Next generation Integrated package for Gravitational Wave Simulation

- Simulation is not a magic stick
  - It does only what you tell it to do
- Simulation is a magic stick
  - It does all what you tell it to do, without any compromise

Simulation tools in HEP

- Accelerator simulations : BLAST (beam plasma & accelerator Simulation Toolkit)
  - (quote from Berkeley Lab HP) Accelerators are a vital part of the DOE-supported infrastructure of discovery science. Learn how we get the most out of them by using advanced computer techniques to optimize performance, ensure cost-effectiveness, and explore new ideas. Through simulation and modeling, we can **maximize performance, look for hidden trouble spots**, and even find new ideas. For particle accelerators, these tools have become **indispensable**.
- Detector simulations : GEANT4 (GEometry ANd Tracking)
  - (quote from Wiki) Geant4 includes facilities for handling geometry, tracking, detector response, run management, visualization and user interface. For many physics simulations, this means **less time needs to be spent on the low level details, and researchers can start immediately on the more important aspects** of the simulation.
- GW detector simulation is to be a combination of these two.

Next generation Integrated package for Gravitational Wave Simulation

- Introduction
  - Propaganda to make GW simulation package to the same level as HEP
  - Rana > “I am a believer”. I guess that the number of optics simulation codes outnumber the controls codes by 100x. And there is basically nothing existing for mechanics. If we already had Finesse linked with our real control system, we could really understand many things. But not enough good people doing simulation.
- It should be simple to study simple physics … not quite
  - Field calculation as an example
- Integrated package
  - Obsolete e2e as a springboard for discussion to prepare for the future
- Design toward future
  - Need to identify what kind of framework is useful to prepare for the future
  - Inputs from the end users based on commissioning and planning for the future
  - What kind of time scale makes this package useful
  - How to push this be realized

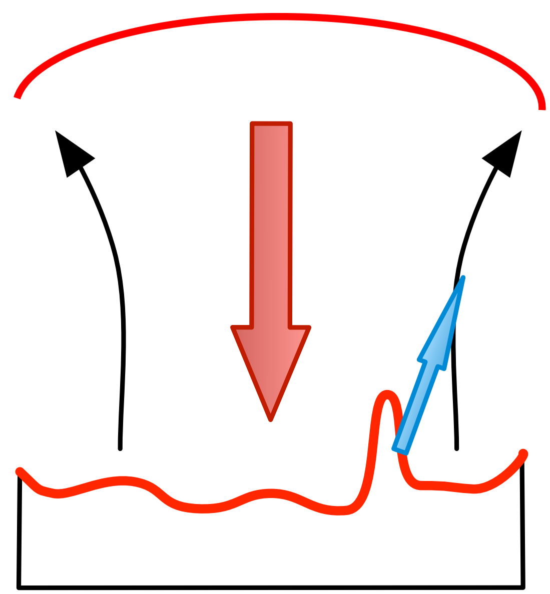
Scratch hairs before, not after, spending lots of money

- Future GW simulation package to be
  - Have necessary simulation components of equal qualities
  - Easy integrations of components
  - Getting started easily to study physics of interest
  - Get the setup and modification easily
  - Get complex system analysis done with reasonably rich information
    - Get details of specific problems on demand
  - Get long time scale analysis done in short time
  - Get results with flexible formats
  - …

Simple question, simple answer,

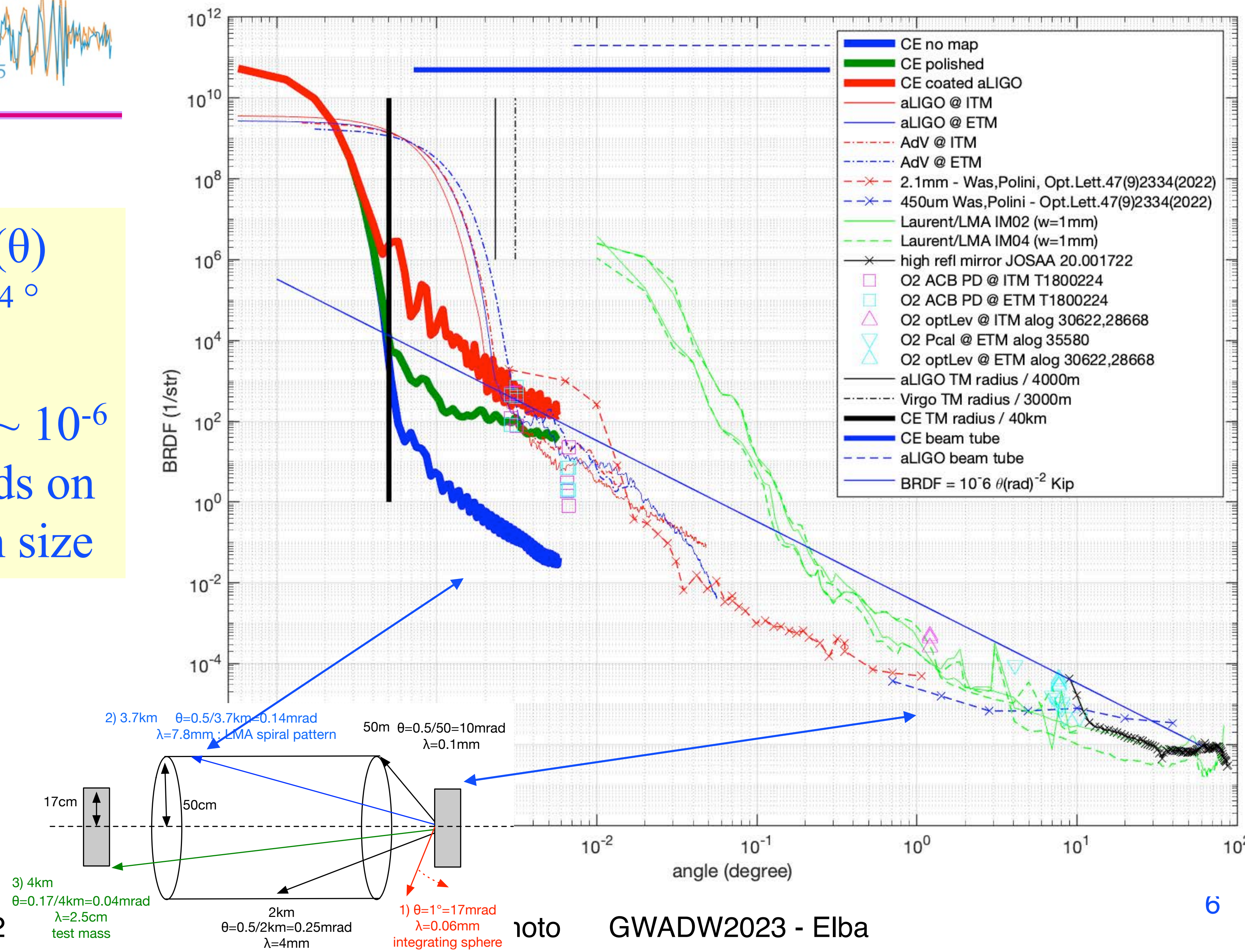
Simulation should take care of difficult calculations behind the scene

