End to End Simulation of LIGO

Hiro Yamamoto LIGO Lab/CIT

- Overview of End to End simulation framework
- Physics in e2e
- Applications
- Issues
- Summary

Simulation group

- H. Yamamoto (1 FTE) : Manager, Salesman, Science programmer
- M. Evans (1 FTE) : Lead Scientist for e2e application
- B. Bhawal (1 FTE), V. Sannibale (1/3 FTE) : Scientist
- B. Sears (1 FTE), M. Araya (1 FTE) : User Interface programmer

LIGO End to End simulation
what is it

- Time domain simulation written in C++
  - » simulating realistically with non linearity automatically included
- Major physics components relevant for LIGO
  - » fields & optics, mechanics, digital and analog electronics, measured noise, etc
- Flexible to design wide varieties of systems
  - » from simple pendulum to full LIGO I to adv.LIGO
- Easy development and maintenance
  - » easy to use graphical front end written in JAVA

LIGO End to End Simulation

the motivation

- Assist detector design, commissioning, and data analysis
- To understand a complex system
  - » ***back of the envelope is not large enough***
  - » complex hardware : pre-stabilized laser, input optics, core optics, seismic isolation system on moving ground, suspension, sensors and actuators
  - » feedback loops : length and alignment controls, feedback to laser
  - » non-linearity : cavity dynamics to actuators
  - » field : non-Gaussian field propagation through non perfect mirrors and lenses
  - » noise : mechanical, thermal, sensor, field-induced, laser, etc : amplitude and frequency : creation, coupling and propagation
  - » wide dynamic range : $10^{-6} \sim 10^{-20}$ m
- As easy as back of the envelope

End to End Simulation
overview

- End to End simulation environment
  - » Simulation programs - program to run
    - – modeler : time series generator
    - – modeler_freq : spectrum analyzer
  - » Description files defining what to simulate - input files
    - – Simple pendulum ~ full LIGO
  - » Graphical Editor to create and edit description files - alfi - editor
- LIGO I simulation packages
  - » Han2k : used for the lock acquisition design ~ 500 parts
  - » SimLIGO : to assist LIGO I commissioning ~ 3000 parts

End to End Simulation
perspective

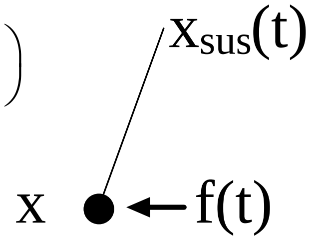
- e2e development started after LIGO 1 design completed (1997 ~)
- LIGO 1 lock acquisition was redesigned successfully using e2e by M.Evans (2000 ~ 2001)
- Major on going efforts (2001 ~)
  - Realistic noise of the locked state interferometer
  - Effect of the thermal lensing on the lock acquisition
  - Alignment control system in realistic condition
  - Other supports for commissioning

e2e physics

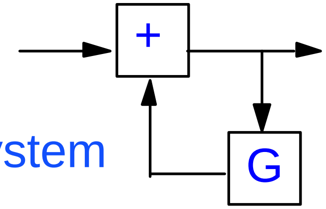
Time domain simulation

- Analog process is simulated by a discretized process with a very small time step ($10^{-7} \sim 10^{-3}$ s)
- Linear system response is handled using digital filter
  - » e2e DF = PF's pziir.m (bilinear trans (s->z) + SOS) + CDS filter.c
  - » Transfer function -> digital filter
  - » Pendulum motion
  - » Analog electronics

$$x = \frac{1}{s^2 + \gamma s + \omega_0^2}\left(\frac{f}{m} + \omega_0^2 x_{sus}\right)$$



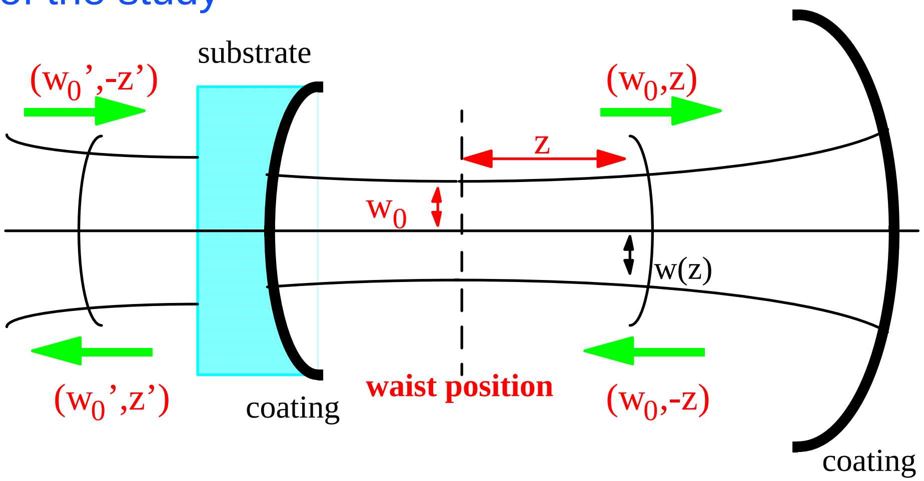
- Easy to include non linear effect
  - » Saturation, e.g.
- A loop should have a delay
  - » Strict chronological ordering
  - » Need to put explicit delay when needed
  - » Simulation time step << time constant of the system



e2e physics

Fields and optics

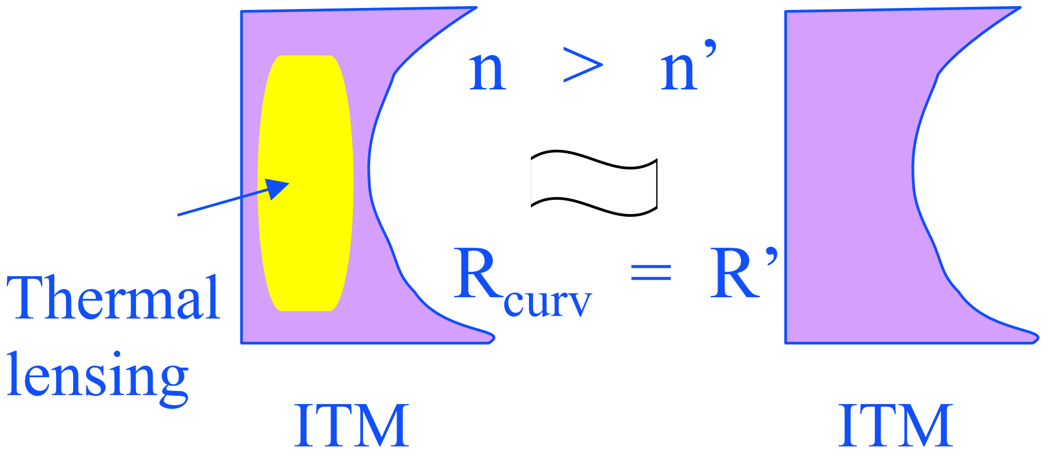
- Time domain modal model
  - » field is expanded using Hermite-Gaussian eigen states
  - » number of modes (n+m) <=4 for most of the study
- Reflection matrix
  - » tilt
  - » vertical shift
  - » curvature mismatch
- Completely modular
  - » Arbitrary planar optics configuration can be constructed by combining mirrors and propagators



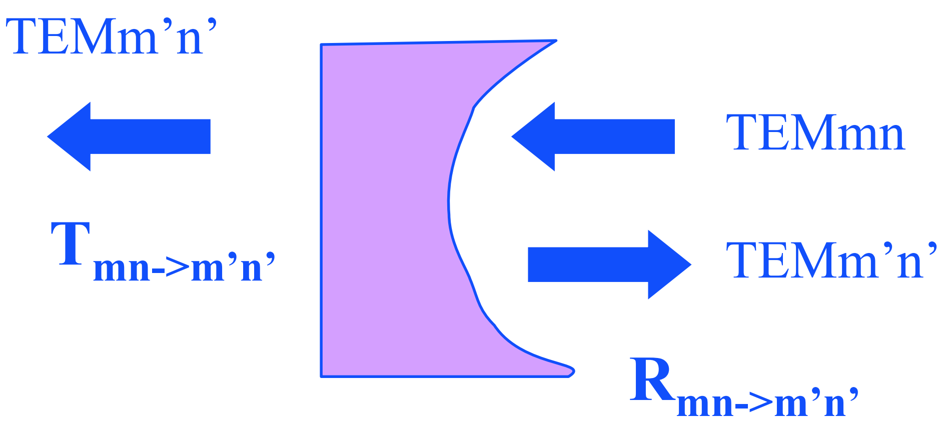
- Photo diodes with arbitrary shapes can be attached anywhere
- Adiabatic calculation for short cavities for faster simulation

e2e physics
optics imperfection

- Simple lens model
  - » LIGO 1
    - – lock, mode mixing



- Mode decomposition matrix - tbd
  - » LIGO 1
    - – actual mirror phase map
    - – more accurate
  - » Adv. LIGO



e2e physics

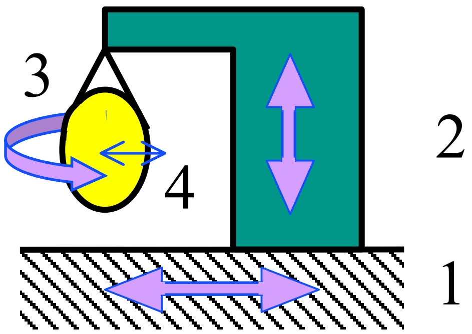
Mechanics simulation

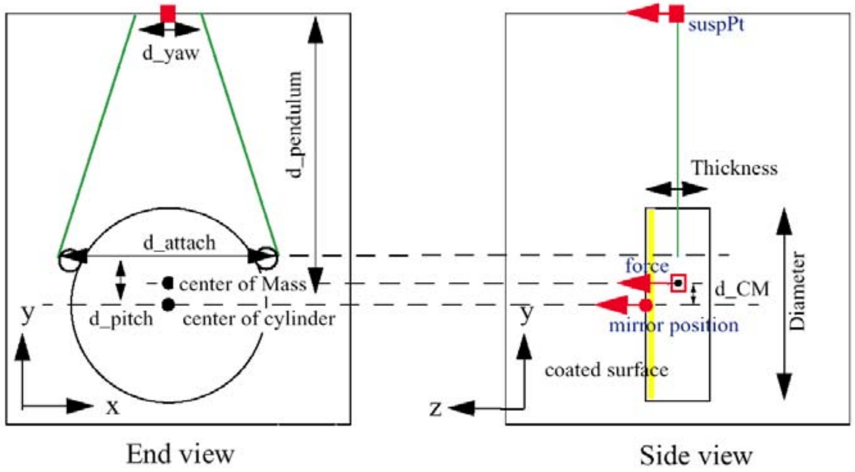
(1) Seismic motion from measurement
- » correlations among stacks
- » fit and use psd or use time series

