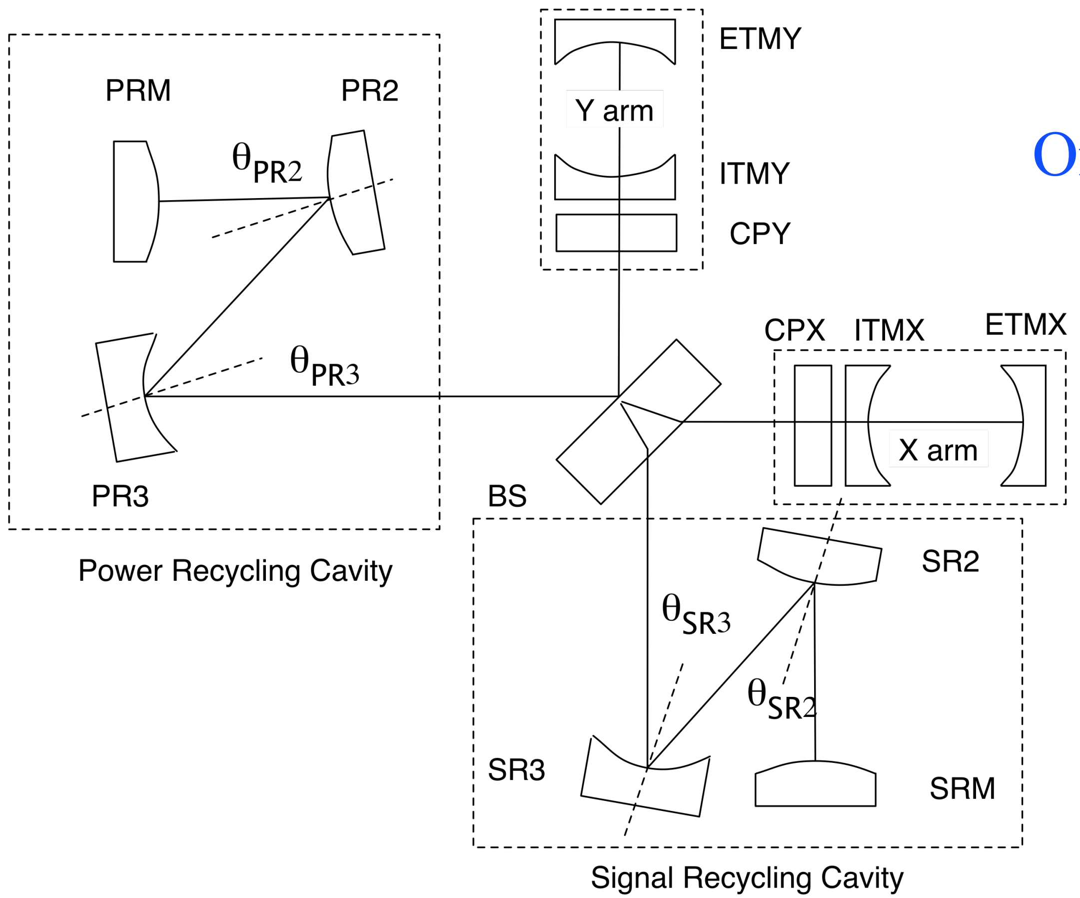
SIS
Stationary Interferometer Simulation

- Overview
  - » Purpose of SIS
  - » How FFT is used
  - » What kind of physics are included
- Application
  - » What kind of analyses were done using SIS
- Internals
  - » The code structure
  - » User Interface

SIS Basic Motivation

- AdvLIGO design tool
- Interferometer configuration trade study
- Effect of finite size optics
  - BS, flat, wedge angle, baffle, etc
- Tolerance of radius of curvature of COC mirrors
- Surface aberration
  - Requirements of the surface quality to satisfy the limit of loss in arm, total of 75ppm
- Subsystem performance simulation
  - TCS, ISC, COC, AOC, ...
- Parametric instability
  - highly distorted field, hard to be expressed by simple functions

