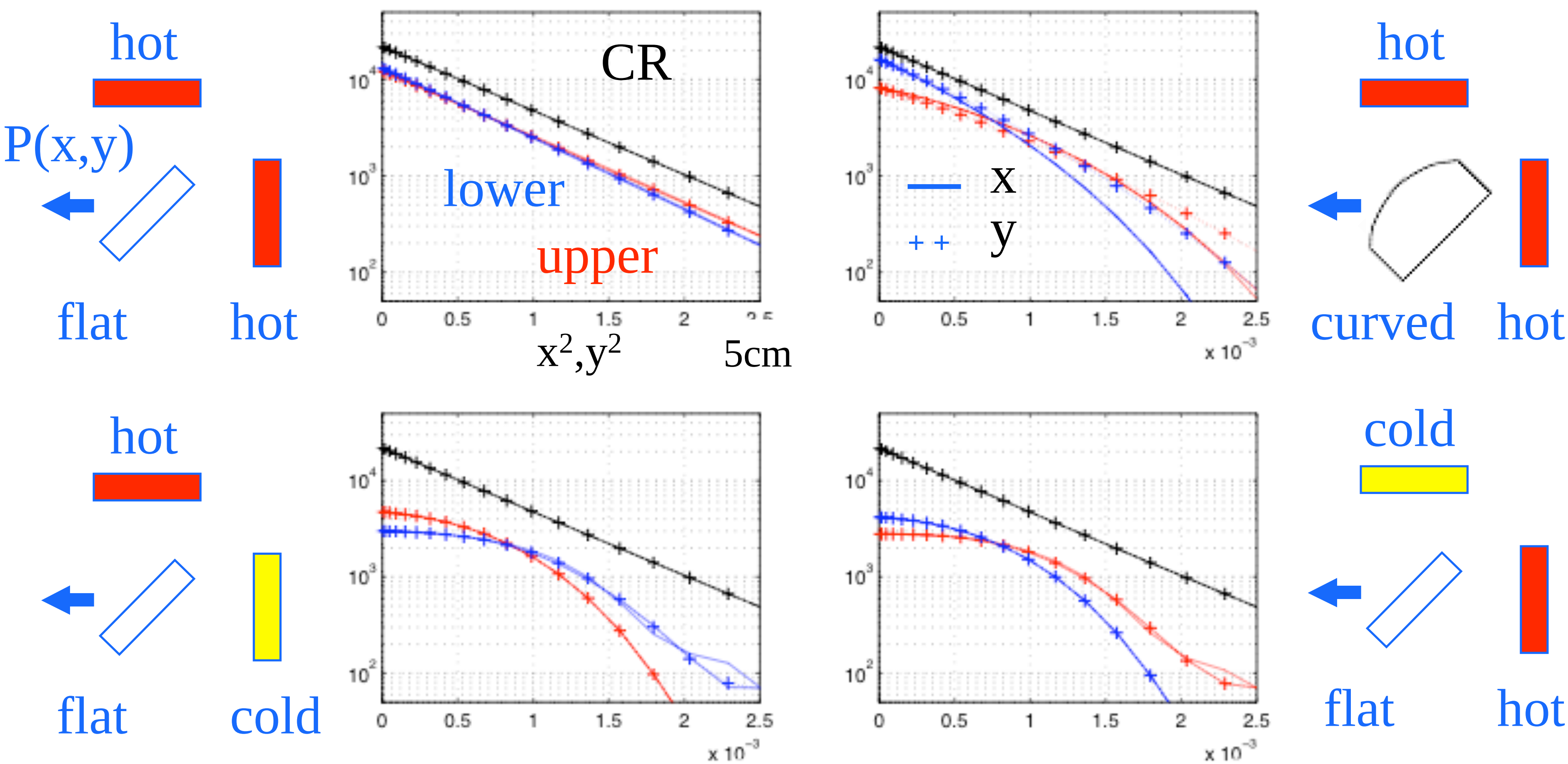
ITM differential heating and beam splitter curvature