(2) Parameterized HYTEC stack

(3) Simple single suspended mirror
- » 4/5 sensors and actuators
- » couple between LSC and ASC

(4) Thermal noise added in an ad hoc way



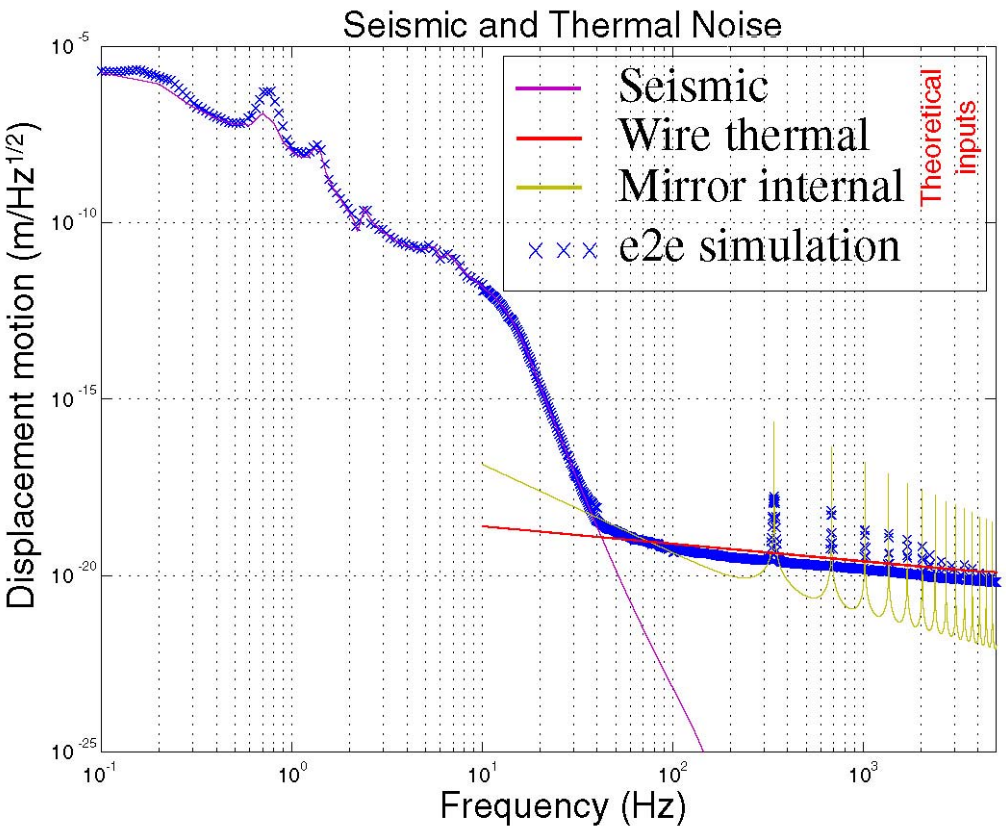


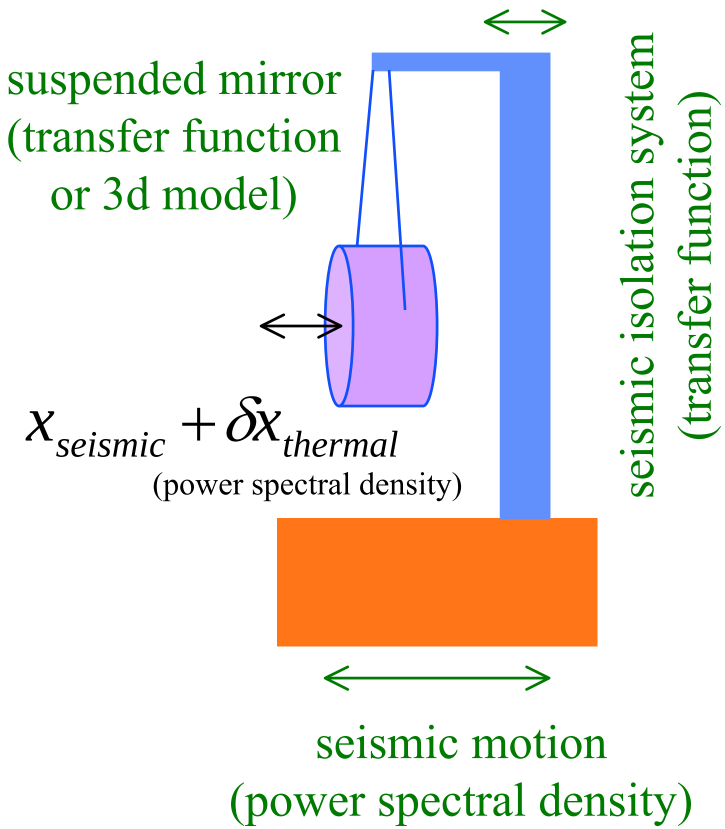
MSE : Mechanical Simulation Engine

- C++ Library to simulate a fully three dimentional mechanical system, developed by G.Cella
  - » modular environments
  - » automatic search for working points
  - » thermal noise and realistic damping simulation
  - » system asymmetries properly propagated
- Stand alone simulation package, with interface to e2e taken into account
  - » frequency and time domain
  - » build and debug a model and integrate to e2e by placing wrapper
  - » integration with other mechanical simulation
    - – For adv. LIGO, there are several sub-system level modeling efforts are already doing on, and MSE can interface to those models.

Mechanical noise of one mirror

seismic & thermal noises





Sensing noise

Shot noise for an arbitrary input

Average number of photons

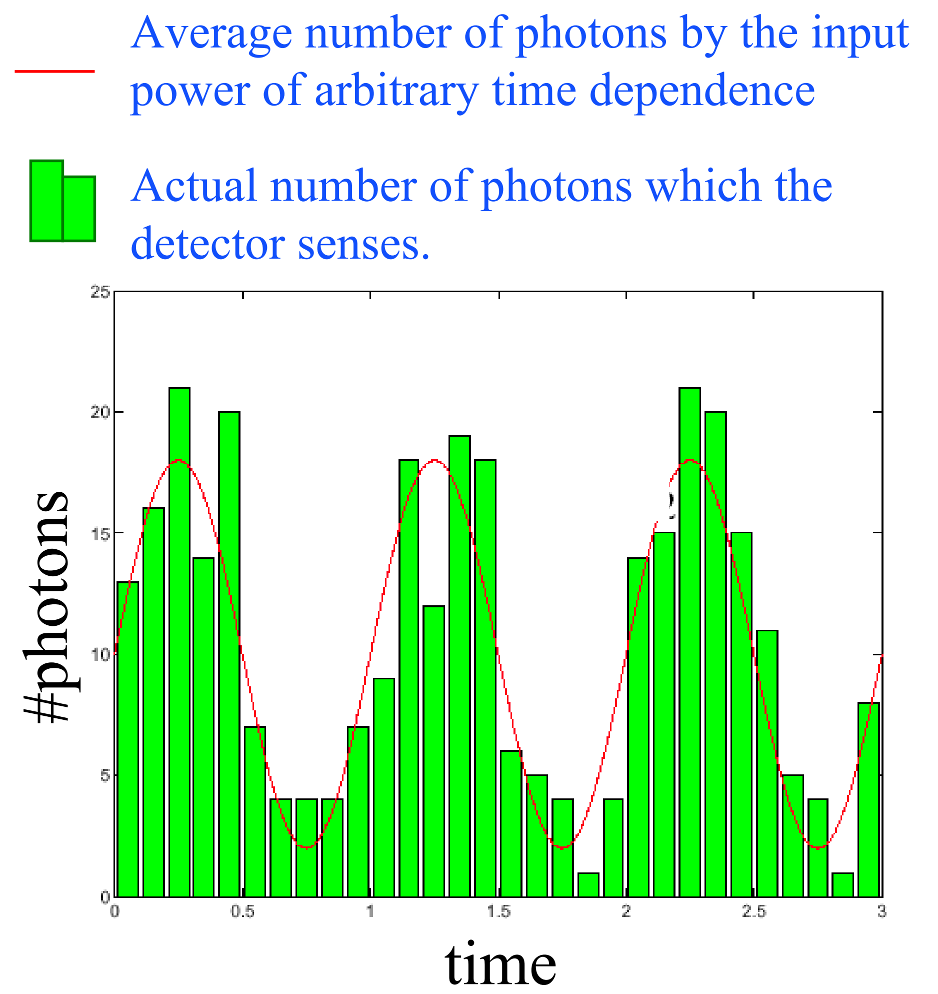
$$n_0(t) = \frac{\eta \cdot P(t) \cdot \Delta t}{h \cdot \nu}$$