- Scattering by mirror surface aberration
- What is FP cavity loss
- Researchers are interested in physics, not how to calculate
  - » Mirror aberrations
    - Continuous aberration
    - Point absorber ~ 1cm
    - Point scatterer ~ 1µm
  - » Many different calculations
  - » Millions of different mirror surface
  - » Cavity conditions
  - » Complex BRDF



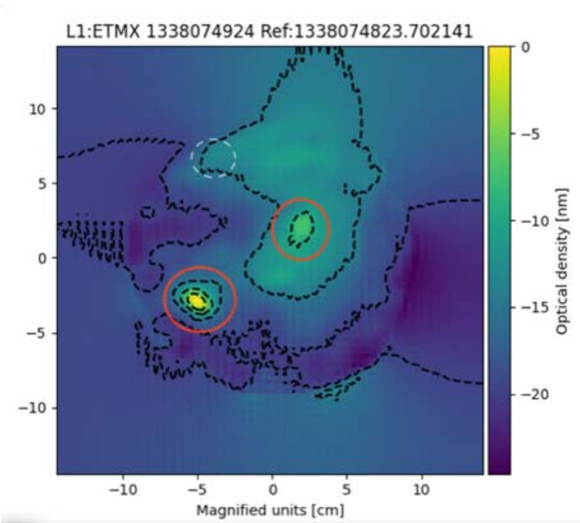
Scattering to wide range of angle

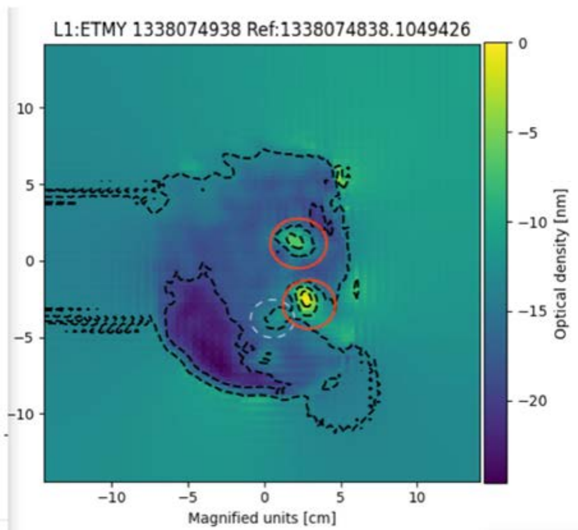
BRDF(θ)
θ > 10^{-4} °
value
$10^{10} \sim 10^{-6}$
Depends on
beam size

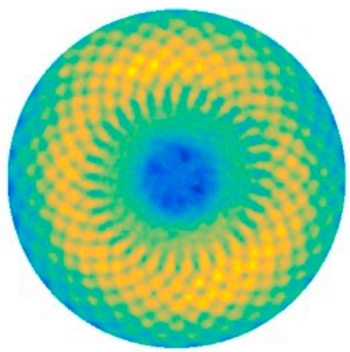


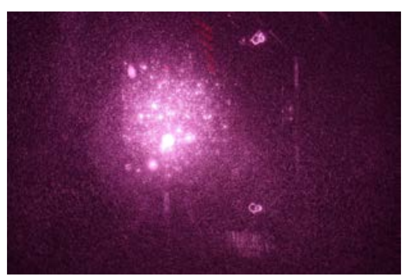
Different faces of mirror surface

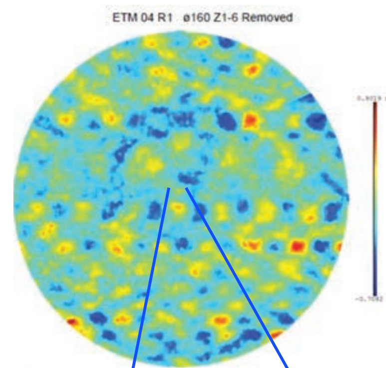
~ impossible to simulate all, need to know what can be calculated and how to integrate data



