e2e introduction

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- e2e basic
  - »what is e2e
  - »how was, can be, will be, used
- mode matching - a poor mans's view
  - »CR vs SB
  - »Upper vs lower SB
- Application
  - »OMC effect

Tools

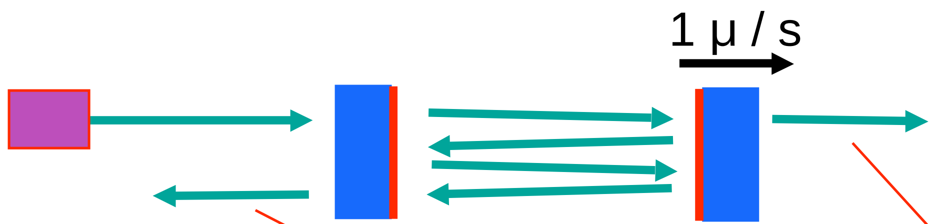
Tool	Pros	Cons
Analytic calculation	❑Underlying mechanism can be easily understood	❑Only simplified case can be analyzed
FFT/ Melody	❑Details of optics can be included (Phase map, Thermal lens)	❑Only static (for now) ❑FFT:not intuitive
e2e	❑Non-stationary process ❑Realistic sensing and controls can be included	❑Limited spatial profile ❑No details of optics

- Modal Model, not so bad
  - Modal Model can be used to study degenerate and/or unstable cavity
  - Valid only when perturbation is small
  - Field source mode is more important than cavity eigenstates

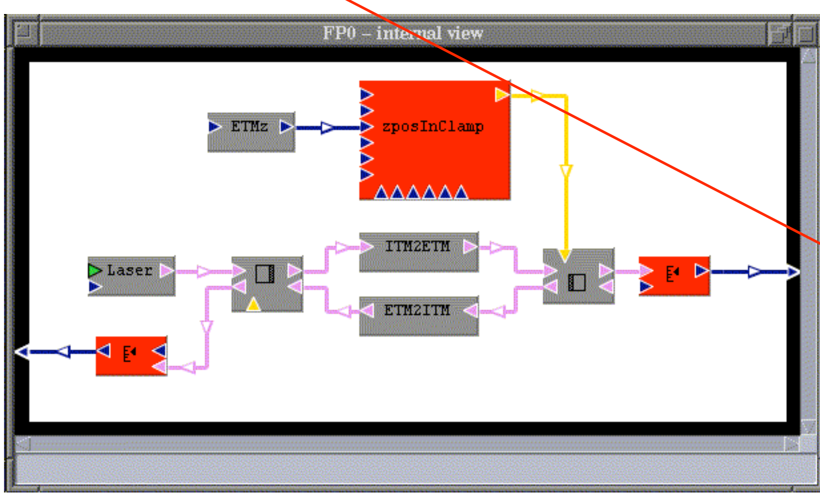
LIGO End to End simulation overview

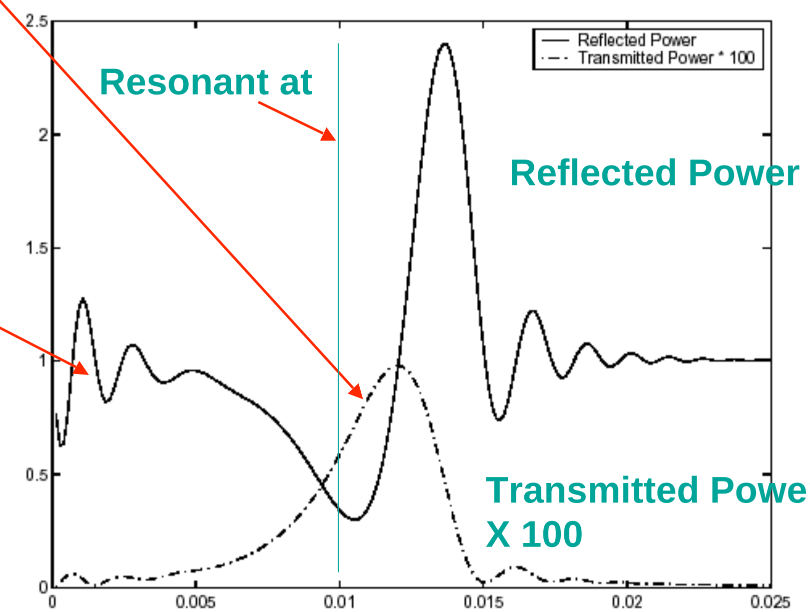
- Time domain simulation written in C++
- Like MATLAB with Interferometer toolbox
- Major physics components and tools relevant for LIGO
  - » fields & optics, mechanics, digital and analog electronics, measured noise, state space model using ABCD matrix, etc
- Flexible to apply for wide varieties of 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