Actual integer number of photons

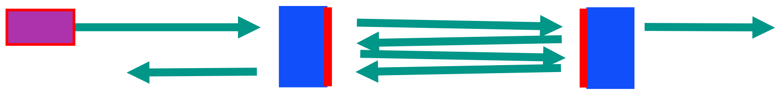
$$n(t) = Poisson(n_0(t))$$

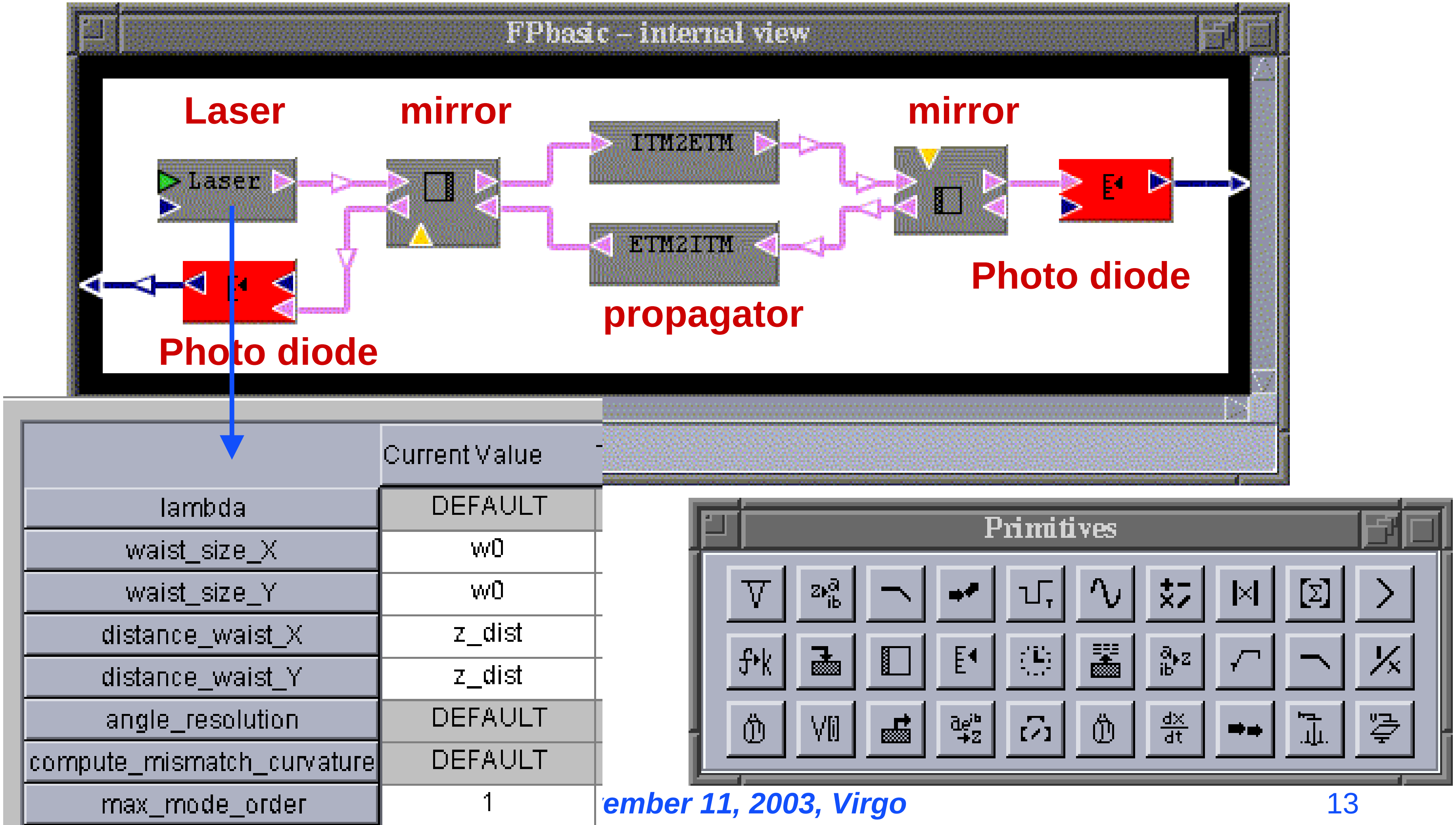
Simulation option

Shot noise can be turned on or off for each photo diode separately.



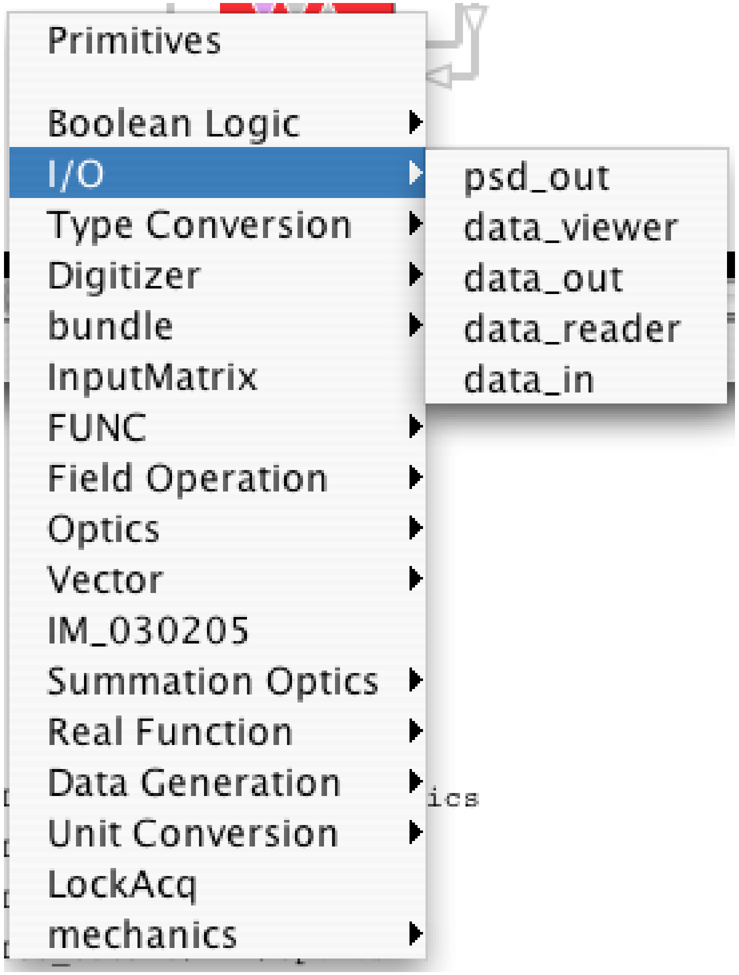
e2e Graphical Editor - alfi





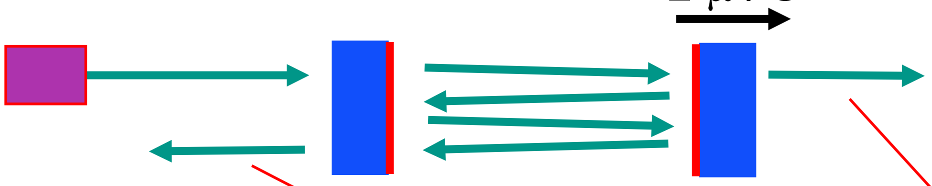
Inputs and outputs

- Description files - box files
  - » what to simulate
  - » use I/O primitives to read and write data
- Macro definitions
  - » all numerical values in box files can be written using symbolic names
  - »
```
% LHO4k.mcr
% optical path lengthsLeng_
RM2BS   = 4.397 [m]       "RM-HR to BS-HR
Leng_BS2ITMx = 4.965 [m]  "BS-HR to ITMx-HR
Leng_BS2ITMy = 4.609 [m]  "BS-HR to ITMy-HR
Leng_ArmX = 3995.055 [m]  "ITMx-HR to ETMx-HR
Leng_ArmY = 3995.055 [m]  "ITMy-HR to ETMy-HR
Leng_PRC = Leng_RM2BS + (Leng_BS2ITMx + Leng_BS2ITMy) / 2
SnpAsy = Leng_BS2ITMx - Leng_BS2ITMy
```
- Outputs
  - » no built in analysis tools
  - » time series
  - » psd
  - » spectrum analyzer

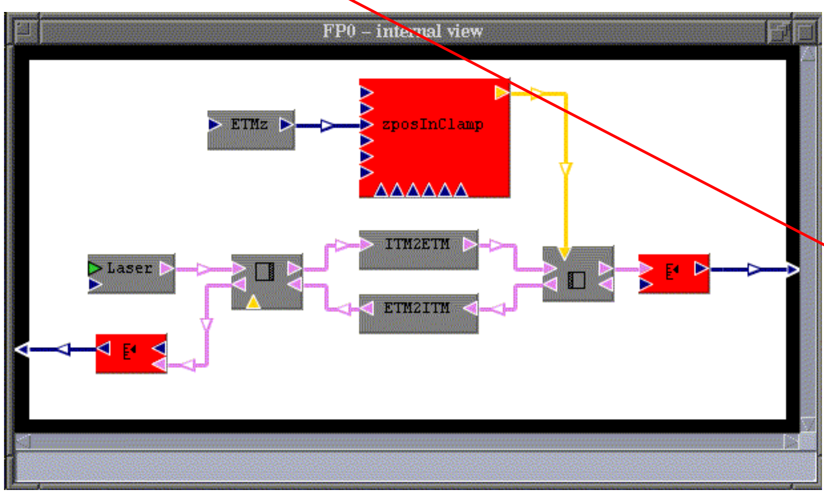


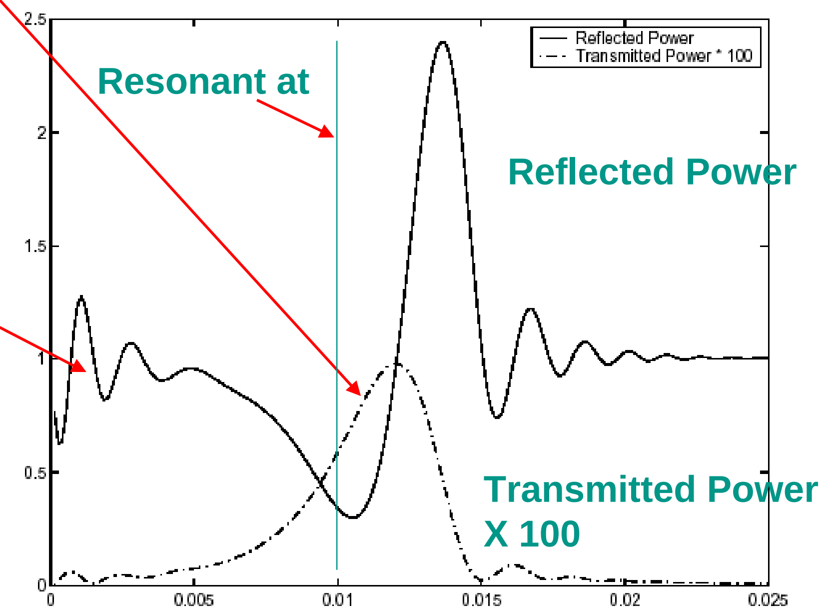
e2e example

Fabry-Perot cavity dynamics



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





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

FUNC primitive module
- command liner in GUI -

- GUI is not always the best tool
- FUNC is an expression parser, based on c-like syntax
- all basic c functions, bessel, hermite
- special functions : time_now(), white_noise, digital_filter(poles, zeros), fp_guoypahse(L,R1,R2), …

mixer module

```
gain = -5; lockTime = 10;
out0 = if ( time_now()<lockTime , in0, in0+gain*in1 );
```