Stationary Interferometer Simulation - overview -

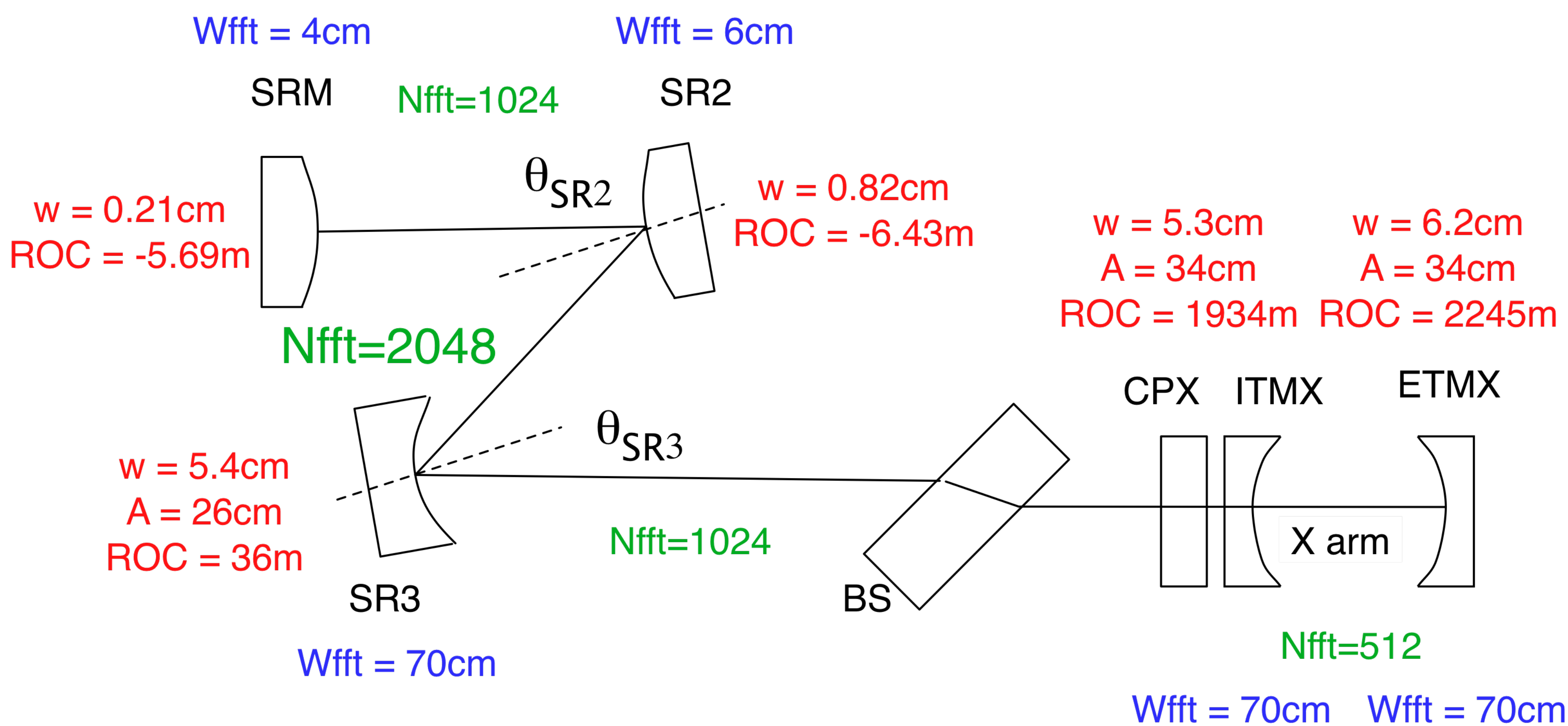


Only coupled cavities so far

PRC - BS - X arm
PRC - BS - Y arm
SRC - BS - X arm
SRC - BS - Y arm

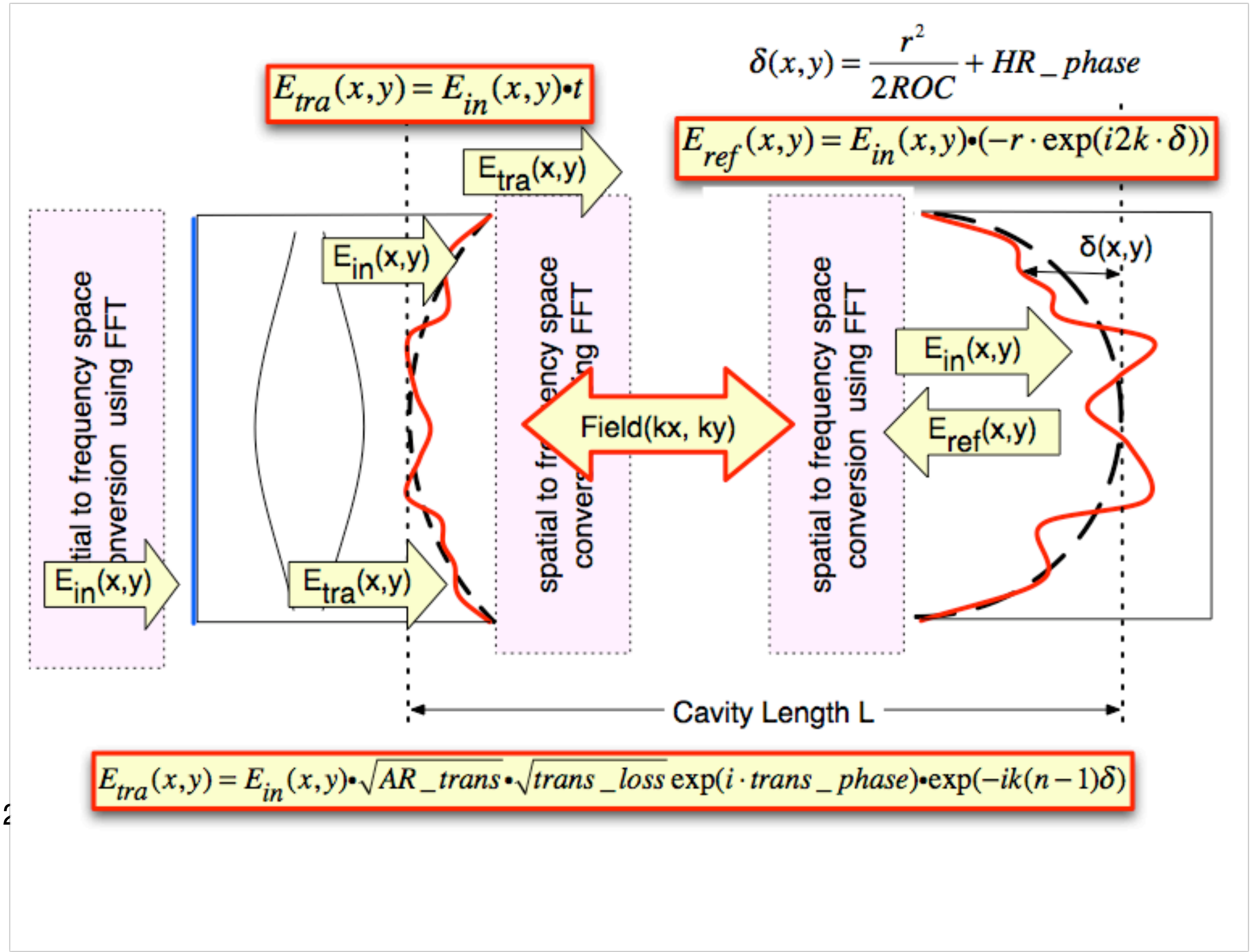
Variable FFT parameters

W for each optic, N for each propagator

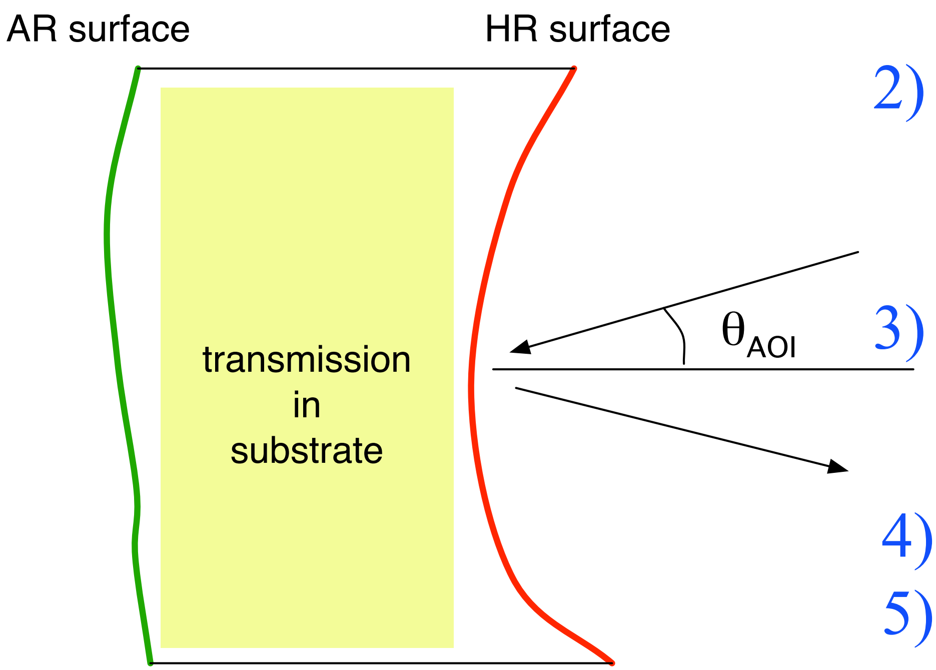


$$\phi(r) = 2\pi \frac{r^2}{2R_{field}\lambda} \qquad d\phi(r) = 2\pi \frac{rdr}{R_{field}\lambda} \sim 2\pi \frac{r^2/N}{R_{field}\lambda} = 2\pi \frac{10^{-2}}{10 \cdot 10^{-6}} / N = 2\pi \cdot 10^3 / N$$

FFT Basic
Optics and fields



Mirror - 1



1) HR/AR surface
   - Surface shape (x,y)
   - Transmittance / reflectance (x,y)

2) Transmission
   - Phase (x,y)
   - Loss (x,y)

3) Finite angle of incidence
   - R*cos(θ), R/cos(θ)

4) Implicit small wedge angle

5) Microscopic shift and rotation

Mirror - 2

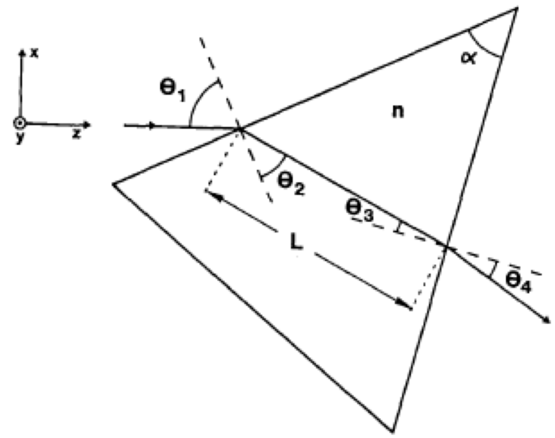
- F(x,y)
  - » C-like math expression
    - – Standard functions – zernike, hermite, etc
    - – (x*x+y*y) / (2 * ITM_RH) for ring heater correction
  - » Build-in functions
    - – Hello-Vinet thermoelastic and thermalphase functions
    - – Random surface generator with f^{-n} spectrum
  - » Data loaded from a file
    - – With specified Zernike terms subtracted
    - – Auto conversion of mesh structure
  - » Combination of these
    - – DATAFILE(“data.dat”,{0,1,2,3,4,10}) + 1e-8*wyko(10,r,theta)