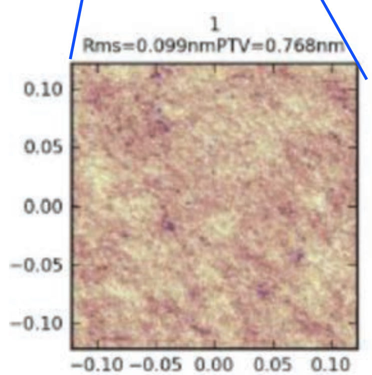




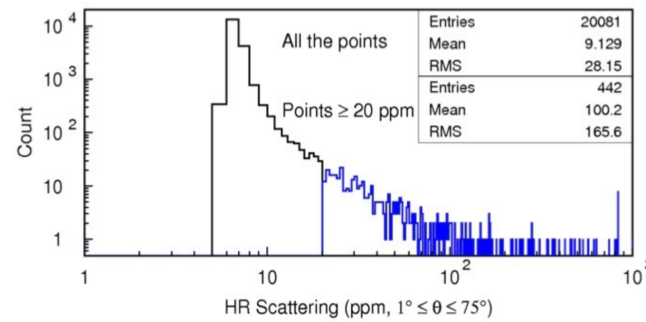




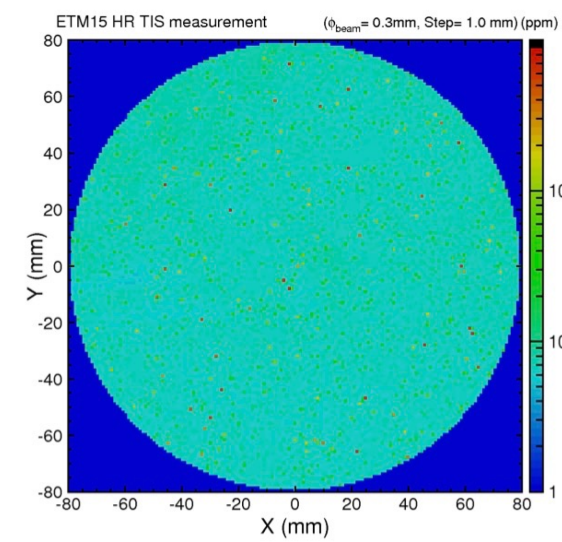
(1) Surface after polishing by ASML
Aperture size 160mm
RMS = 0.1732nm, PV=1.611nm



(3) Surface after polishing measured by PMM(phase measuring microscope) with magnification of 50.
0.25mm x 0.25mm square near center.
RMS = 0.099nm, PV=0.768nm

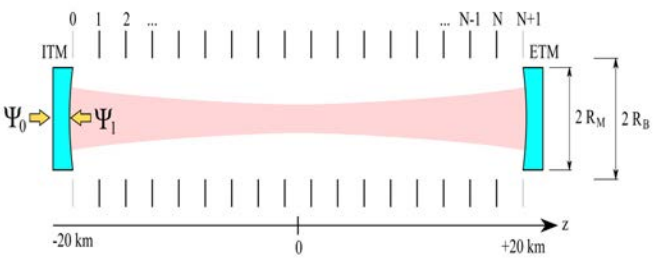


(2) Surface after multilayer coating by ion spatt
Aperture160mm
RMS = 0.563nm, PV=4.436nm



Complemental tools and calculations

- Beam tube baffles

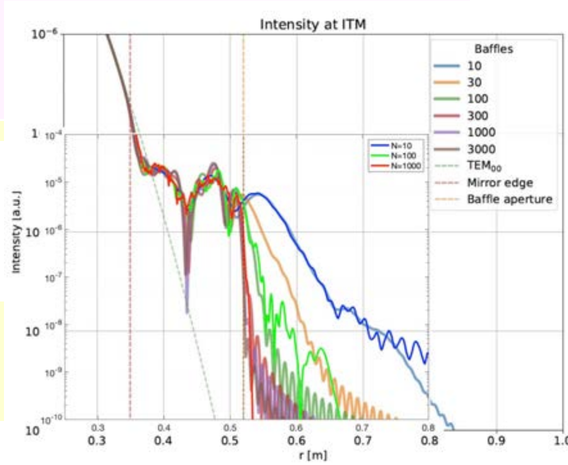


CE-T2100011 – Gabriele
Modal model using Laguerre
Axisymmetric system
Many modes needed

$$(1 - P_{RTL})\Psi_1 = t_{ITM} C_0 \Psi_I$$

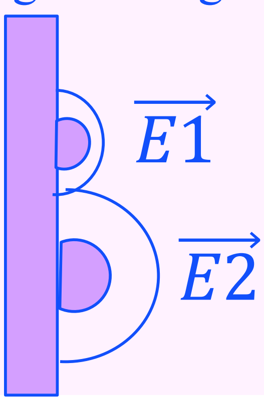
CE-T2300004 – Hiro
FFT
Arbitrary field shape
~~Notoriously slow~~
Serrations vs mirror aberration

```
Eout = fftshift(
ifft2(ifftshift(
Pmap).*fft2(
ifftshift(Ein))))
```

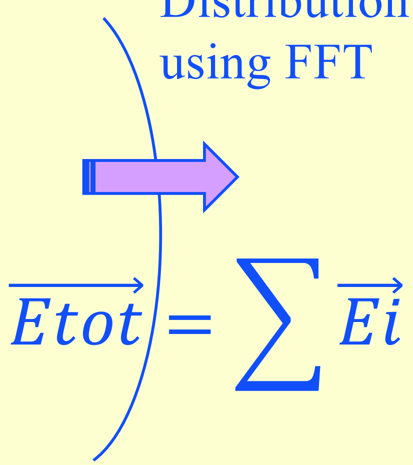


- Power distribution by point scatterers – O(nm)