Power only thermal

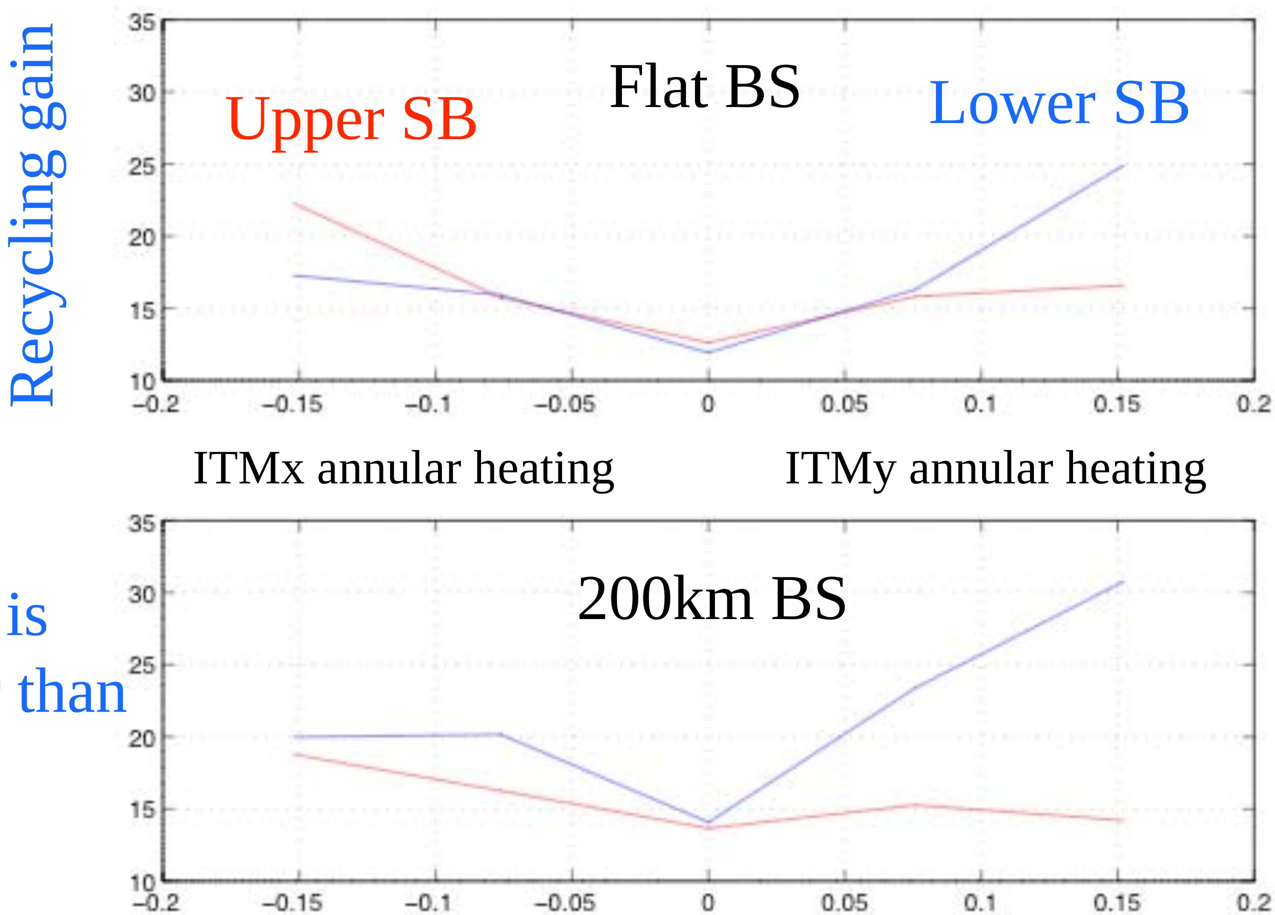
- Linear line : gaussian
- Blue vs red : sideband imbalance
- --- vs + + + : astigmatism

Power on Symmetric port

P(x,0) vs x^2, P(0,y) vs y^2



SB gain imbalance vs differential heating



60mW Gaussian On both

ITMx is cooler than ITMy

ITMx is hotter than ITMy

-200 mW

200 mW

Modal model calculation to understand FFT results

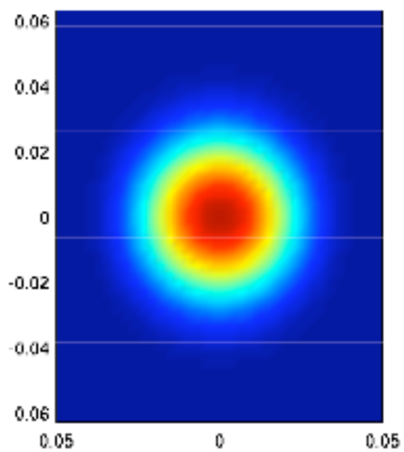
- Carrier field is insensitive to thermal state of ITMs and BS curvature
  - » CR reflected by arm does not have higher mode excited
  - » SB reflected has higher order mode excited due to curvature mismatch
- Michelson cavity can induce imbalance of upper and lower sidebands
  - » Oscillation phase part change sign, but Gouy phase and mode coupling due to curvature mismatch are SB sign independent.
  - » Sideband imbalance in PRM is observable when two cavities in PRM are different

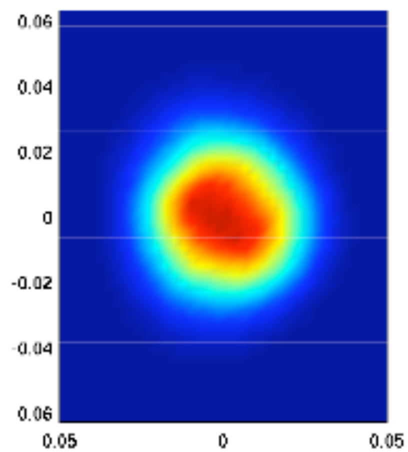
$$\mathrm{Propagator} = 1 - r_{RM} \cdot r_{ITM} \cdot \exp(-i\phi)$$

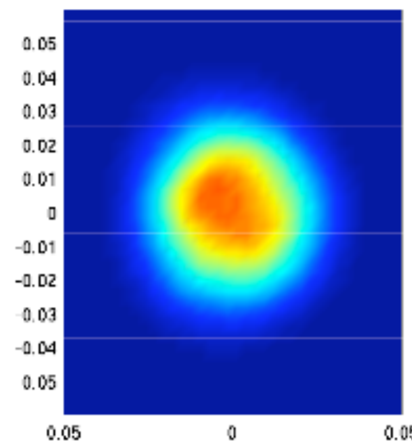
$$\phi = k_{SB} \cdot d\ell_{snp} - c_1 \cdot \eta - c_2 \cdot \alpha^2$$

Dark Port sideband profile by FFT
- ideal vs reality-prime -

upper SB







200k BS curvature

No phase map
Symmetric heating

With phase map
Symmetric heating

With phase map
Differential heating

lower SB