Mirror - 3

- Hello-Vinet thermoelastic and thermalphase functions
  - » `THERMOELASTIC( beamSize, Psubs, Pcoat [, T0] )`
  - » `THERMALPHASE( beamSize, Psubs, Pcoat [, T0] )`
- Fused silica
- When arguments are negative, absolute absorption powers are calculated using the previous distribution
  - » Iteration to find a stationary thermal state
    - – First run : no thermal effect
    - – Second run : thermal effect using the power in the first run
    - – Nth run : thermal effect using the power in the previous run
  - » Several times of iteration

Beam Splitter

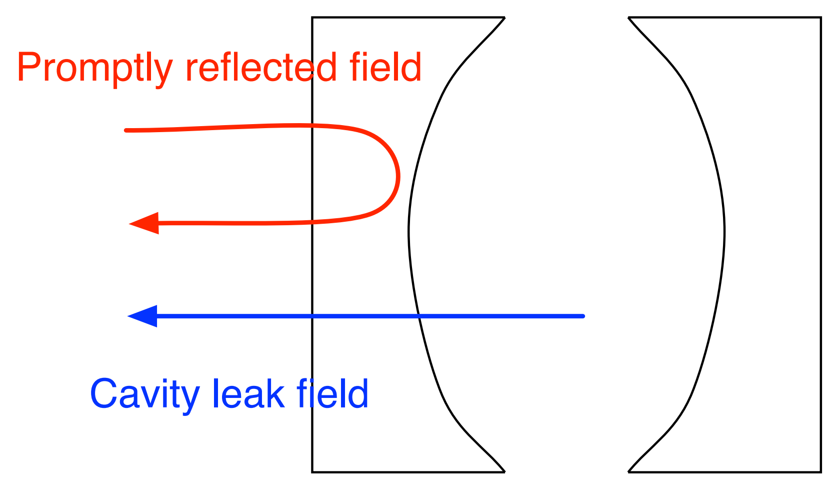
- Mirror object
  - Without
    - Transmission property
    - Hello-Vinet thermal functions
    - Angle of incidence
  - With
    - Wedge angle



$$\mathbf{M}_{\rm prt} = \begin{vmatrix} \dfrac{\cos\theta_2 \cos\theta_4}{\cos\theta_1 \cos\theta_3} & \dfrac{L \cos\theta_1 \cos\theta_4}{n \cos\theta_2 \cos\theta_3} \\ 0 & \dfrac{\cos\theta_1 \cos\theta_3}{\cos\theta_2 \cos\theta_4} \end{vmatrix}$$

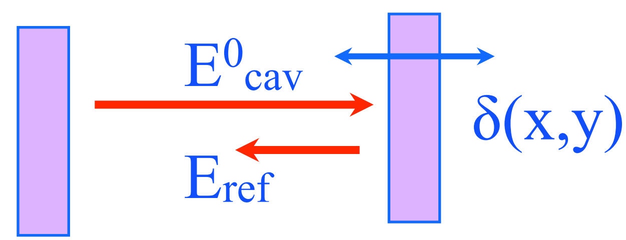
Dynamics
Locking using CR error signal

- Error signal = imag(CR*SB)
  ~ imag(CR * promptly reflected CR)
- Adjust ETM to lock arm,
  adjust RM to lock recycling cavity



Dynamics
Signal Sideband Generation

- Calculate stationary field in the arm in a static cavity system
- Calculate signal field generated by a stationary motion of ITM and ETM
  - » Motion = $\delta(x,y)\ \sin(\Omega_{AF}\ t)$



- Calculate stationary field in the static cavity system with this induced field ($\Omega = \omega_0 + \Omega_{AF}$) as the source

$$E_{ref}(x,y,t) = \exp(2ik\delta(x,y)\cdot\sin(\Omega_{AF}t))\bullet\exp(i\omega_0 t)\bullet E_{in}(x,y)$$

$$\approx \{\exp(i(\omega_0+\Omega_{AF})t) - \exp(i(\omega_0-\Omega_{AF})t)\}\bullet k\delta(x,y)\bullet E_{in}(x,y)$$

$$+\exp(i\omega_0 t)\bullet E_{in}(x,y)$$

TELESCOPE

- Telescope can be attached to any cavity fields by using
  - TELE_SPACE(distance)
  - TELE_LENS(fNumber, radius, x0, y0)
  - TELE_MIRROR(ROC, thetaAOI, phiAOI, radius, x0, y0)
- Same Nfft
- Automatic scaling of Wfft

Analysis tool

- No data visualization
  - Save data and use matlab
- Fit fields by effective Gaussian shape
  - w_x, w_y, ROC_x, ROC_y, x0, y0
- Mode expansion
  - Hermite, Laguerre with arbitrary number of nodes

```
+++ Field "toRM" +++
Mode base  : z = -1.707187      z0 = 0.74866
           : w = 0.001253804    R = -2.0355
Fit result : (wX,wY)=(0.0012309, 0.0015143) R(x/y) = (-1.860827, -1.770486)
             (x0,y0)=(-4.334e-09 , -1.387e-10 )  power / HMfrac = 14.44152 / 0.07849

 Amplitude = ( Re, Im ) [ subPower, fraction ]
     only those modes are listed whose powers > 10^-8 of the total power
HG( 0 , 0 ) = (-3.6480170222451,2.4981415189107e-05)  [ 13.308028195214, 0.92151171216148 ]
HG( 2 , 0 ) = (-0.2226676904413,-0.17207008010871)    [ 0.079189012835078, 0.0054834271262119 ]
HG( 0 , 2 ) = (-0.1481305109545,0.099965321393146)    [ 0.031935713756877, 0.0022113820192973 ]
```

To be done

- Implement full configuration
  - Single recycling, Dual recycling
  - Locking algorithm
  - Fast convergence algorithm
- Speed up the XR3-XR2 cavity simulation
- n(x,y,z) : 3D refractive index table to calculate the BS thermal lens effect

SIS Applications

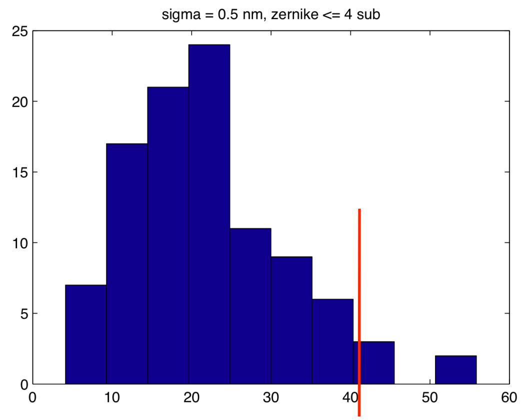
- FP arm
  - Study of surface specification
  - Comparison of test mass surfaces polished by 3 vendors
  - Compensation Plate Thermal shied non uniformity
  - Thermal deformation and loss in the arm
- Coupled cavity
  - Diffraction in the stable cavity
  - Trade study of stable and marginally stable cavity
    - Wedge angle effect
  - Astigmatism due to finite angle of incidence
  - Surface roughness specification of recycling mirror optics
  - Optimal Michelson cavity mode with small ITM thermal effect – on going