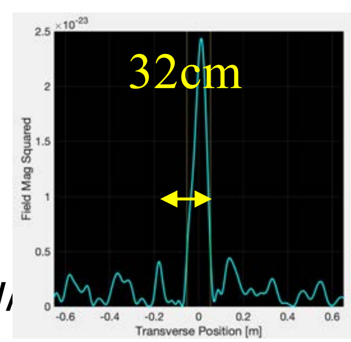
Analytic
Huygens integral

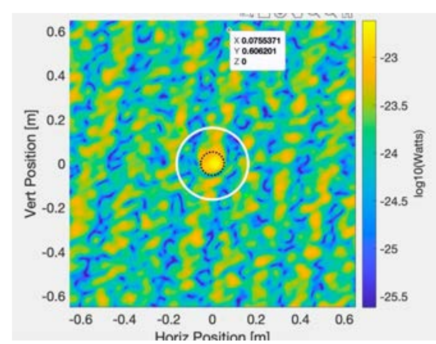


Distribution
using FFT



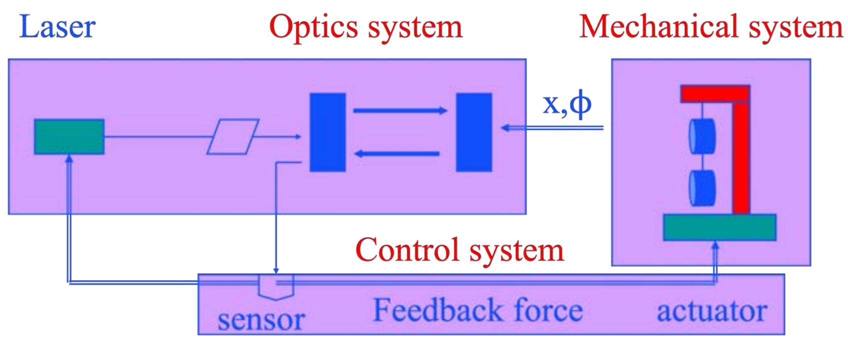
9k random sources, average radius of 30nm, height 0.3nm





Well defined problem, Necessary components and integration

- 25 years ago, iLIGO needed lock acquisition strategies
- Fundamental elements to be integrated
  - » Seismic motion and suspension systems
  - » Optical systems
  - » Control systems



- End to End model – e2e – was developed
  - » Object oriented concept of C++ was fully utilized to add elements easily and connect them easily, designed and developed by Matt Evans
  - » Simple version of these elements are embedded in this C++ framework
    - – Transfer functions and state space models for SUS/SEI
    - – low order HG model for the field calculation
    - – C++ codes are compiled and linked dynamically for control system design
    - – Mechanical Simulation Library (MSE) was developed by G.Cella (T030158)
  - » GUI was prepared to ease the development and simulation configuration maintenance
  - » Quick turn around of length sensing and control design and lock test

Issues

- Interferometers use different locking strategies and faces different challenges
  - » Noise, noise, noise …, e2e helps nothing for this
  - » Original e2e design concept is outdated
  - » Details of optics and control systems need to be studied more flexibly
  - » Stray light simulation as a first class citizen
  - » Needs new framework design, based on new necessity
- e2e is a realistic time domain simulation package
  - » It starts from an empty cavity, and one needs to lock the system to study quasi-stationary state, tedious
  - » Repetition of complex evolutions with time step of 10μs each, million times repetitions for 10 seconds of process, so slow
- All fundamental tools in e2e are too simple and outdated
  - » Field – simple HG based model without maps
  - » Mechanical systems – simple parametrization using transfer functions and state space models
  - » Control systems are based on hand-made filters

Real challenge

- Albert > You can lead a horse to water, but you cannot make it drink.
- Alan > I think that constructing such a thing is a huge effort, and people will challenge the need. It would be good if you could demonstrate an important effect that needs to be understood for future detectors, that would require such a fully integrated simulation package, and would fail if we try the "piecemeal" approach of using a more targeted simulation tool like e2e or Finesse.

What to solve

- Integration of subsystems
  - » Complete enough to address Noise, noise, noise … problems
  - » Stray light analysis
  - » Full simulation of the ASC system that includes realistic optics and mechanical systems
  - » Quantitative effects of the up-conversion effects due to non linear response
- Time domain
  - » Study effects with long time constant, like thermal effect, in a short time
  - » Optimize IFO operation condition using early warning signal
  - » Simulated plant – imitate responses of interferometer components (G2200168, G1301255)
- Flexible simulation framework – last, but not the least
  - » Often, interesting possibilities can be studied based on physics we understand now, but often we need to develop or customize codes to get it done. What if we can study just by connecting existing building blocks.

Flexible simulation Framework

- What kind of flexibility is needed
- What kind of questions/answers do users want
  - » aLIGO, AdVirgo, KAGRA commissioning experience
  - » CE, ET, Voyager design challenge
- What kind of physics needs to be prepared
- What kind of tools are best suited
  - » How to integrate different kinds of physics elements
  - » How to integrate different kinds of simulation tools with different time scale
    - – Time domain 10μs ~ 1s, Frequency domain, FFT, other tools
  - » Common front-end and/or GUI
  - » What environment
    - – Easy development and debugging

Time-line

- After O4 starts
  - » Call for meetings to collect requests from the users
  - » Call for meetings to discuss the design of the simulation framework
  - » Repeat meetings with actual code / frame development
- Due dates
  - » Make the package useful for the CE and ET design ~ 3 - 5 years
- Stepwise evolution
  - » Each simulation tool evolves as is now, with the unified goal in mind
- How to organize this effort
  - » HEP GEANT4 is organized by international GEANT4 collaboration
  - » Organize a central working group

Extra slides

mumble

Two years ago, late-Stavros suggested to make the GW simulation to the level of HEP. With my HEP background before LIGO, I could understand what he meant. I started and could not push too much. May be, I had not good enough idea of the goal and approach.

When I gave a talk about simulation at IFAE, Mario Martinez asked the question “In high energy physics, anything could be simulated by proper combination of existing simulation tools, can it be done in gravitation wave experiment?”

I said “No, we don’t have enough experience to get enough tools ready yet”.

When I visited Virgo last year, Stavros said again to push the GW simulation to be more mature as HEP. I said “we don’t have enough things in hand now”. He said “it is important to start, even with empty hand.”

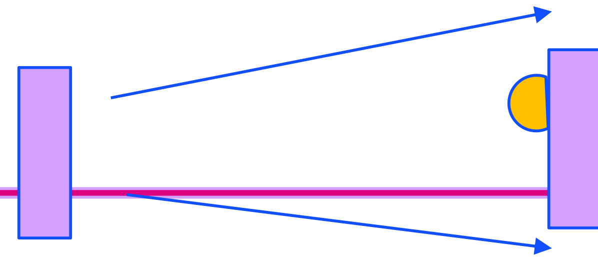
I think my answer is correct as of now, but. we may need to start to think about how to make the maturity of the GW simulation toolbox to the level of HEP.