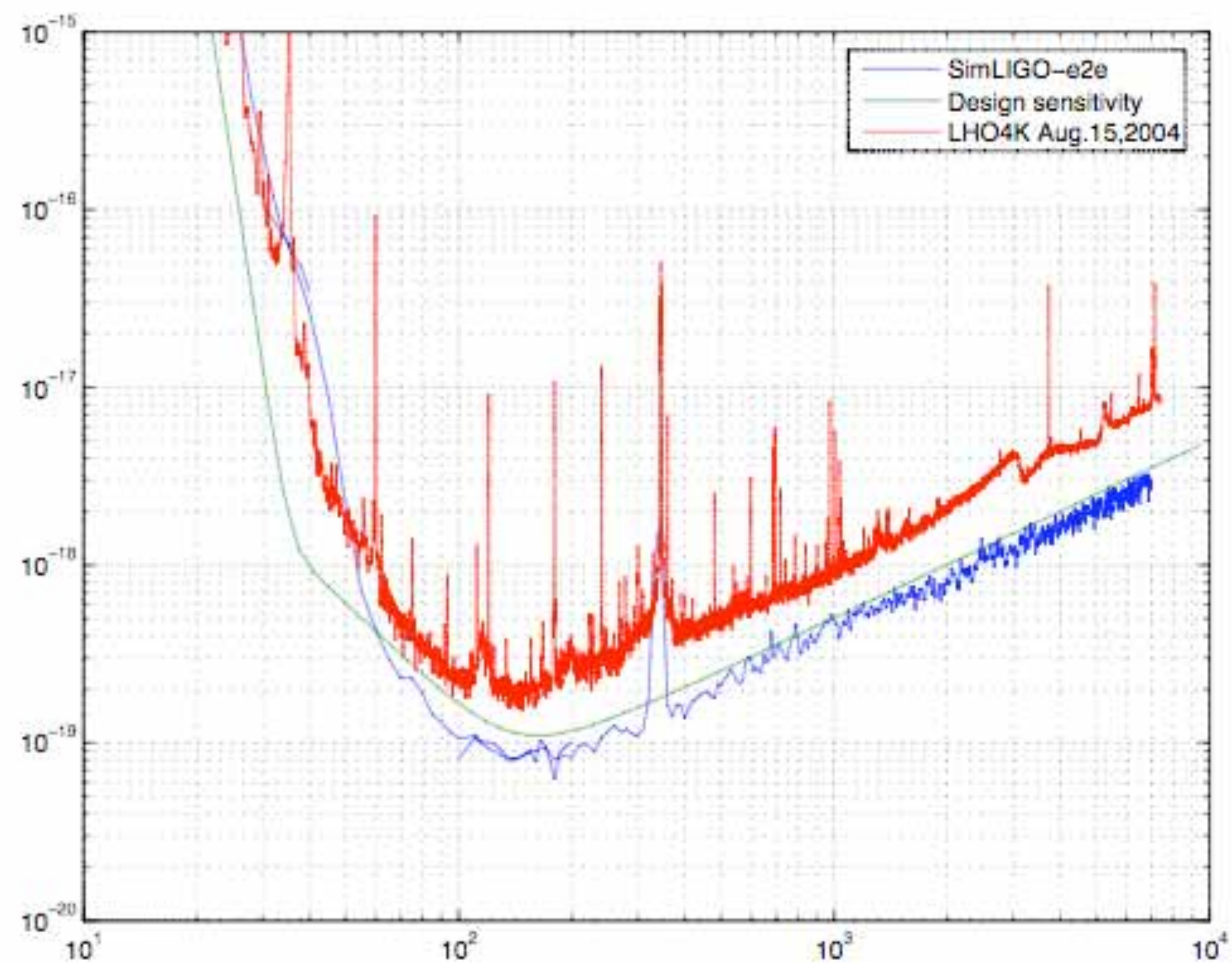


Power = 1 W, T_{ITM}=0.03, T_{ETM}=100ppm, L_{cavity} = 4000m

LIGO e2e usage

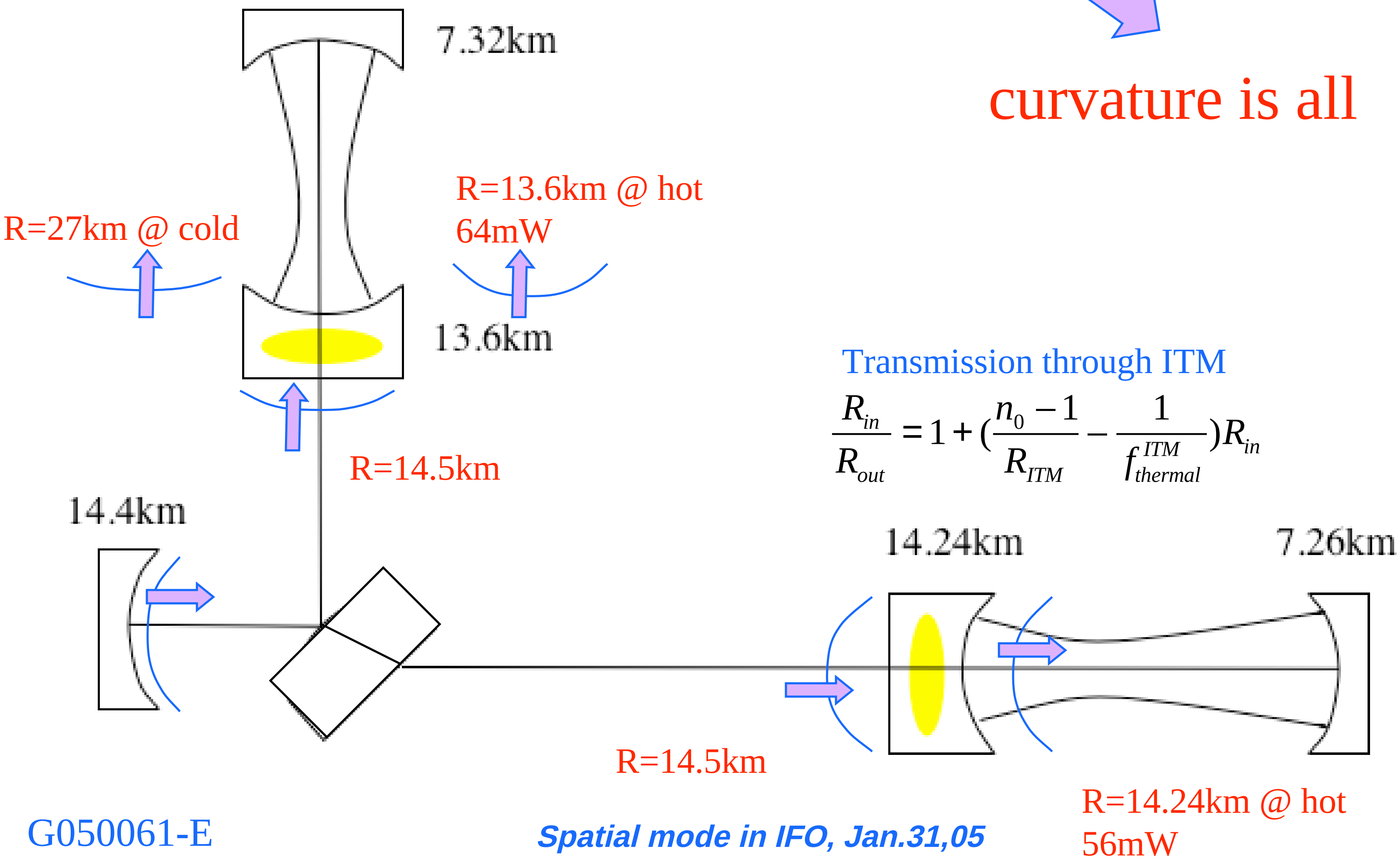
- LIGO I
  - » Lock acquisition design, original and improvements
  - » Robust alignment control design
  - » Effect of thermal lensing
  - » Cross check with other calculation
    - – ASC matrix miscalculation found
    - – LIGO I 4k Schnupp asymmetry mis-design found
  - » Detailed study of input beam (mode cleaner and mode matching telescope)
- Adv.LIGO
  - » Lock acquisition
  - » Radiation pressure and alignment control