mirror rms requirement

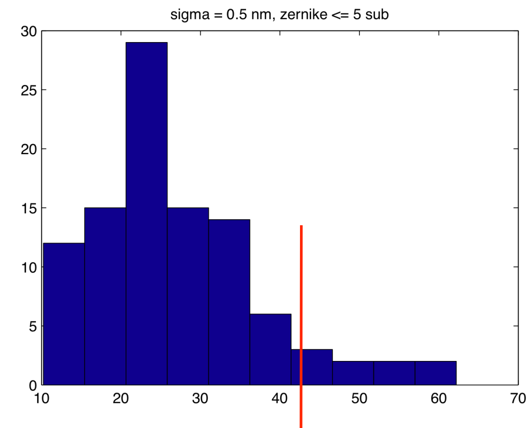
Zernike <=4 subtracted

Zernike <=5 subtracted

rms = 0.5nm

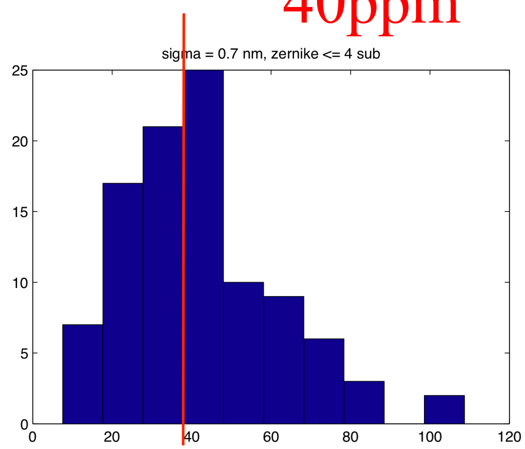


40ppm

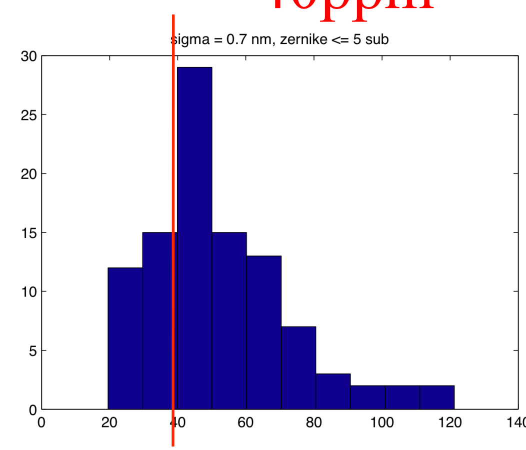


40ppm

rms = 0.7nm



40ppm



40ppm

Thermal effect and arm power loss and signal loss

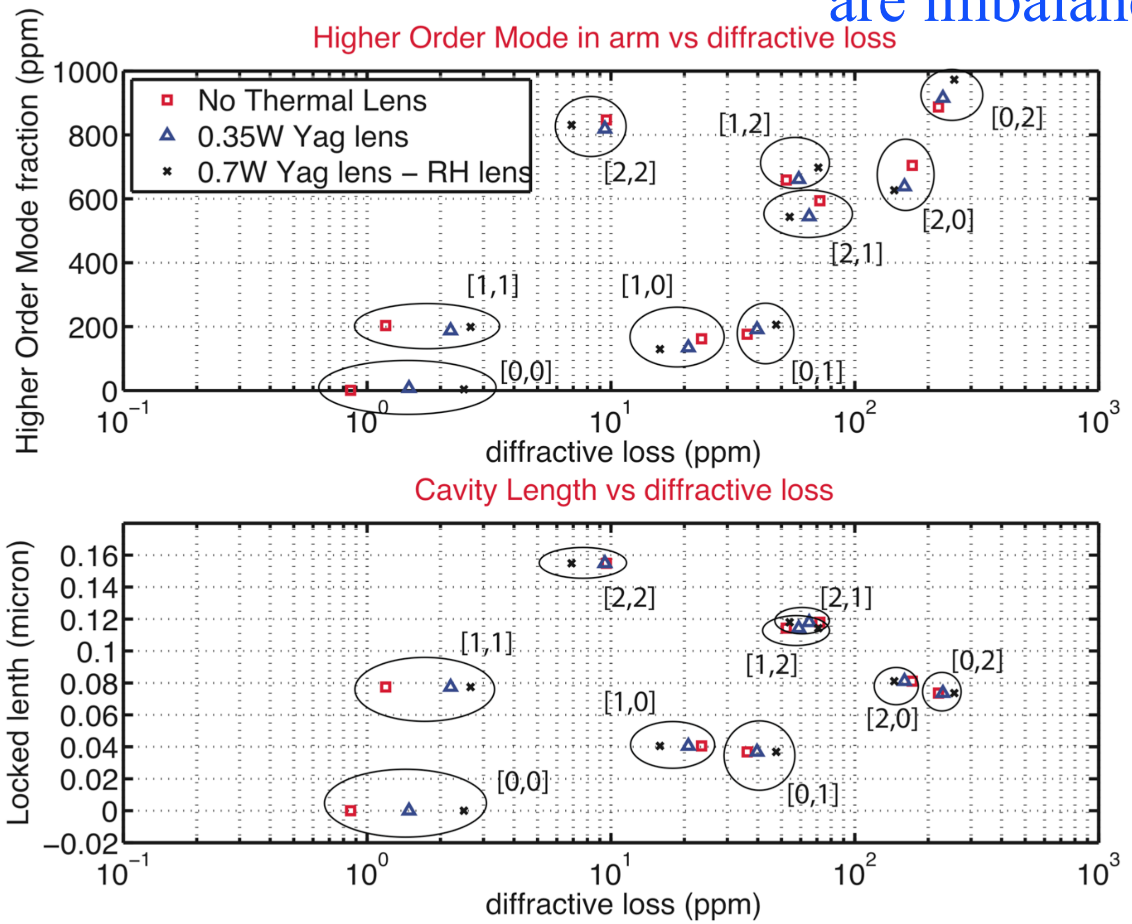
- Absorption rate vs arm power loss
- Effect of absorption imbalance
- Effect of the ITM thermal lens on the resonating mode in the arm cavity
- Signal loss due to thermal effect
- Using one ring heater vs two ring heaters

Thermoelastic bumps affect resonating mode

Large loss when absorptions are imbalanced

Thermoelastic
[a,b]: absorption in ppm
ITM 0.5*a
ETM 0.5*b

Thermal lens (ITM+CP)
□ perfect cancelation
△ pure 0.5ppm abs
✖ 1ppm abs + RH lens