Roughly speak, GW = optics + mechanics + controls. What is important is not to simulate everything to the limit, but is to understand what are necessary ingredients and how to integrate. Tools will be numerical simulations, analytic calculations and hybrid of these two. There are experts of each part, but few people grasp the entire vision. Also, we may not understand the quality of the inputs, like optic data, so that we can use the simulation to the limit.

I hope we can start sharing ideas what do we miss now, what will be necessary and useful tools for the future. When one says "I want to do this" and if simulation package is not capable, one will say "simulation cannot do this". But if we start sharing wish lists now and start thinking what are the good ways to realize, when one says "I want to do this", there may be simulation package ready to say "go for it".

We all need to collaborate, we means “developers and users / commissioning experts”.

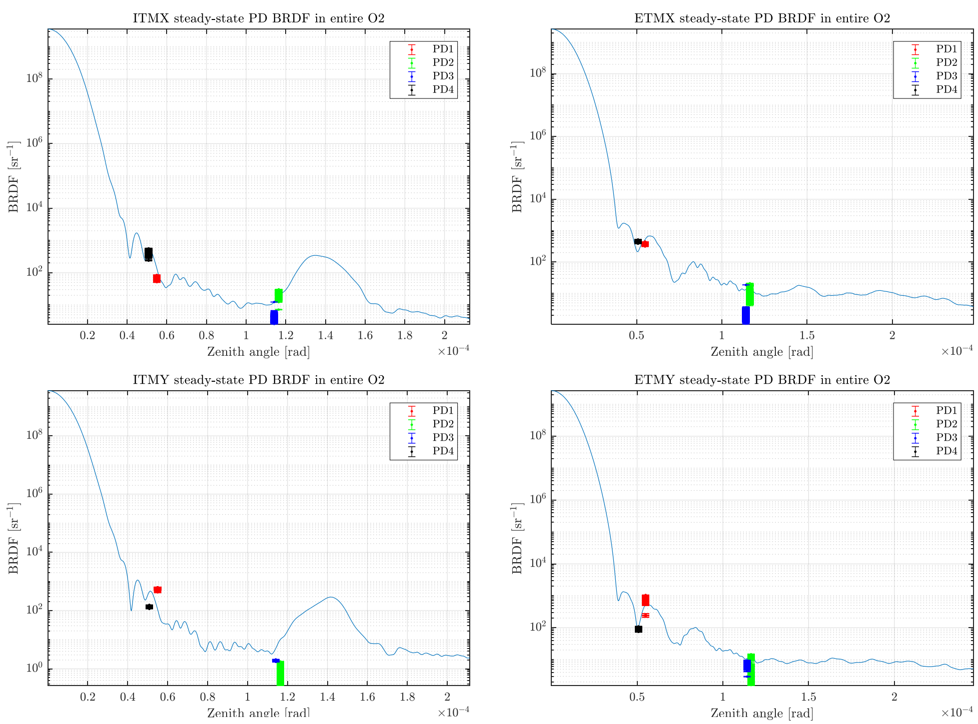
aLIGO examples

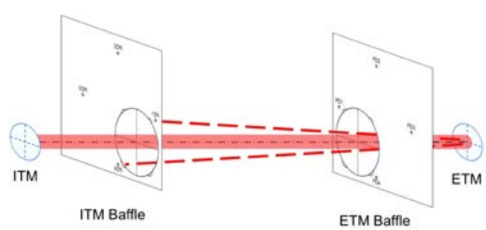


Thermal bump
Seed size ~ 10μ
Absorption ~ 10%
Bump size ~ 1cm

Beam is not gaussian

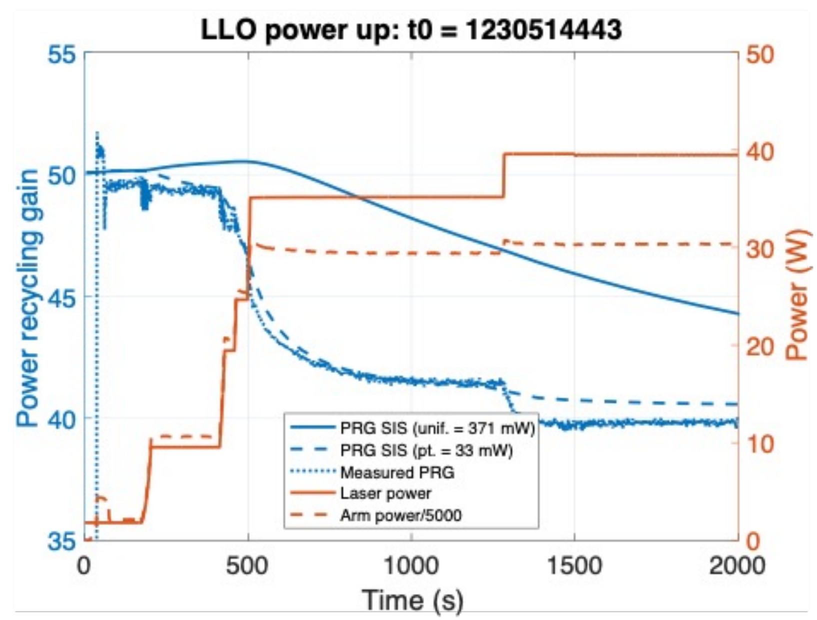
LLO : Power around test mass





(b)