FUNC C++ : compile and link as a shared library

First LIGO simulation Han2k

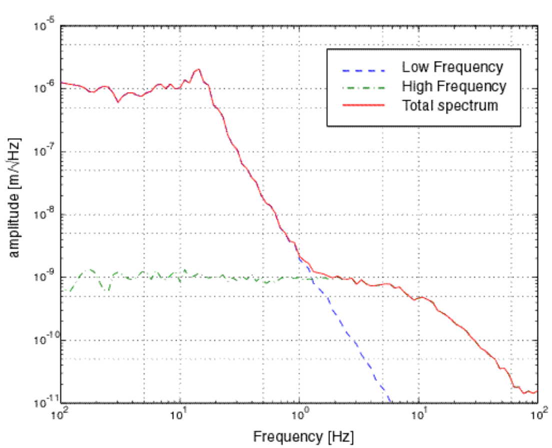
- Matt Evans Thesis
- Purpose
  - » design and develop the LHO 2k IFO locking servo
  - » simulate the major characteristics of length degree of freedom under 20 Hz.
- Simulation includes
  - » Scalar field approximation
  - » 1 DOF, everywhere
  - » saturation of actuators
  - » Simplified seismic motion and correlation
  - » Analog LSC, no ASC
  - » no frequency noise, no shot noise, no sensor/actuator/electronic noise

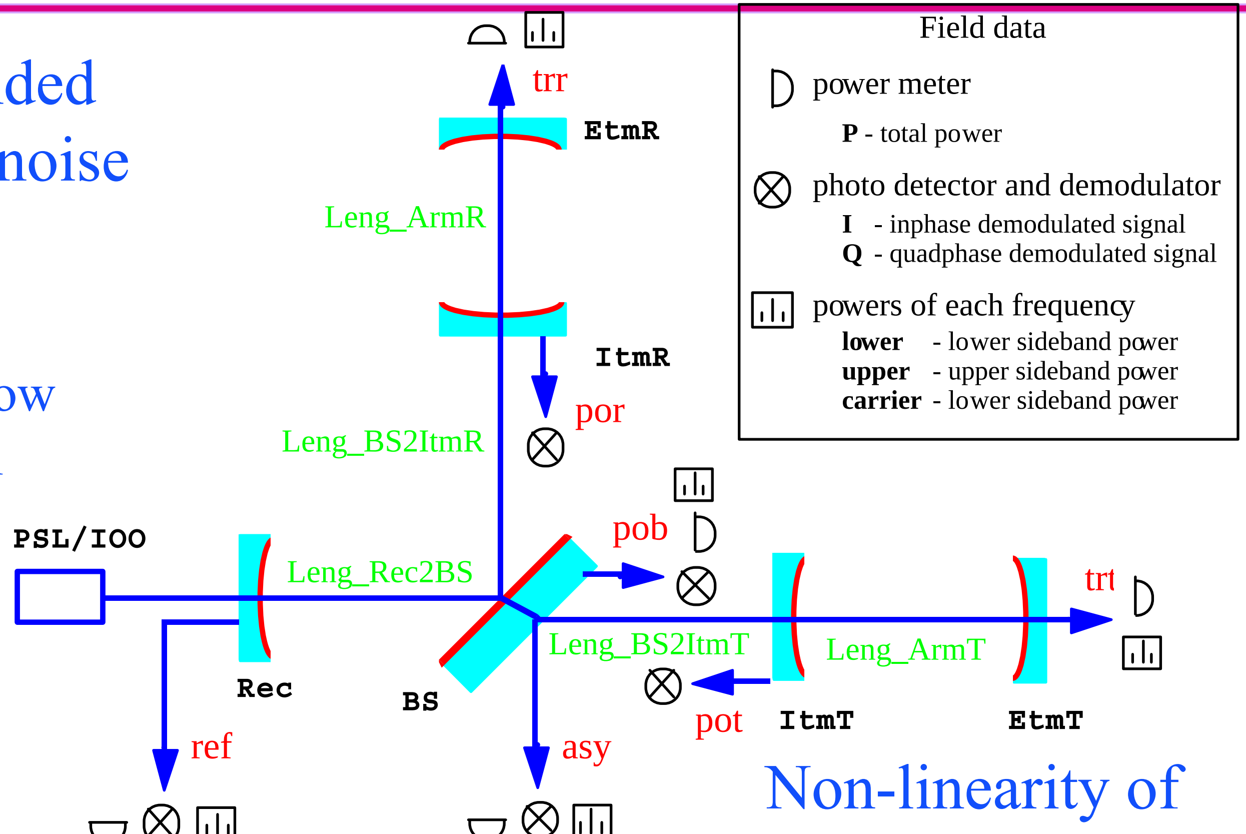
Hanford 2k simulation setup

6 independent suspended mirrors with seismic noise

corner station :

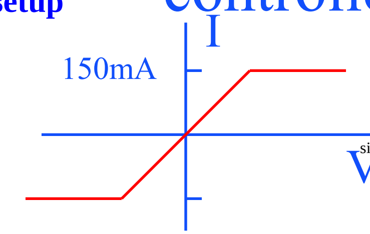
strong correlation in the low frequency seismic motion

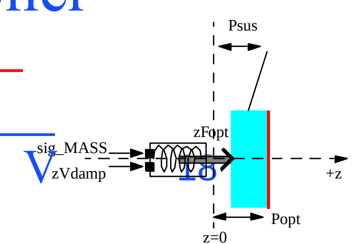




Han2k optics setup

Non-linearity of controller

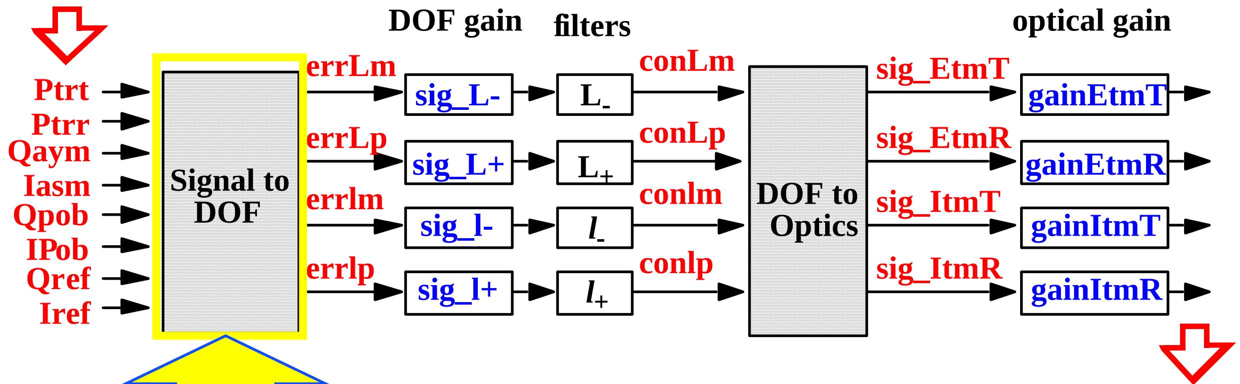




Automated Control Matrix System

LIGO T000105 Matt Evans

Field signal

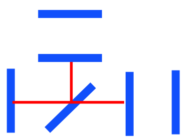


Same c code used in LIGO servo and in simulation

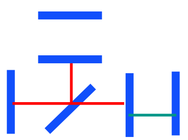
Actuation of mass

Multi step locking

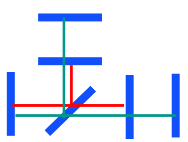
State 1 : Nothing is controlled. This is the starting point for lock acquisition.



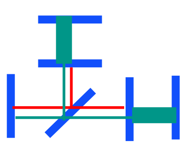
State 2 : The power recycling cavity is held on a carrier anti-resonance. In this state the sidebands resonate in the recycling cavity.



State 3 : One of the ETMs is controlled and the carrier resonates in the controlled arm.



State 4 : The remaining ETM is controlled and the carrier resonates in both arms and the recycling cavity.

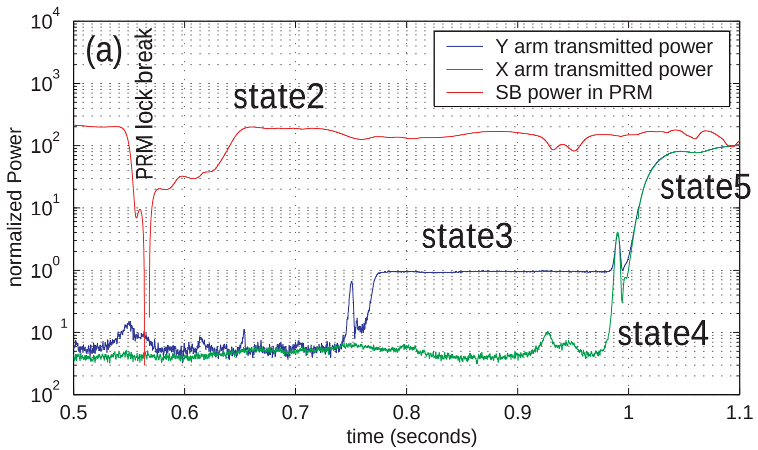


State 5 : The power in the IFO has stabilized at its operating level. This is the ending point for lock acquisition.