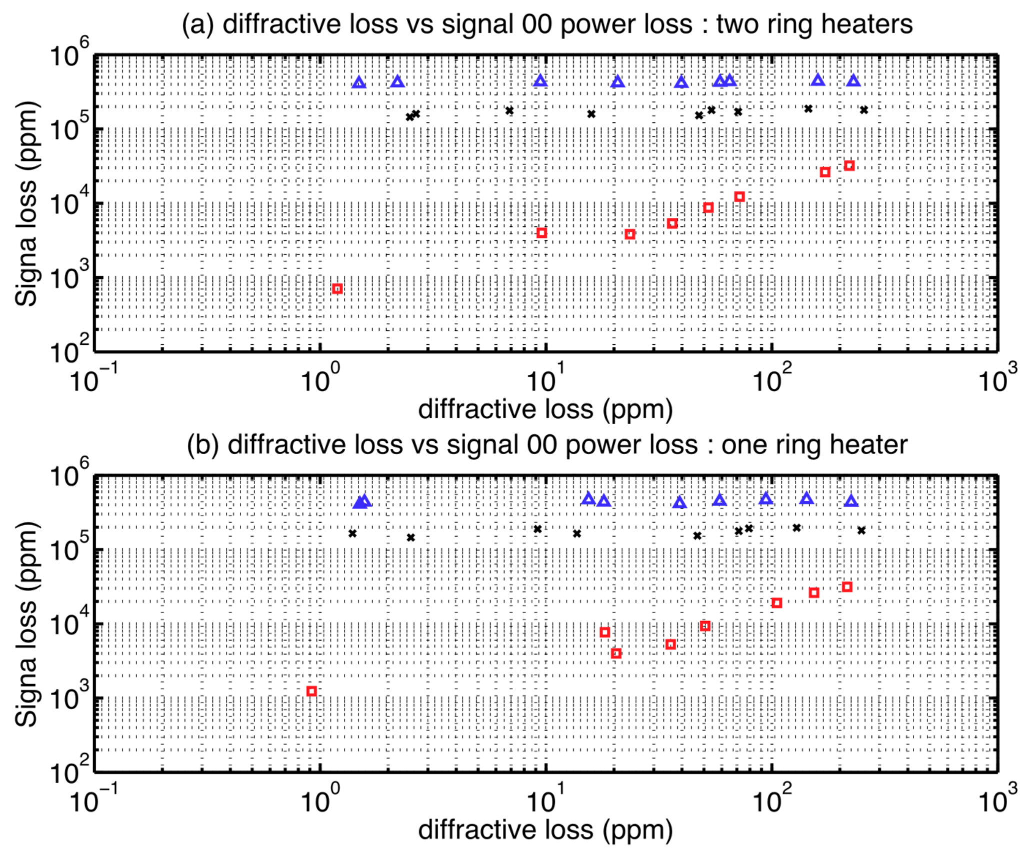
Thermal lens affects the signal loss

TEM00 mode power coming out of the arm

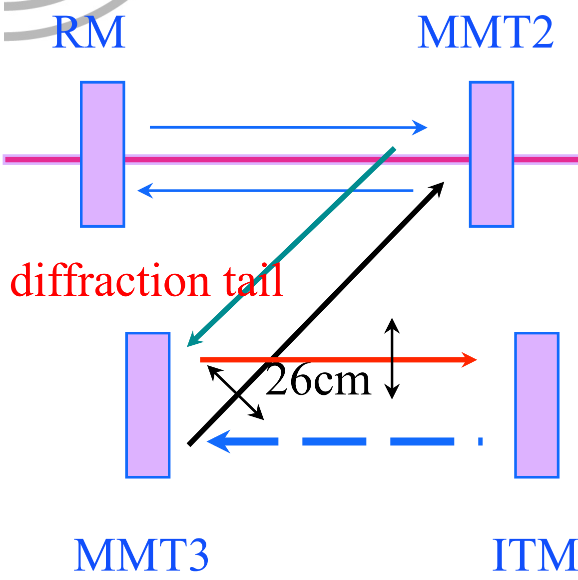
Transient of fast lens (ring heater lens) to slow lens (compensation plate)

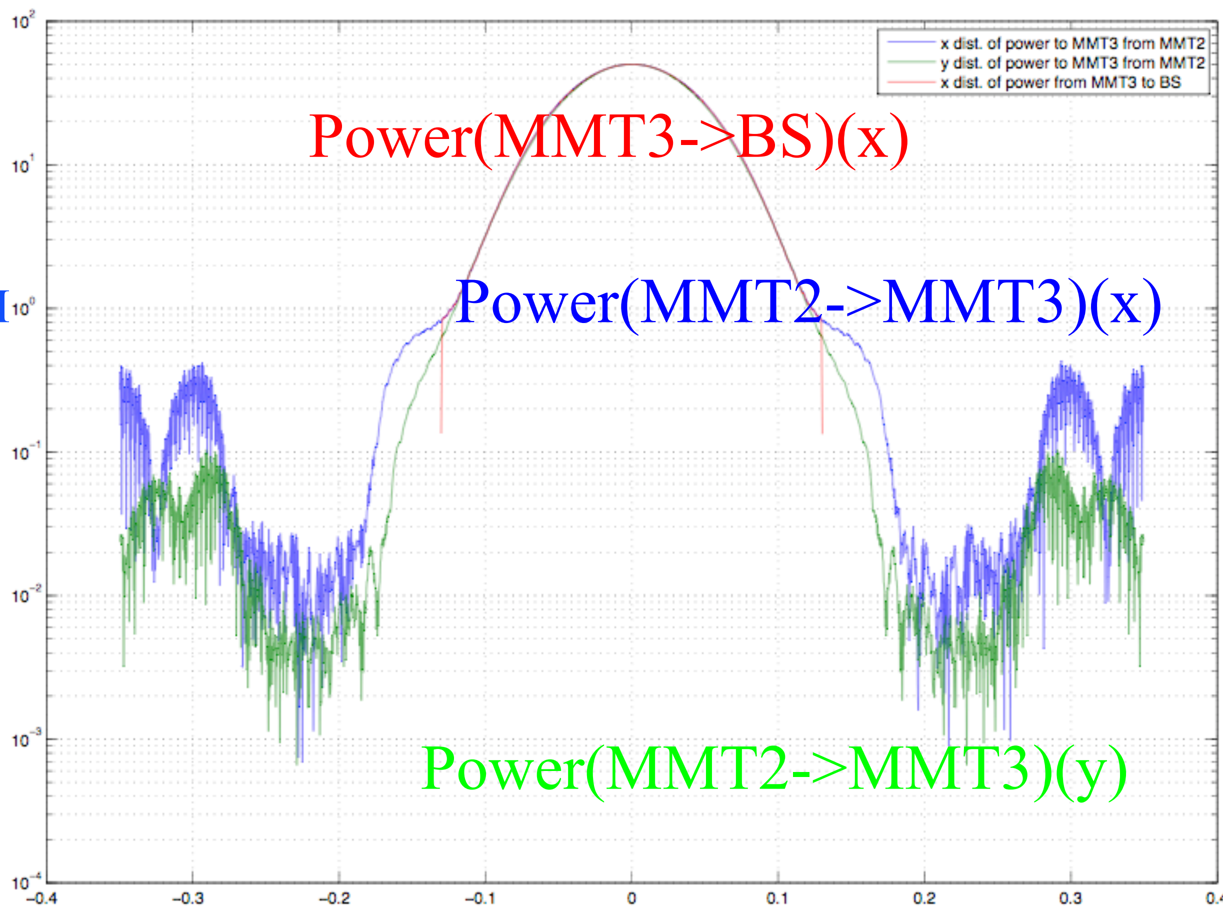
Thermal lens (ITM+CP)

- □ perfect cancelation
- △ pure 0.5ppm abs
- ✖ 1ppm abs + RH lens



Power loss on MMT3 (ITMY<->SRM case)





loss = 330ppm
(energy outside of MMT3 surface)

Loss under different conditions

MMT aperture (cm)	beam size on ITM (cm)	Coupled cavity	loss on MMT3 (ppm)
26cm	6cm	Y-arm + SRM(*)	330
26cm	6cm	X-arm + SRM(*)	600
28cm	6cm	Y-arm + SRM	140
26cm	5.5cm (**)	Y-arm + SRM	47
26cm	5.5cm (**)	X-arm + SRM	60