Sensitivity curve



Mode matching
based on simple lens/mirror

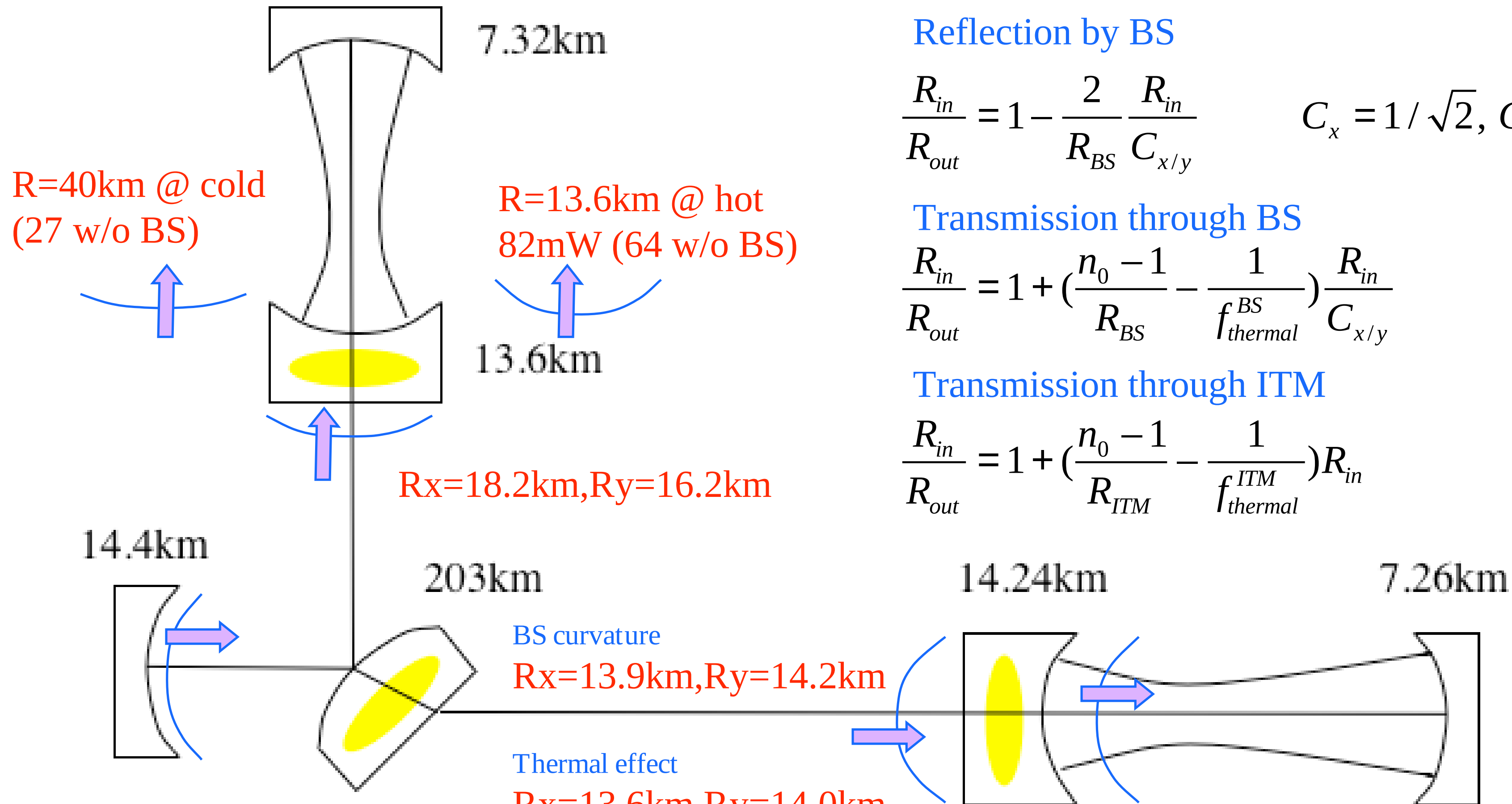
curvature is all



Transmission through ITM

$$\frac{R_{in}}{R_{out}} = 1 + \left(\frac{n_0 - 1}{R_{ITM}} - \frac{1}{f_{thermal}^{ITM}}\right) R_{in}$$

Mode matching with BS



Reflection by BS

$$\frac{R_{in}}{R_{out}} = 1 - \frac{2}{R_{BS}} \frac{R_{in}}{C_{x/y}} \qquad C_x = 1/\sqrt{2},\ C_y = \sqrt{2}$$

Transmission through BS

$$\frac{R_{in}}{R_{out}} = 1 + \left(\frac{n_0 - 1}{R_{BS}} - \frac{1}{f^{BS}_{thermal}}\right)\frac{R_{in}}{C_{x/y}}$$

Transmission through ITM

$$\frac{R_{in}}{R_{out}} = 1 + \left(\frac{n_0 - 1}{R_{ITM}} - \frac{1}{f^{ITM}_{thermal}}\right) R_{in}$$