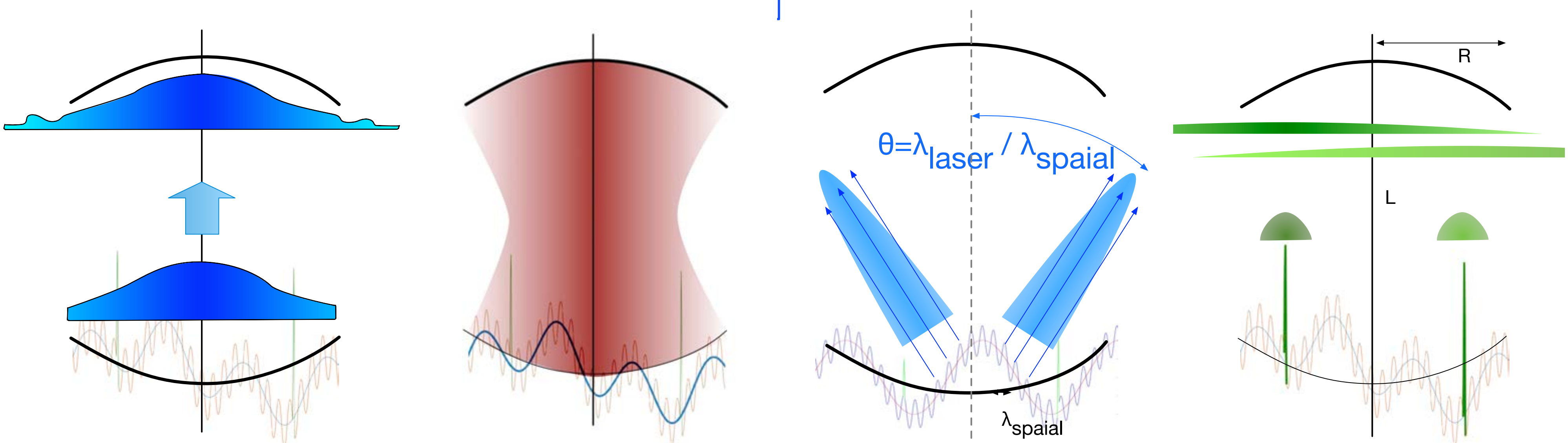
Input power vs PRG



Time evolution of power recycling gain during a power-up at LLO. The laser power is shown on the left-hand axis and PRG is shown on the right-hand axis. Also shown are two SIS models of the power-recycling gain assuming surface deformation on a single ETM from uniform coating and a point absorber, respectively.

Sources of field loss in a cavity ~ categorize losses

Scattered fields in cavity | Scattered fields go out of cavity



Mirror finite aperture	Surface figure error	Micro roughness - PSD	Point defects
Non gaussian diffraction tail ~ θ^{-3}	Change of resonating field and larger tail	Fixed angle scattering by interference of far field	Scattering by small sources located randomly
1.9ppm for aLIGO 0.02ppm for AdVirgo	H1x:20ppm,H1y=16ppm L1x:18ppm,L1y=15ppm	10~20ppm ?	10~30ppm ?
Airy ring outside of mirror $\theta < 0.003°$	$\lambda s > 5mm$ or $\theta < 0.01°$	$\lambda s < 1mm$ or $\theta > 0.06°$, $BRDF \sim 1/\theta^n$, $n \sim 1.5\text{-}3$	All angle, measurable at large angle ?

One scenario
design of beam tube baffle

- Input : physics specification
  - specification of the FP cavity
  - seismic motions
  - Baffle characterization
- Internal : dirty calculations and optimizations
  - Resonating field in the cavity with broadening due to mirror surface aberration
  - Interaction with moving baffles to calculate back scattering and diffraction
  - Coupling of these noises sources to the main interferometer fields
- Output : interesting outputs
  - Noise spectrum with optimal baffle spacing
- Support tools : make results useful
  - Flexible specification of mirror surface aberration
  - Flexible specification of baffles and interactions
  - Data analysis tools to understand the output

Next generation Integrated package for Gravitational Wave Simulation

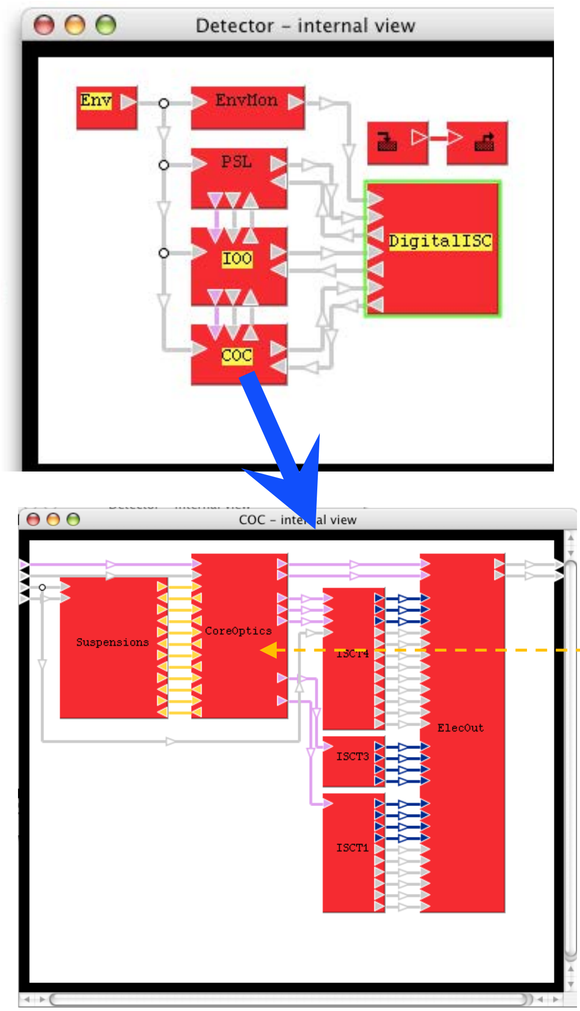
In the High Energy Physics community, there is a simulation package GEANT4, (following quote from Wiki) “which includes facilities for handling geometry, tracking, detector response, run management, visualization and user interface. For many physics simulations, this means less time needs to be spent on the low level details, and researchers can start immediately on the more important aspects of the simulation.” Last year, late-Stavros proposed to start developing simulation package of the similar quality for the gravitational wave science.