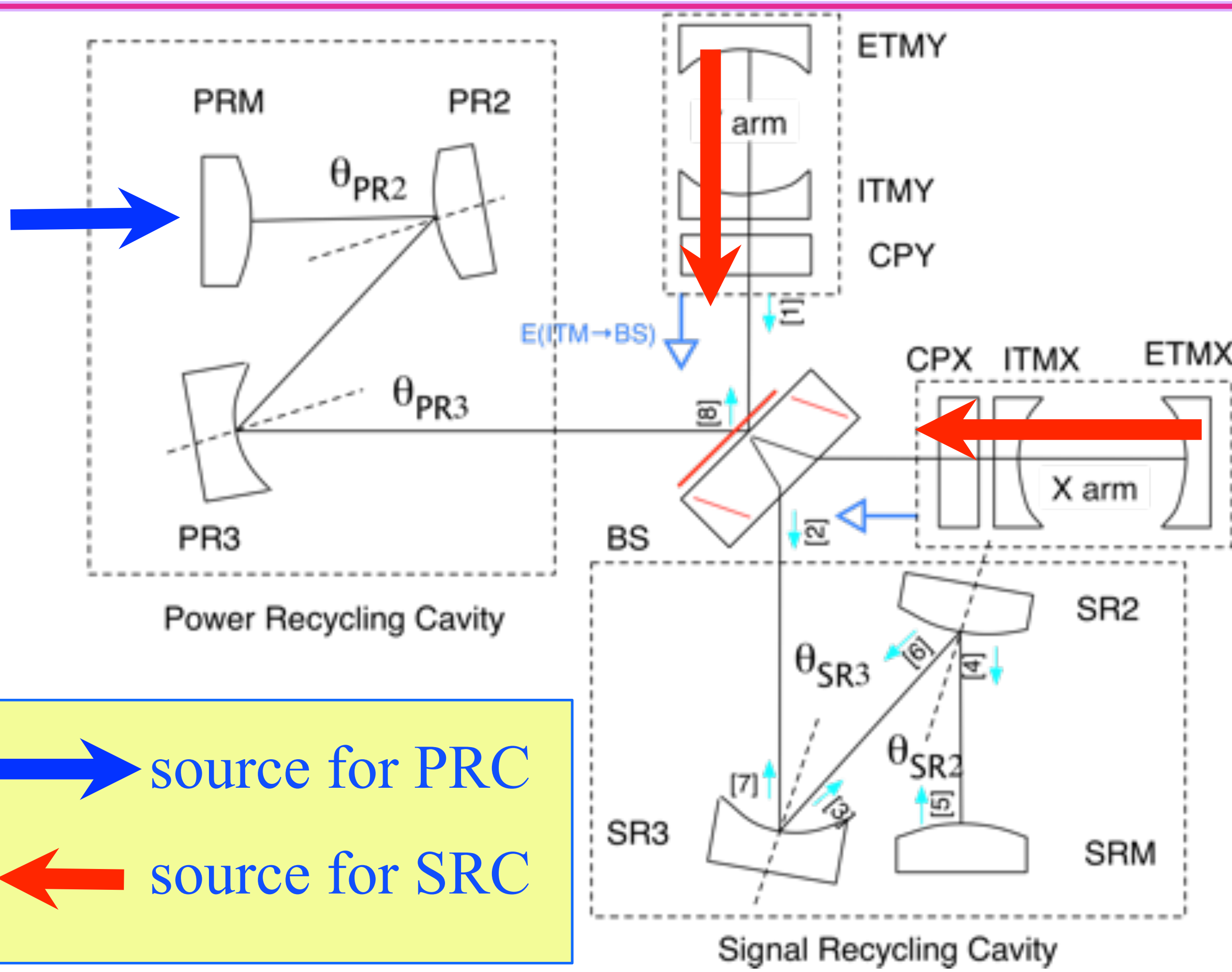
ETM ROC ITM ROC 2076m + 2076m

ETM ROC ITM ROC 1971m + 2191m

(*) When a baffle is plac nt of ITMY, Y-arm+SRM configuration comes very close to X-arm+SRM case.
(**) http://ilog.ligo-wa.c du:7285/advligo/Test_Mass_Beam_Sizes, asymmetric case with 5.5cm on ITM and 6.2cm on ETM.

With the baffle size of Mike's choice - 214mm x 249mm - the beam going through a baffle is cut off by 250ppm. If the baffle size of 1cm larger in both direction (224mm x 259mm), the cutoff is 55ppm. The numbers in the above table were calculated without baffles.

Astigmatism by the stable Michelson cavity



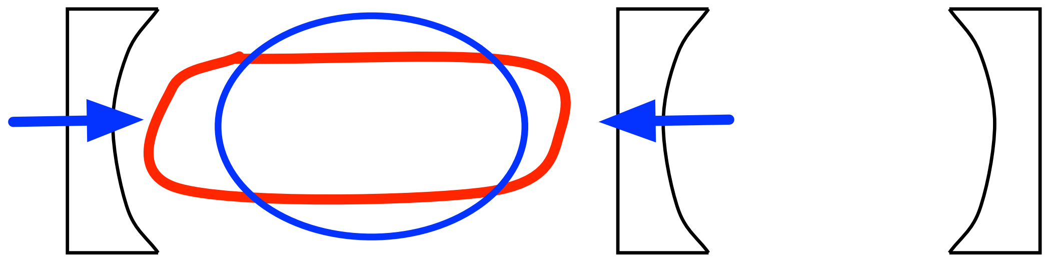
source for PRC

source for SRC

Locked
arm and PRC/
SRC locked.
field resonant in
RC

SRC detuned
lock, then add $\lambda/4$
offset
field non-resonant
in RC

Locked and detuned case



Recycling cavity resonating mode

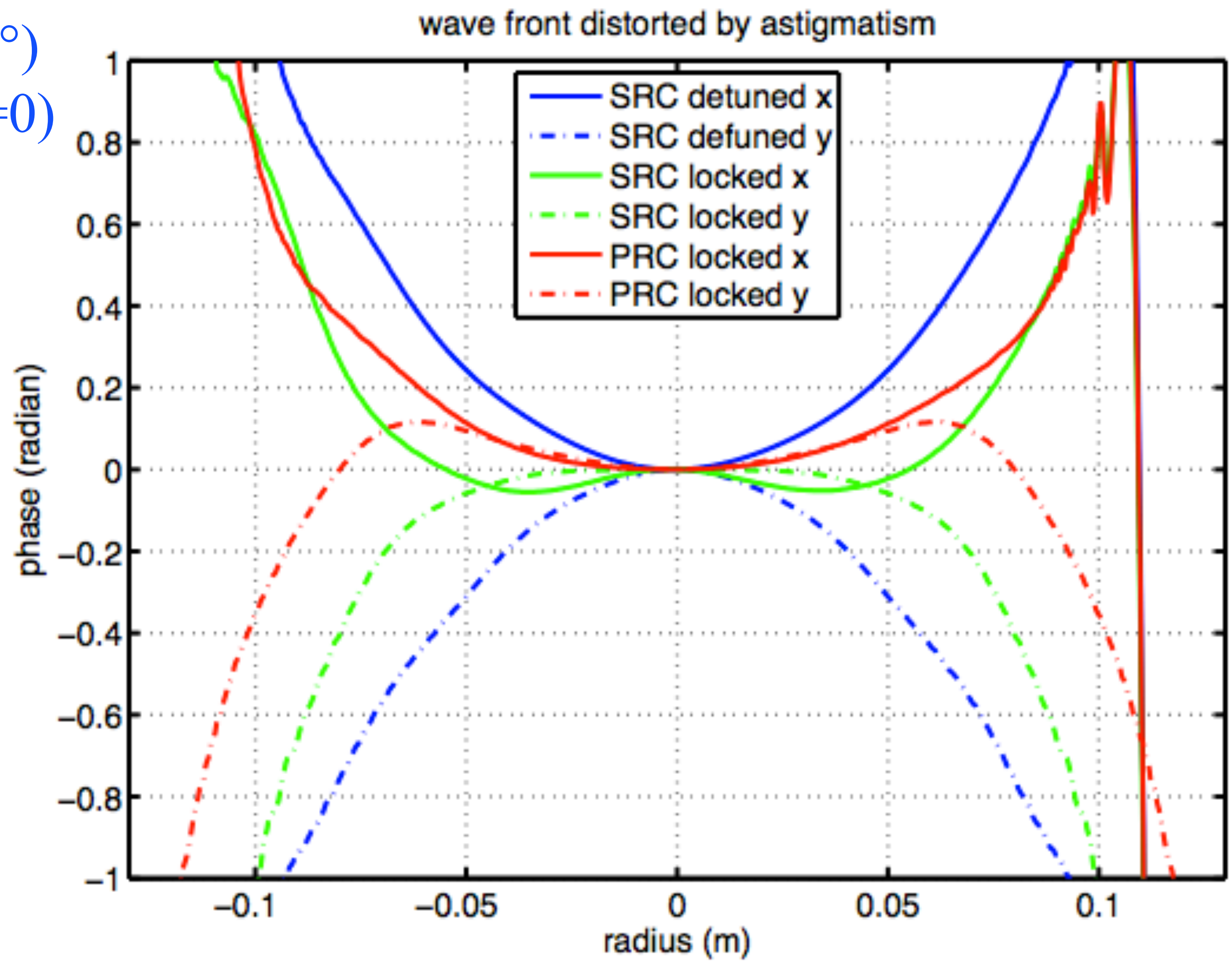
Field determined by the injected source field
Locked case : this mode is resonant
Detuned case : this mode is anti resonant

Wave front distortion by astigmatism

field from R3 to R2

phase(θ_2=2°, θ_3=2°)
- phase(θ_2=0, θ_3=0)