$$\frac{1}{f^{BS}_{thermal}} = \frac{1}{2}\frac{1}{2}\frac{4}{10}\frac{1}{f^{ITM}_{thermal}(hot)}$$

R=14.24km @ hot
52mW (54 w/o BS)
only BS effect

3 IFOs
based on pure lens calculation

power in mW

	without BS curvature P(ITMx) / P(ITMy)	with BS curvature P(ITMx) / P(ITMy)
LHO2k	67 / 73	57 / 110
LHO4k	54 / 64	52 / 82
LLO4k	59 / 62	55 / 83

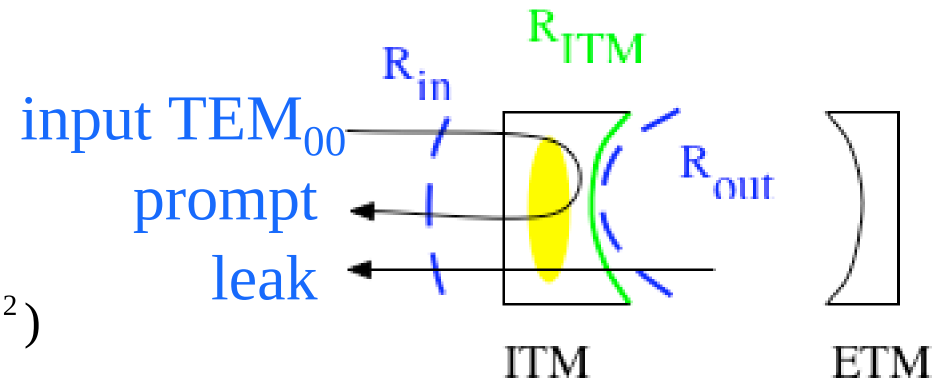
Effects of mode matching in PRM

- Carrier field is insensitive to thermal state of ITMs and BS
- Michelson cavity can induce imbalance of upper and lower sidebands
- Mismatch on ITMx (ITMy) enhances upper (lower) SB