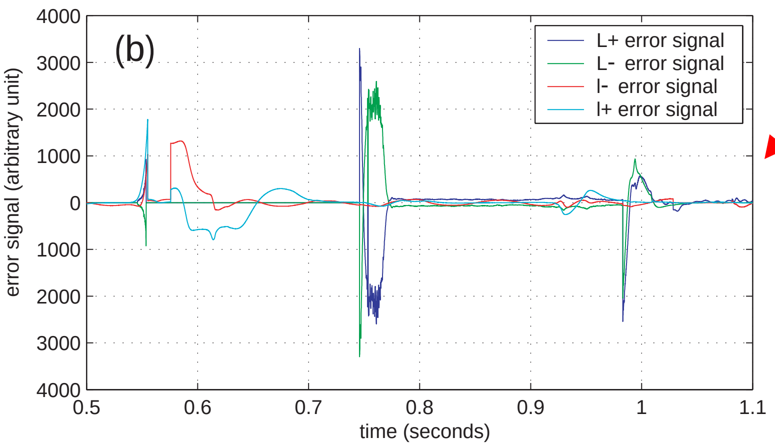
Lock acquisition

real and simulated

Figure 1. LHO 2k IFO data

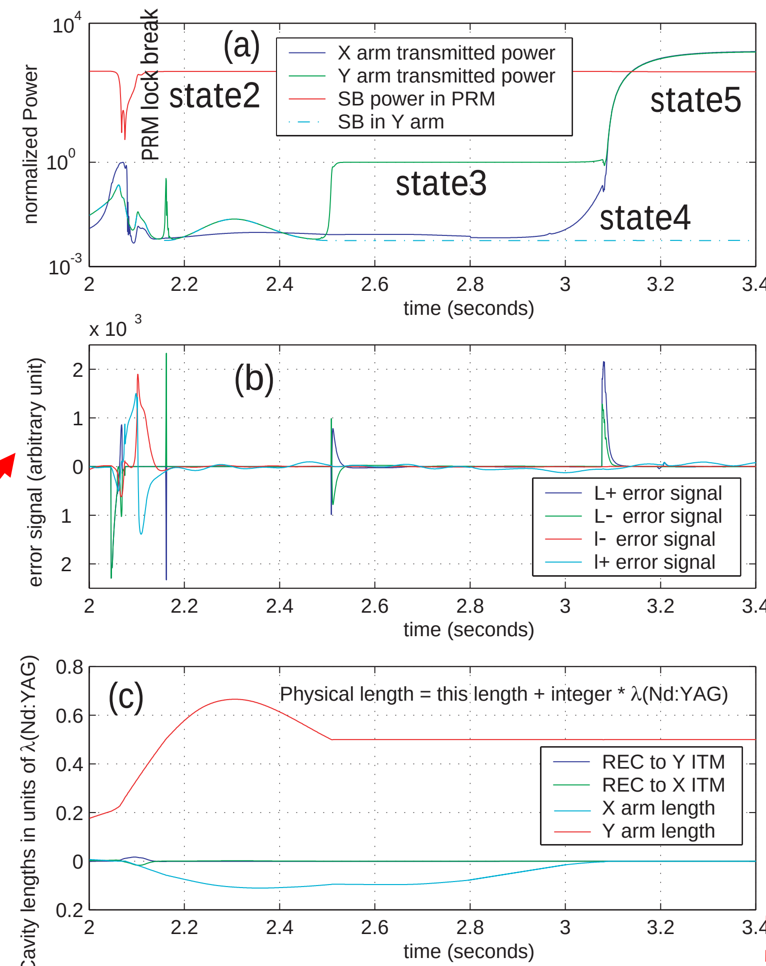


Arm powers are normalized by the power when one arm is locked.
SB power is normalized by the input SB power.



observable

Figure 2. Simulated signal

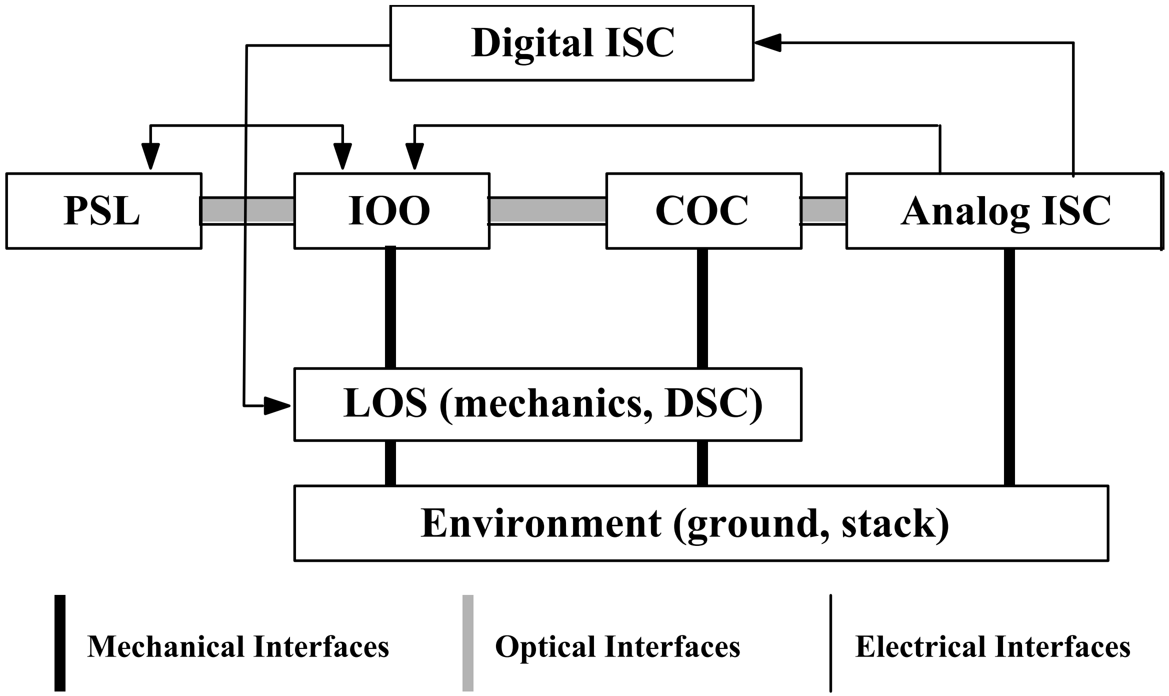


Not experimentally observable

Second generation LIGO simulation SimLIGO

- Assist noise hunting, noise reduction and lock stability study in the commissioning phase
- Performance of as-built LIGO
  - » effect of the difference of two arms, etc
- Noise study
  - » Non-linearity
    - – cavity dynamics, electronic saturations, digitization, etc
  - » Bilinear coupling
- Sophisticated lock acquisition
- Alignment control in not-so idealistic environment
- Upgrade trade study

SimLIGO
System structure



SimLIGO
A Detailed Model of LIGO IFO

- Modal beam representation
  - » alignment, mode matching, thermal lensing
- 3D mechanics
  - » Correlation of seismic motions in corner station
  - » 6x6 stack transfer function
  - » 3D optics with 4/5 local sensor/actuator pairs
- Complete analog and digital electronics chains with noise
  - » Common mode feedback
  - » Wave Front Sensors
  - » “Noise characterization of the LHO 4km IFO LSC/DSC electronics” by PF and RA, 12-19 March 2002 included

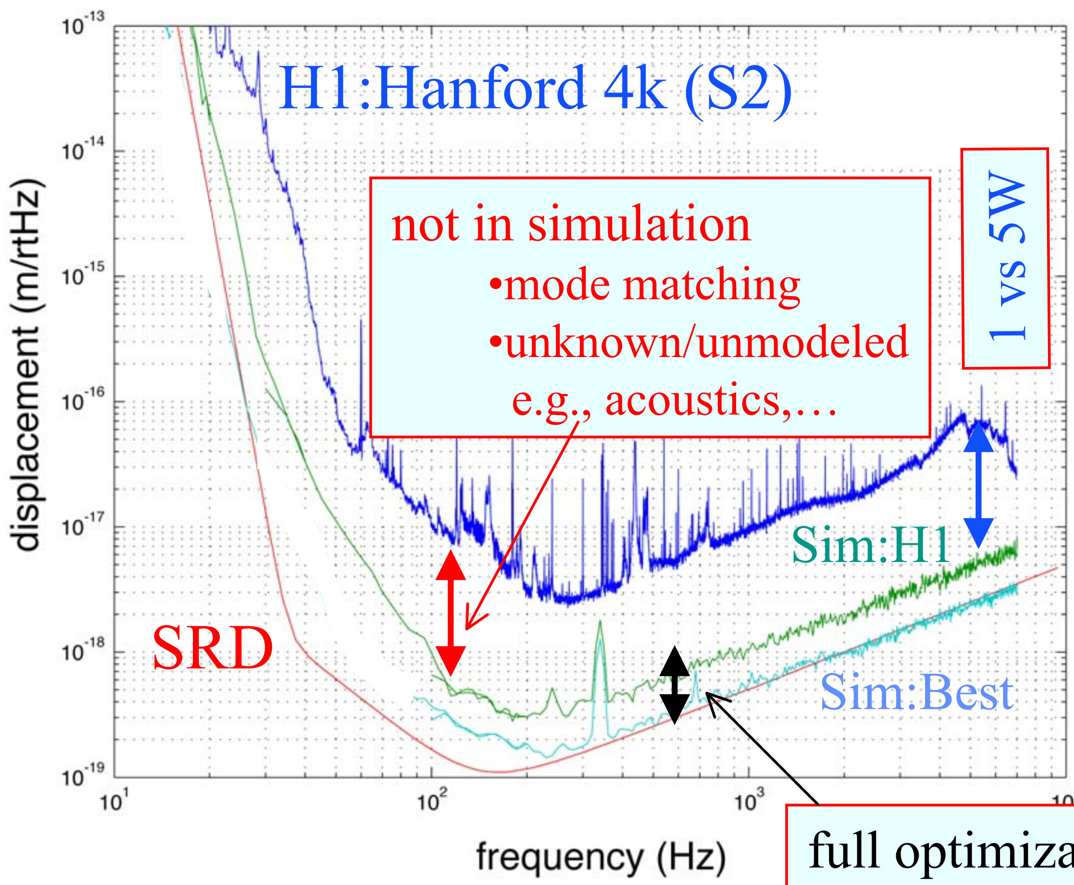
SimLIGO
key applications

- Understanding the sensitivity curve
- Robust lock acquisition - from cold to hot
  - » beam profile (original one used scalar model)
  - » thermal lensing effect
  - » signal reliability - mode matching not necessarily good
  - » 4k Schupp asymmetry problem detected
- Robust alignment control - in a realistic condition
  - » ASC is a problem of linear system, but
    - – noisy and gain varying system
  - » SimLIGO can provide qualitatively similar nice play ground
  - » Robust algorithm with reliable signal