SRC locked ~
PRC locked

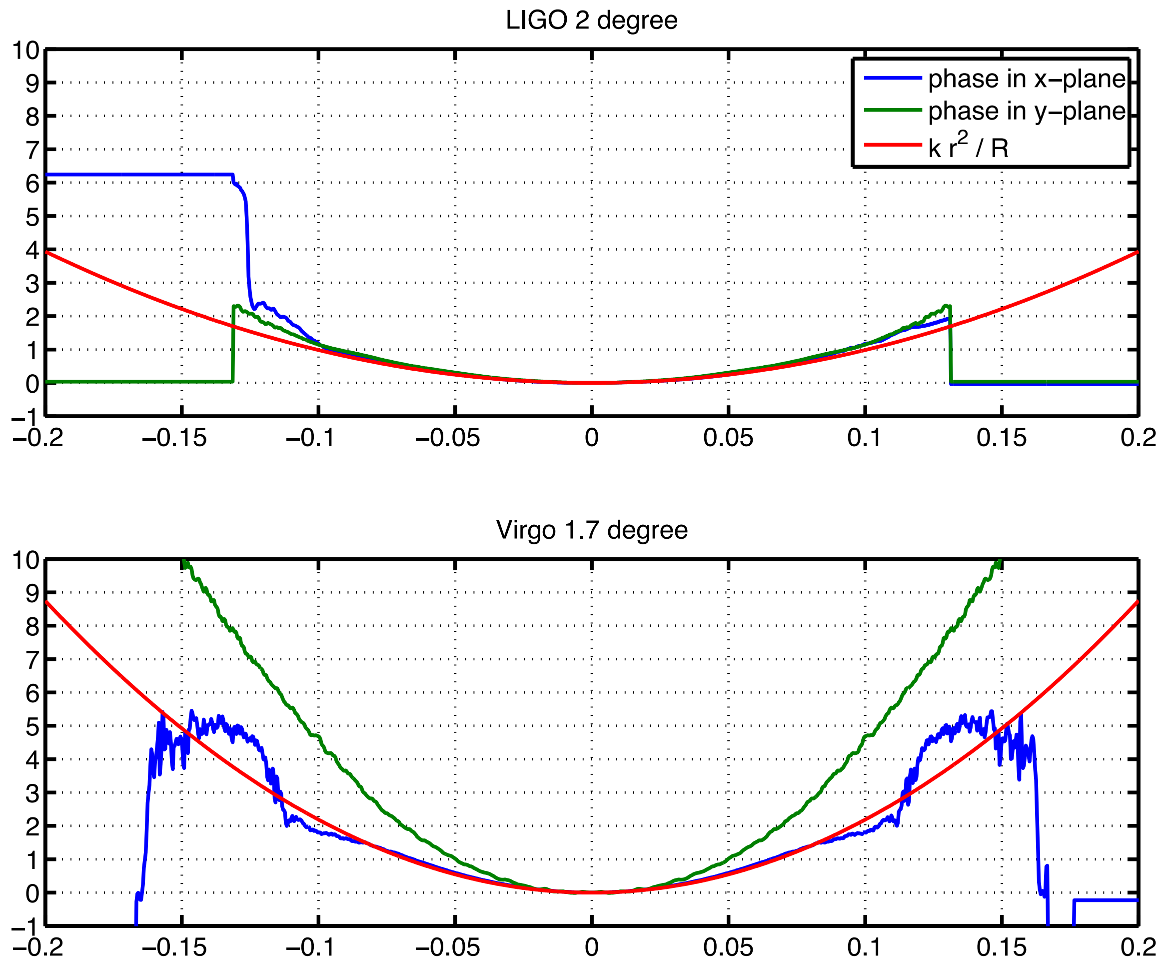


G0900912-v1

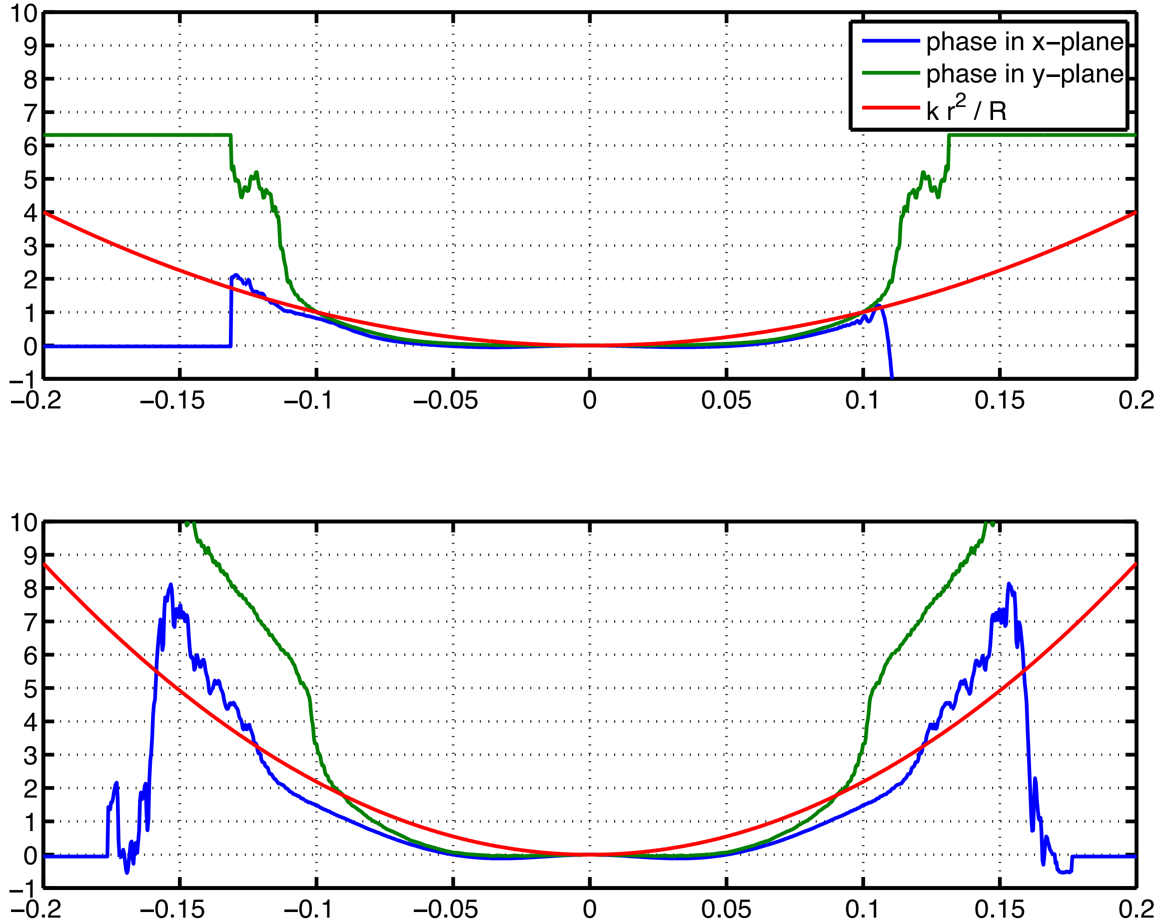
LIGO vs Virgo detuned case

$$\frac{k \cdot r^2}{2R \cdot \cos(\theta)} - \frac{k \cdot r^2}{2R} = \frac{k \cdot r^2}{4} \frac{\theta^2}{R}$$