Reflection by arm cavity with curvature mismatch

$$\alpha = \frac{z}{z_0}\left(1 - \frac{R_{ITM}}{R_{out}}\right)$$

E_{mn} is the mode in PRC which couples to the arm when α=0

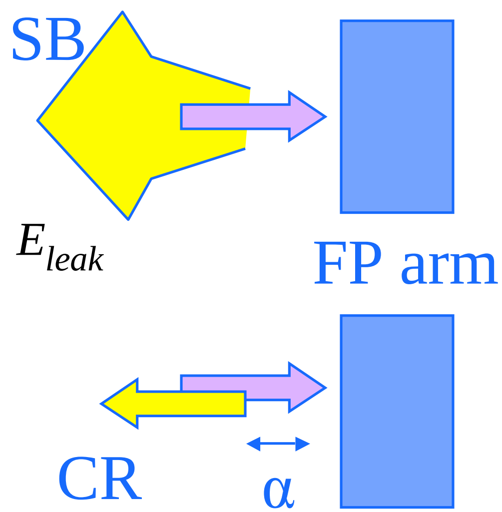


$$E_{SB} = \frac{1}{1+i\alpha}E_{00} - \frac{i\alpha/\sqrt{2}}{(1+i\alpha)^3}(E_{02}+E_{20}) + O(\alpha^2)$$

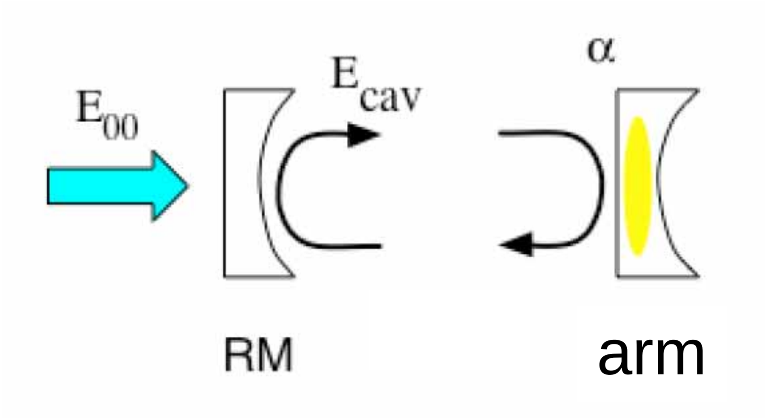
$$E_{CR} = \frac{1}{1+i\alpha}E_{00} - \frac{i\alpha/\sqrt{2}}{(1+i\alpha)^3}(E_{02}+E_{20}) + O(\alpha^2) \quad \Leftarrow E_{prompt}$$

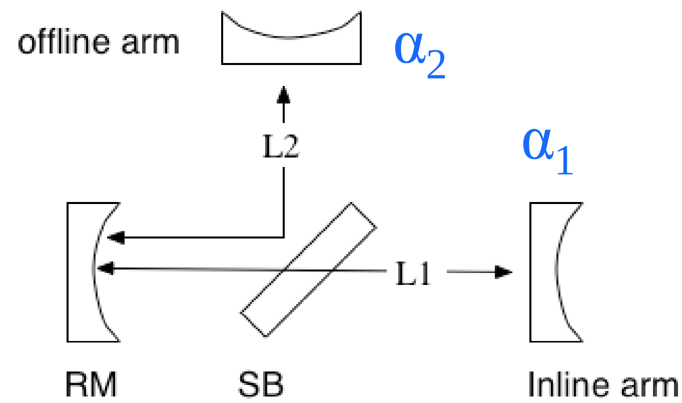
$$-2\frac{1}{1+i\alpha/2}\left(\frac{1}{1+i\alpha/2}E_{00} - \frac{i\alpha/2/\sqrt{2}}{(1+i\alpha/2)^3}(E_{02}+E_{20}) + O(\alpha^2)\right) \quad \Leftarrow E_{leak}$$

$$= -\frac{1}{1+i\alpha}E_{00} + O(\alpha^2)$$



Sideband imbalance in curvature mismatched FPs





$$E_{cav} = \sum_{m,n} \frac{C_{mn}(\alpha) \cdot HG_{mn}}{1 - r_{RM} \cdot \exp(i\phi)}$$