Application : sensitivity

"as built LIGO" will get there, almost

still work in progress
details in T030063



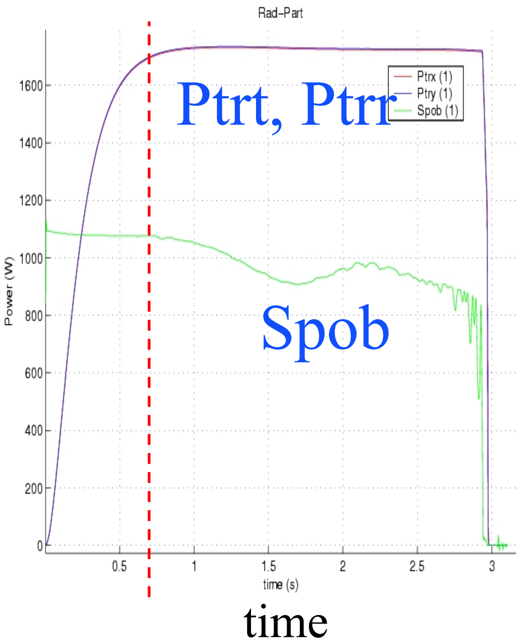
full optimization
•full dark port power etc

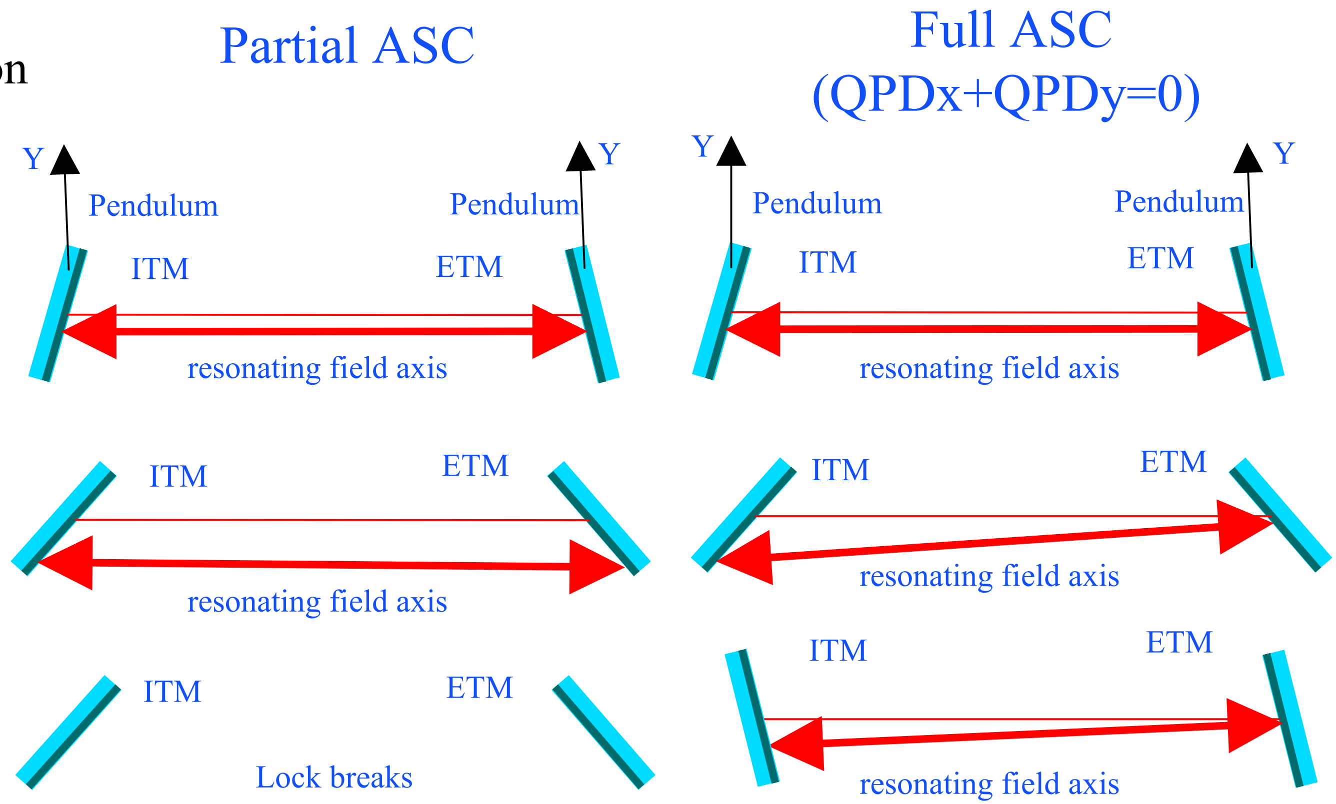
- Time domain simulation
- Interferometer with length and alignment controls
- realistic noise propagation
- signal extraction same as real experiment
- bilinear coupling automatically included

Radiation Pressure on the Pitch dof

ASC design is sensitive to radiation pressure

CR and SB power evolution toward the lock loss

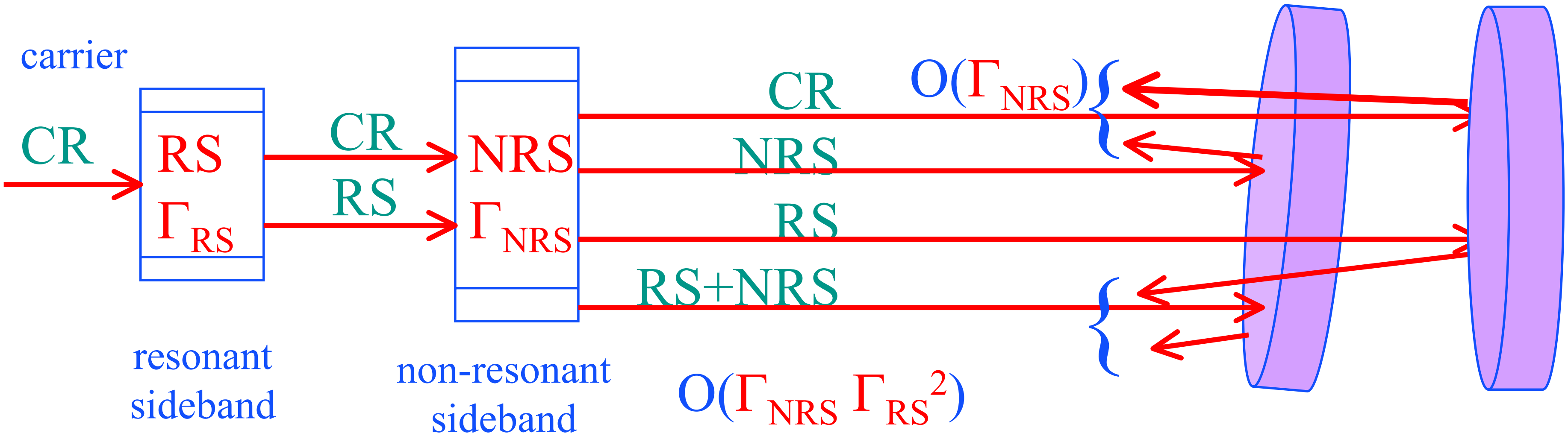




Application : demodulation
simple, but not so simple

P.Fritchel et al
"Alignment of an interferometric gravitational wave detector"
Appl. Opt. 37, 6734

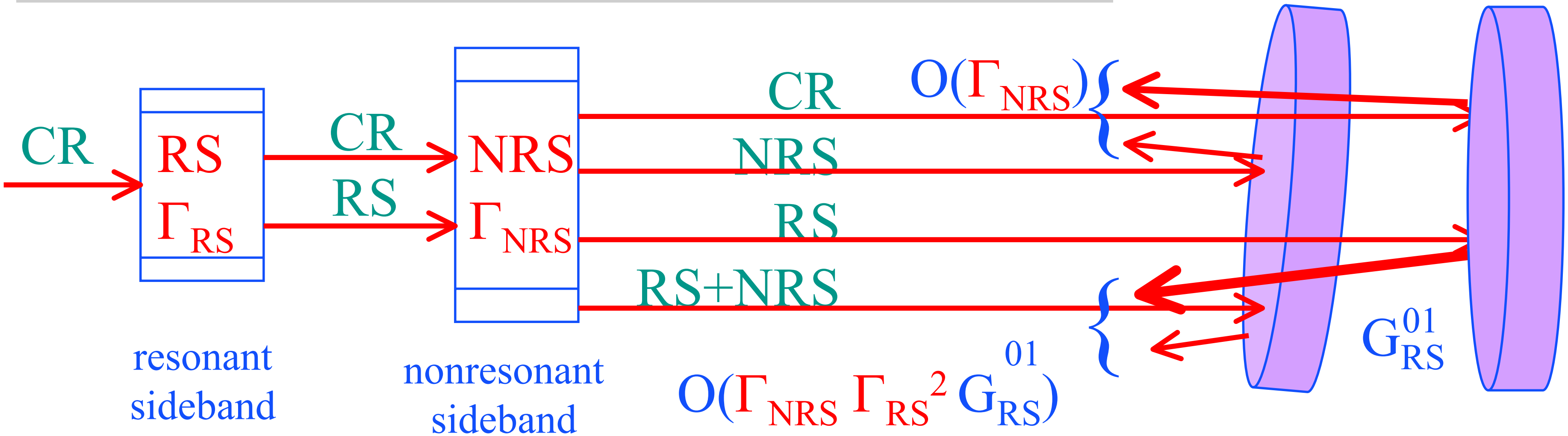
The recycling mirror tilt can be detected solely by reflected field demodulated by NRS frequency. $O(\Gamma_{NRS}) >> O(\Gamma_{NRS}\,\Gamma_{RS}^2)$



Application : demodulation
simple, but not so simple

From: Daniel Sigg <sigg_d@ligo.caltech.edu>
Subject: WFS3/4 mystery
Dear WFSer,
Biplab may have found the reason for the discrepancy between measurements and predication of WFS 3 and 4.
…
Dah! I guess it's obvious once you see it.