R(LIGO)=36m
R(Virgo)=12m

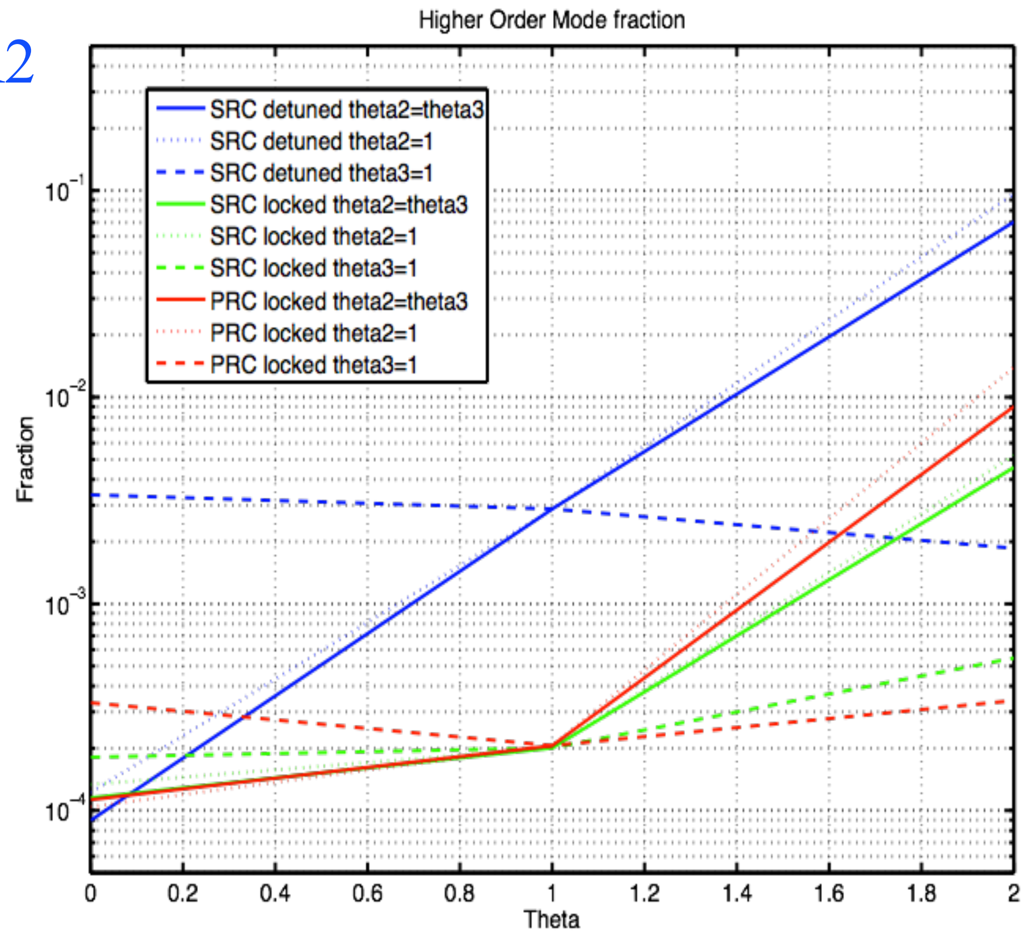


LIGO vs Virgo locked case



Angle dependence of HOM strong dependence on θ_3

field from R3 to R2



SIS Internals

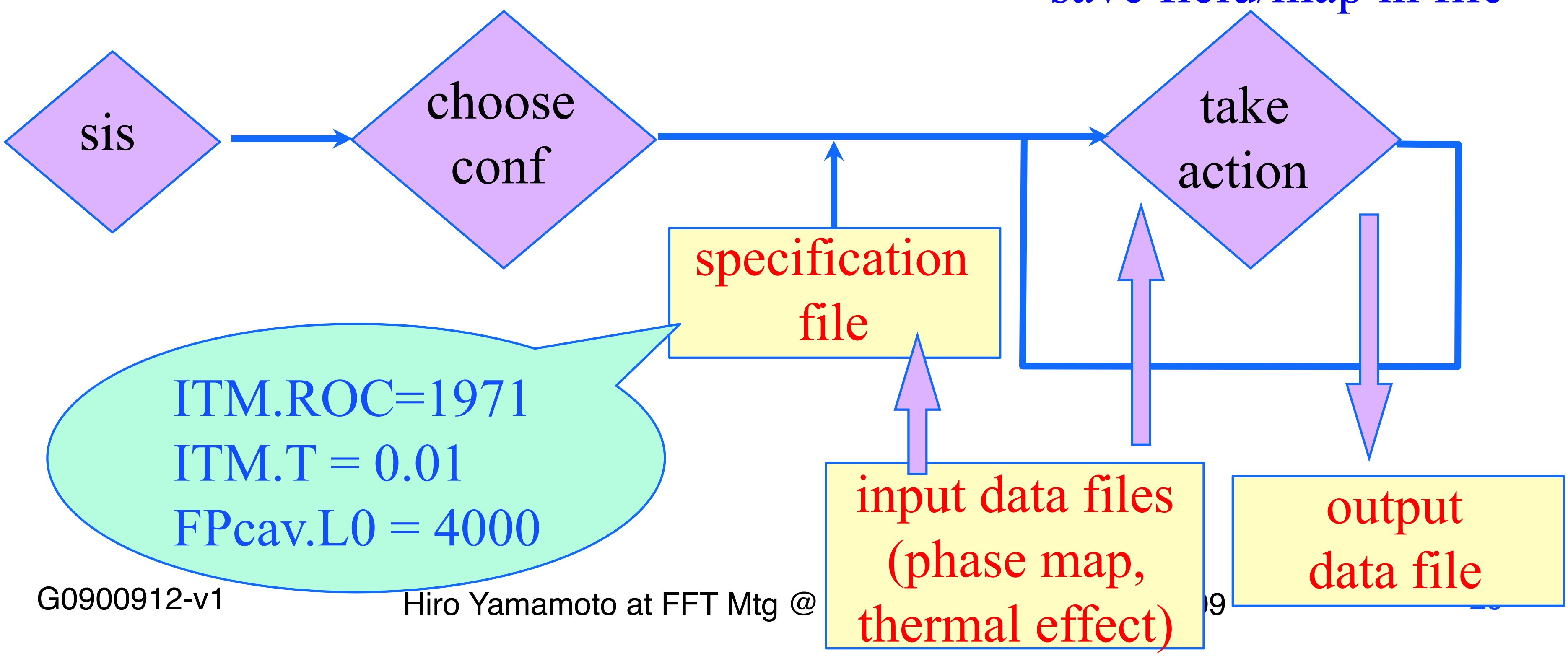
- Object oriented code using C++
  - » ease of modification, adding compensation plate, degenerate to non-degenerate Michelson cavity, etc
  - » e2e code reused
    - – Expression parser to handle mathematical formula
- FFT with adaptive grid size
  - » fftw for FFT calculation
  - » The beam size changes in a concentric configuration
  - » Mode matching telescopes can strongly focus beams
  - » Use of different number of grids (128, ..., 2048)

Using SIS workflow

- FP
- MSCC
- SCC

- PRM
- SRM
- DRM

- change setup
- lock
- analyze field / mirror
- save field/map in file



Using SIS specification file

```
ITM.opt.T = 0.005
ITM.opt.R = 1 - ITM.opt.T
ITM.opt.ROC = 1971
ITM.opt.trans_phase = THERMALPHASE( beamWidth, PsubsPwr, PcoatPwr )
ITM.opt.HR_phase = THERMOELASTIC( beamWidth, PsubsPwr, PcoatPwr ) + rr/
(2*ROC_TCS) + DATAFILE( ITMMAP.dat )

ETM.opt.ROC = 2191
ETM.oscillation.amplitude = 1e-15  % 1e-9*x for rotational oscillation
ETM.opt.HR_phase = THERMOELASTIC( beamWidth, PsubsPwr, PcoatPwr ) + rr/
(2*ROC_TCS) + DATAFILE( ETMMAP.dat )

inputBeam.beamType = "LG"
inputBeam.power = 1
inputBeam.waistSize = 0
inputBeam.waistPosition = 0
inputBeam.matchToCavity = 1   % calculate waistSize and waistPosition to match
with the cold cavity
```

Using SIS main menu of actions

Field calculation

```
lock        : Lock the cavity
calcField   : Calculate stationary field
signalGen   : Generate audio signal by sinusoidal motion of mirrors
timeTrace   : Move mirror and save field evolution
telescope   : calculate telescope outputs
```

analysis

```
delL        : Print and set the cavity length
modeAmp     : Decompose a field by LG or HG
saveField   : Save field in a file
mirrorInfo  : View mirror information
storeMap    : Store mirror maps
summary     : Print summary status
```

setting

```
simSpec     : Set simulation parameters
loadSimSpec : load simulation setup
runSpec     : Set run conditions, like convergence criteria
```