Now is a good time to start this kind of package to get ready for O4, O5 and beyond, and for the Einstein Telescope and Cosmic Explorer. There are some simulation tools for a limited purpose, like FINESSE for field calculations, but we need integrations of various elements, seismic motions and isolation, fields and optics and control systems. We have observed many unknown noises and the package needs to be prepared so that the integration is flexible enough to simulate many interesting possibilities.

This is a talk to call for to start a collaboration to develop this kind of package so that more scientists can utilize the simulation to study what they are interested in, without much bothering how to use the tool.

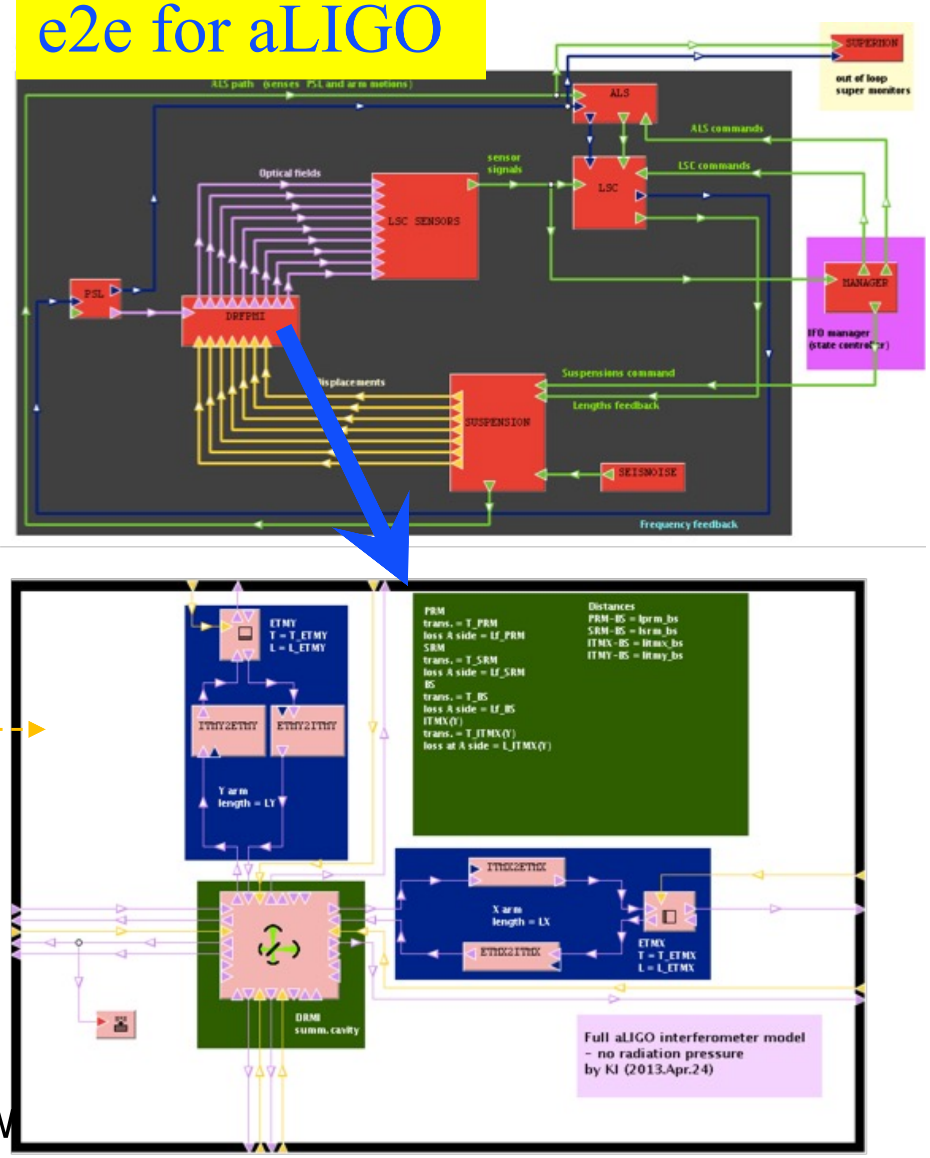
e2e simulation setups iLIGO vs aLIGO

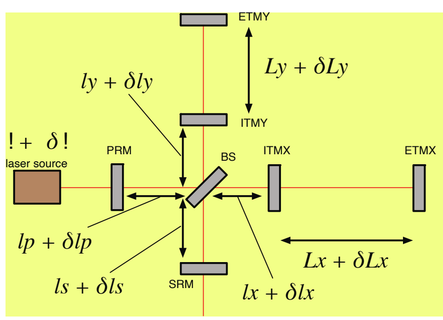
e2e for iLIGO



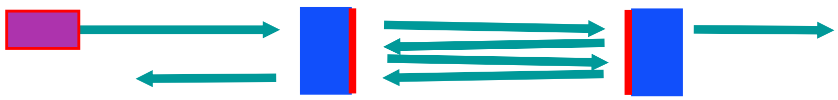
- PRM vs DRMI
- Guided lock vs ALS lock using green
- Single suspension vs triple & quad susp
- Hard coded control vs FUNCX
- Necessary noises