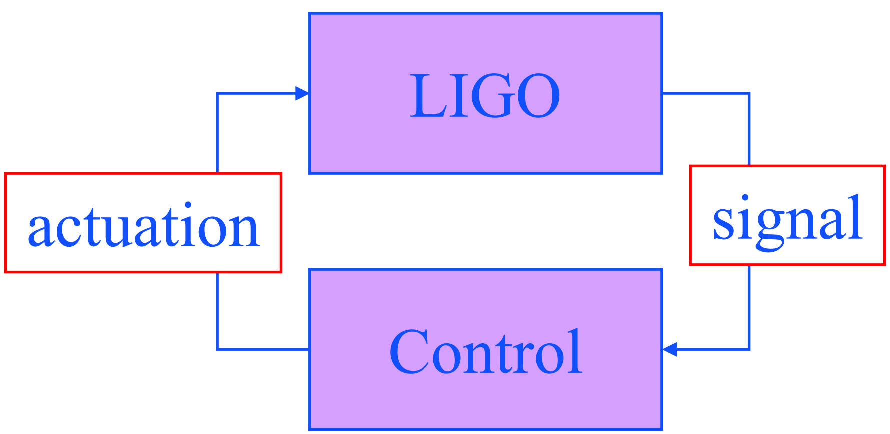
From: e2e
Sub: Re:WFS mystery
I am stupid, but I do all I am told to do honestly.



Application : ASC

linear system is simple - but hard to do it right

Weekly Report (May 22, 2003):
(Matt) … The trouble is that the ASC sensing matrix is not diagonal and not easily diagonalized (due to noise and gain variation). I have developed an algorithm for producing a robust control matrix. The resulting control matrix gives stable control in SimLIGO and will (hopefully) be tested at LHO next week.
Private communication:
Tests on H1 indicate that more work is necessary to account for extreme gain variation in WFS2 seen in H1 but not seen in SimLIGO, probably due to mode-overlap/thermal lens difference.



simple solution using matrix inversion
$a = G_1*s_1 - G_2*s_2 \sim O(s)$

When high gain is needed, G>>1

$$\sigma_a \sim G * \sigma_s$$
$$\delta a(t) \sim G * \delta s(t)$$

sophisticated solution by trial and error using simulation with reasonable noise and gain fluctuation may be needed

Application : lock acquisition revisited
hot LIGO will be cool, woops, not (1)

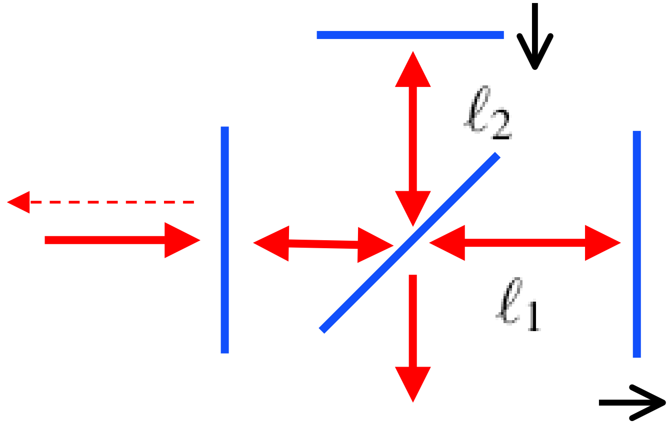
Study when LIGO heating improves mode matching

G030176 (LSC, March)

- PRM nears optimally coupled for SBs
  - »e-mail in April from Daniel Sigg to Commissioning group

Here is another task for the commissioning list: Fix the asymmetry of the two 4K interferometers (by 55mm). (Matt et al. triggered me off.) … Why didn't we notice this earlier?

D.Sigg, T030066 : Schnupp Asymmetry of the 4K Interferometers



$\ell_1 - \ell_2 = 300mm$ value for 2k IFO used also for 4k IFO

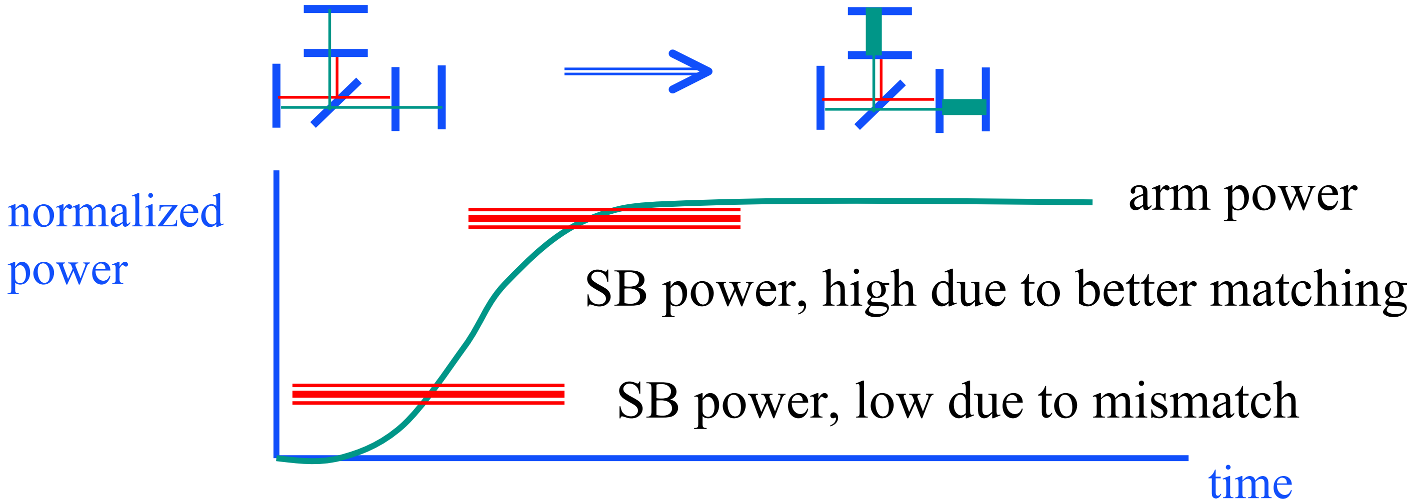
$\ell_1 - \ell_2 = 355mm$ should be for 4k IFO to be fixed

Application : lock acquisition revisited
hot LIGO will be cool, woops, not (2)

Study when LIGO heating improves mode matching

G030176 (LSC, March)

- State 4 singularity happens later and longer



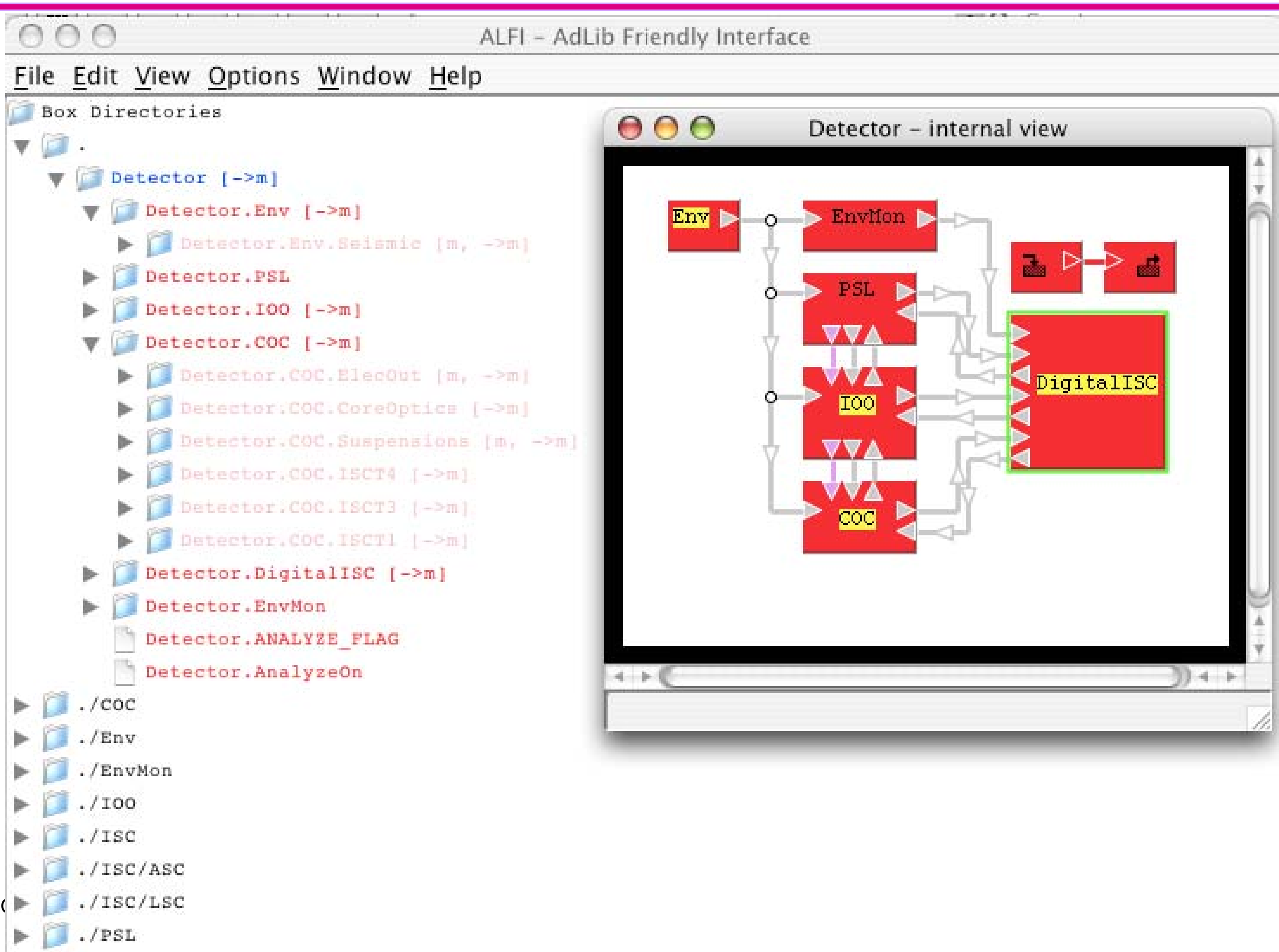
- Use non-resonant SBs on reflection to avoid these issues?
  - »New control schemes using NRS being studied using simulation T030089

LIGO simulation without programming

- Package distributed
  - » SimLIGO box files
  - » auxiliary files
    - – macro files, run instructions, support apps
  - » matlab files for easy analysis of e2e outputs
  - » modeler < run.in to generate time series and psds
  - » **5 lines in unix terminal to generate the sensitivity curve**
- Macro files - text file
  - » lengths and mirror quantities
  - » noise : on-off
  - » control : on-off
  - » shaking mirrors : length and angle - linear, periodic, random
  - » configurations : FP, PRM, full LIGO

Main box of SimLIGO

two views of alfi and ptimitive menu

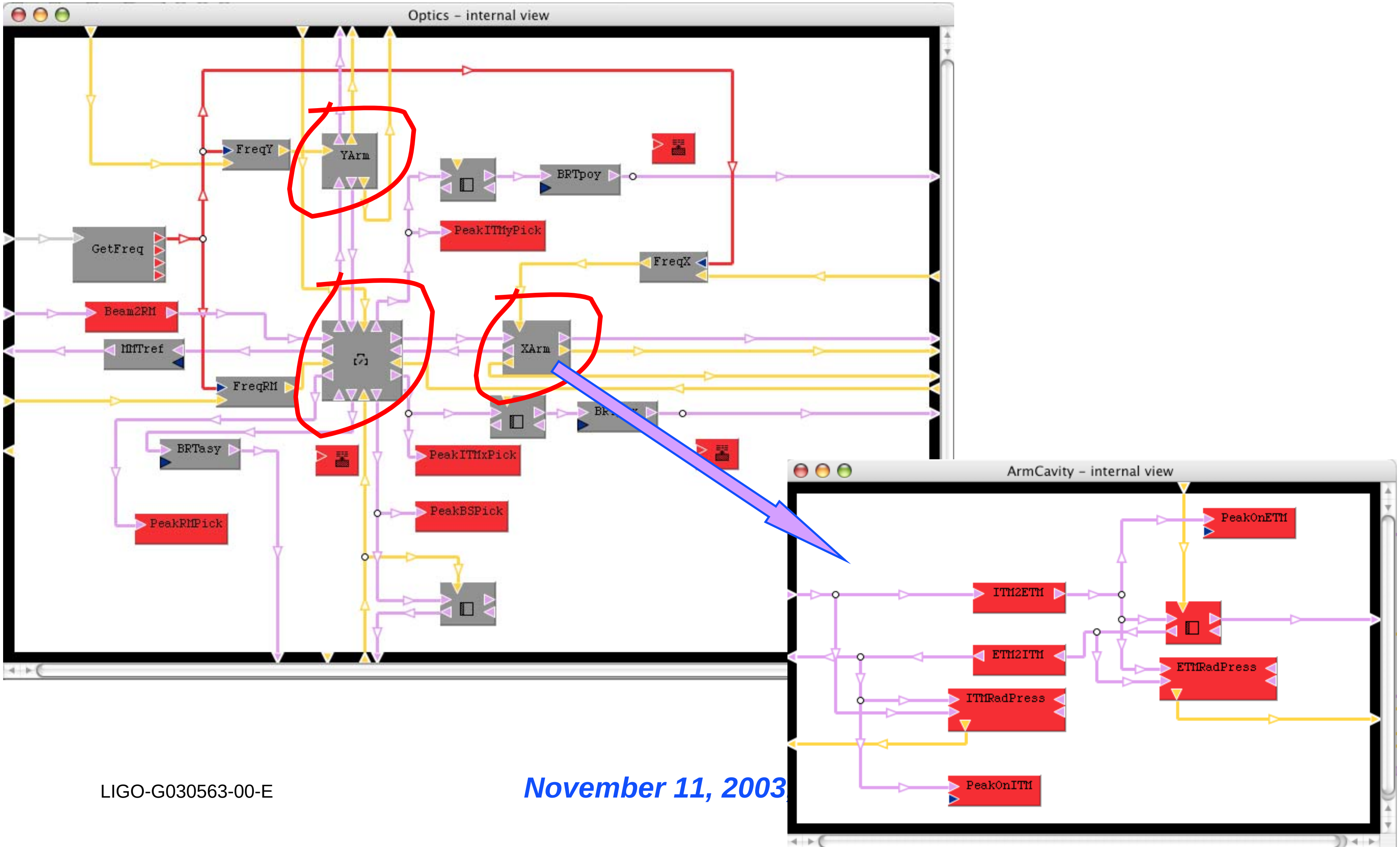


COC box

suspension, core optics and analog stuff

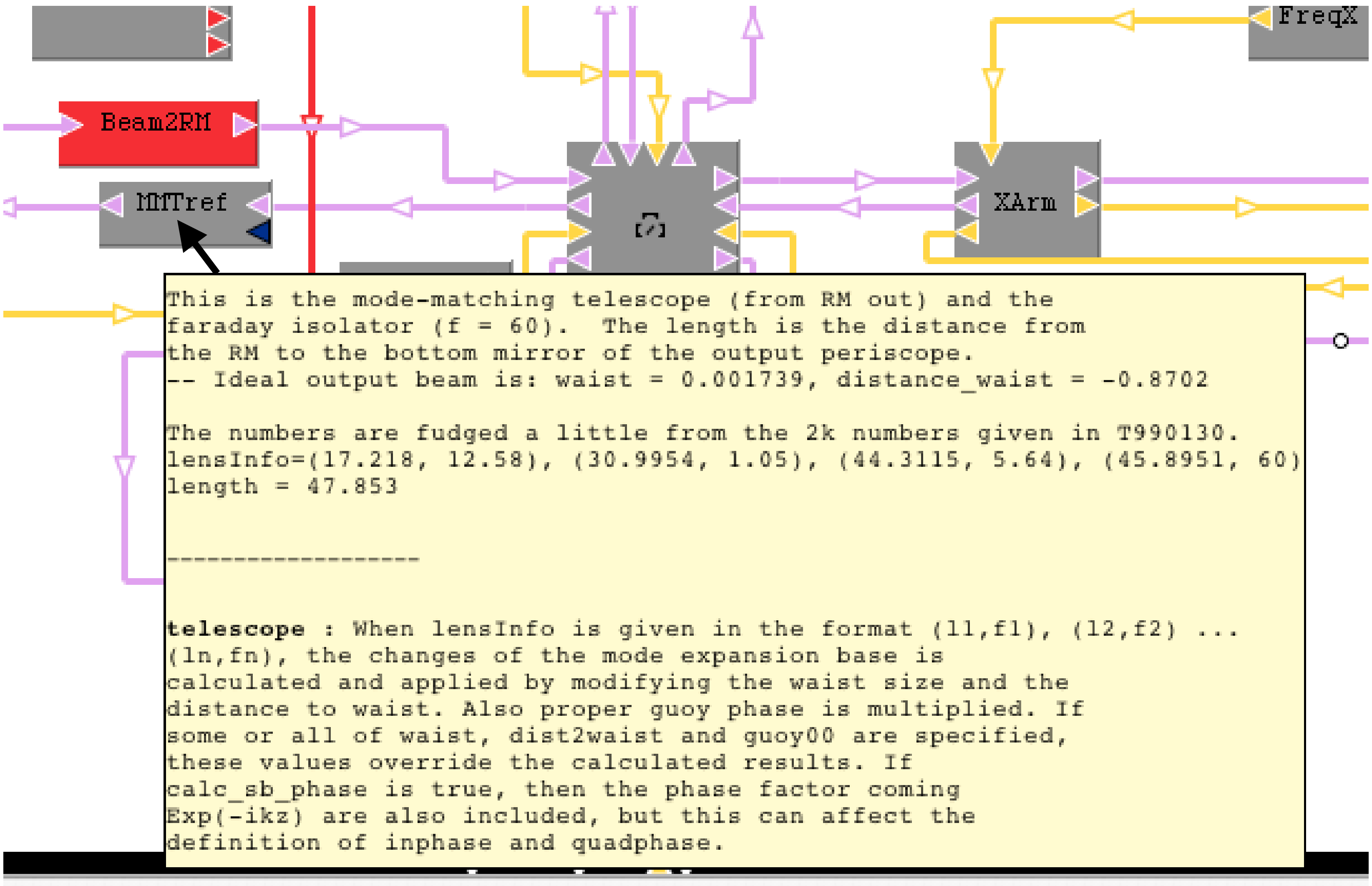
Optics

PRM, arm, radiation pressure, telescope, f-l hack, etc



COC

when you want to know what is MMTref, just…



Profile of SimLIGO

cpu usage point of view

```
Profiler of 3352 action calls per time step << built-in functions
+++++++++++++++++++++++++++++++++++++++++++++++++++++++
Profile of 41 module usage sorted by total times
 index :   frac    :  total   :time/tick :#module : name
       :    (%)    :  (sec)   :(microsec):        :
-----------------------------------------------------------
     0 : 45.24     : 16.99    : 2179     : 1      : rec_sum << m+n<=2, 1 thread
     1 : 10.6      : 3.981    : 510.4    : 278    : FUNC_2x2
     2 : 7.929     : 2.979    : 381.9    : 119    : FUNC_16x16
     3 : 7.679     : 2.885    : 369.8    : 210    : FUNC_1x1
     4 : 4.922     : 1.849    : 237      : 29     : pd_demod
     5 : 4.615     : 1.733    : 222.2    : 122    : FUNC_4x4
     6 : 4.075     : 1.531    : 196.2    : 12     : mirror2

Profile of 583 box usage sorted by total times << use-defined functions
 index :   frac    :  total   :time/tick :#module : name
       :    (%)    :  (sec)   :(microsec):        :
-----------------------------------------------------------
     0 : 100       : 37.57    : 4816     : 1      : Detector
     1 : 94.34     : 35.44    : 4543     : 1      : Detector.COC
     2 : 54.08     : 20.31    : 2604     : 1      : Detector.COC.CoreOptics
     3 : 24.56     : 9.224    : 1183     : 1      : Detector.COC.Suspensions
     4 : 16.54     : 6.215    : 796.8    : 6      : Controller
     5 : 7.916     : 2.974    : 381.2    : 6      : Mech
```

Summary

- Simulation engine and interface are ready
- LIGO simulation is ready
  - » lock, ASC design
  - » useful information for commissioning
- LIGO simulation needs improvements
  - » Michelson cavity is degenerate and badly mode mismatched
    - – better method than a simple modal model
    - – more serious when applying for adv.LIGO
  - » Better frequency noise handling
    - – Michelson cavity model has a flaw which severely limit the simulation of frequency noise feedback
  - » Is double precision enough?
  - » more noise, more reality
    - – scattering noise
    - – acoustic coupling
    - – beam clipping