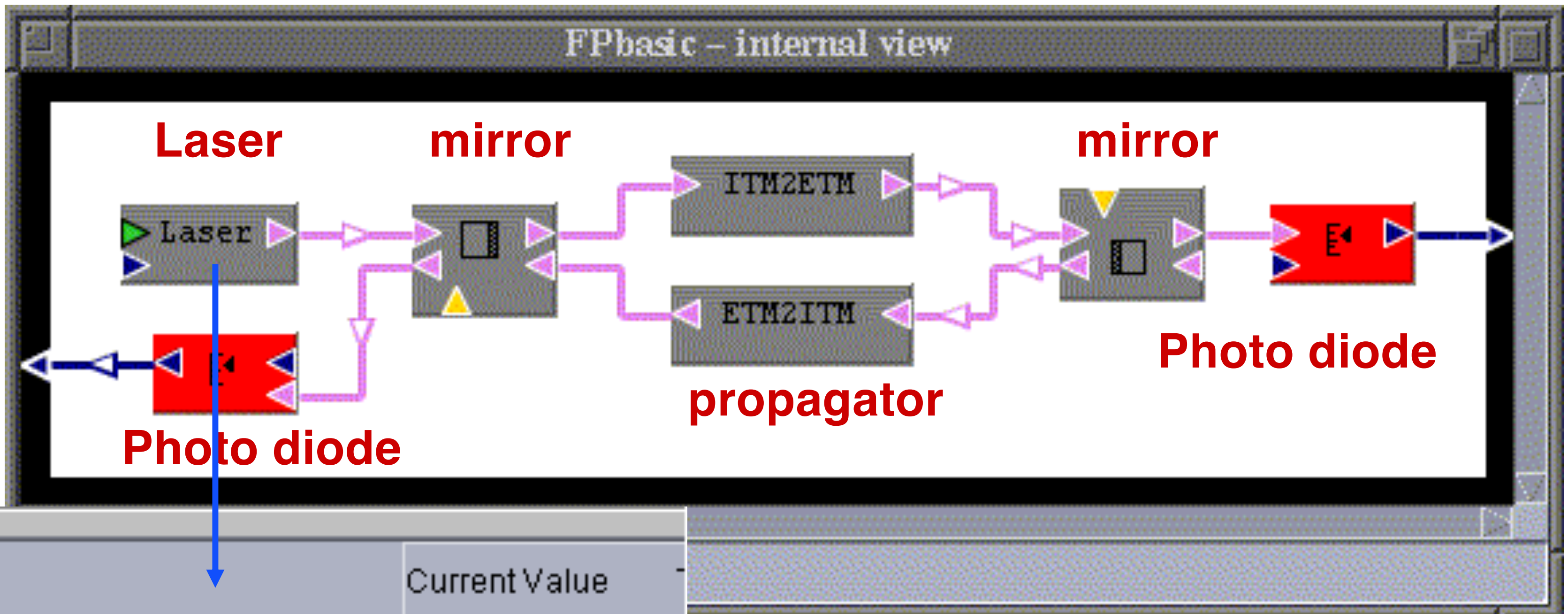
e2e for aLIGO





e2e Graphical Editor

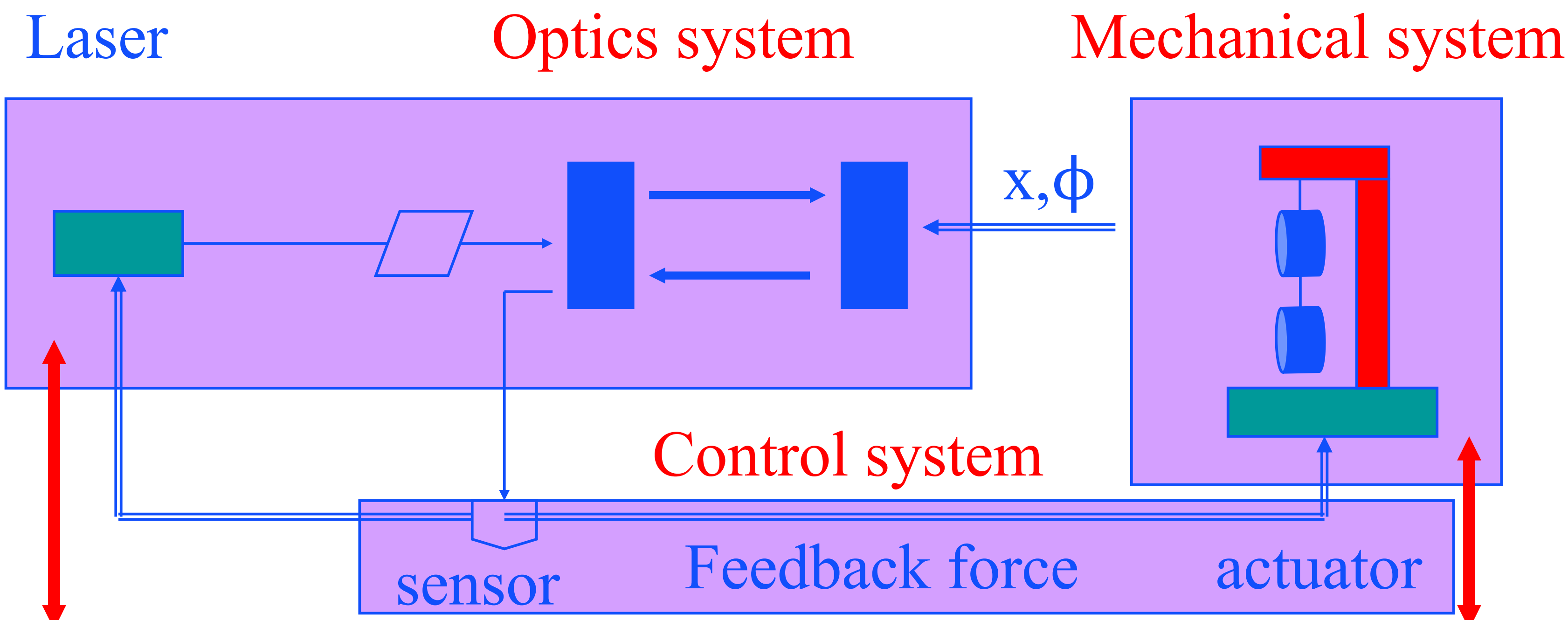




	Current Value
lambda	DEFAULT
waist_size_X	w0
waist_size_Y	w0
distance_waist_X	z_dist
distance_waist_Y	z_dist
angle_resolution	DEFAULT
compute_mismatch_curvature	DEFAULT
max_mode_order	1

End to End Simulation

coarse view



- Time domain modal model
- Objects : laser, mirror, photo diode, …
- Any planar interferometer
    - Fabry-Perot, Mode cleaner,LIGO I,
    - Advanced LIGO,…

- Transfer function using Digital filter
- Single Suspended mirror
- Mechanical Simulation Engine (object-oriented)