$$\phi_{CR,00} = -2k_{CR}L + 2\eta_{00} - \arctan(\alpha)$$

$$\phi_{SB}(k_{SB}L) = \phi_{CR,00} - 2k_{SB}L + \delta\phi(\alpha,\eta)$$

$$\phi_{SB}(k_{SB}L,\alpha) \neq \phi_{SB}(-k_{SB}L,\alpha)$$

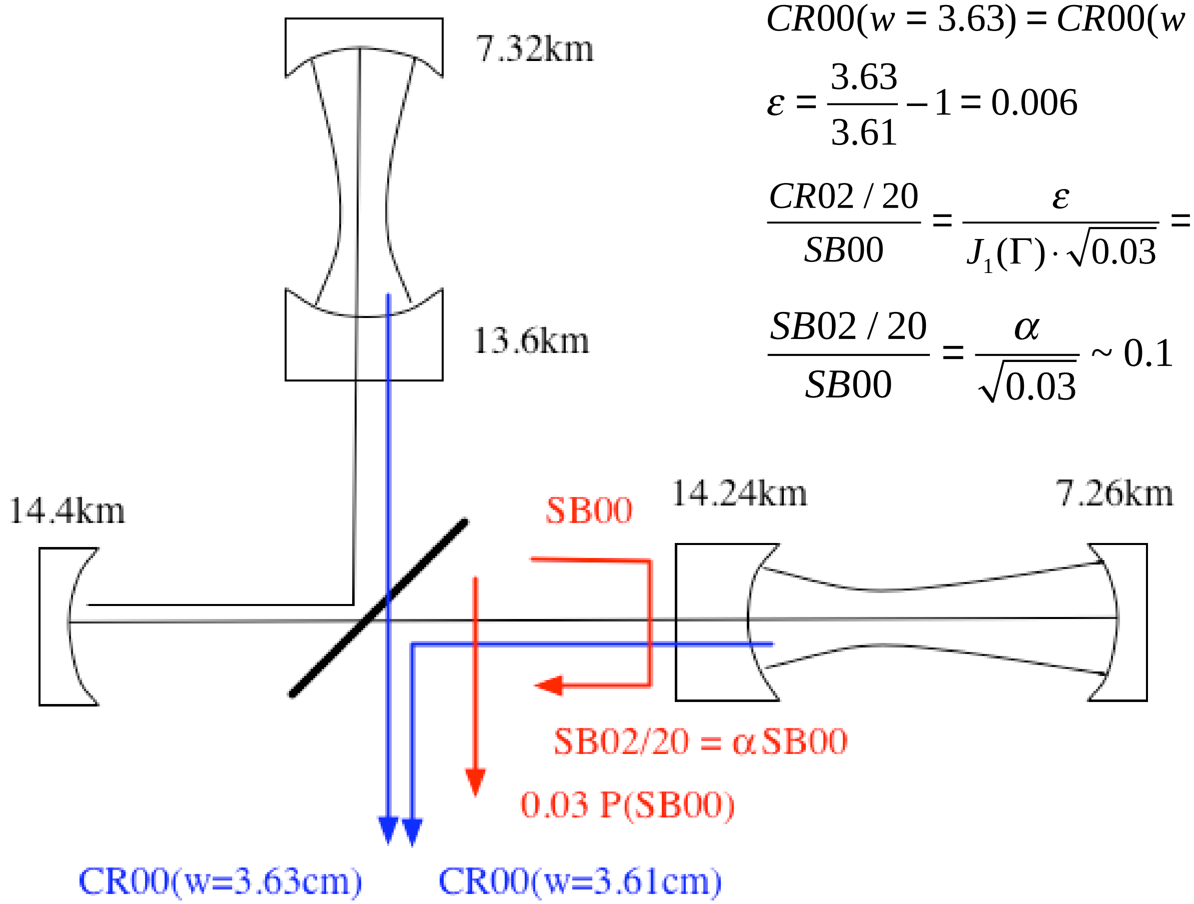
$$P(k_{SB}L,\alpha) \neq P(-k_{SB}L,\alpha)$$

$$k_{SB}L_1 = -k_{SB}L_2 = \frac{\pi \cdot \delta L_{syn}}{\lambda_{SB}}$$

$$P(k_{SB}L_1,\alpha_1) = P(-k_{SB}L_2,\alpha_1)$$

$$P(k_{SB}L_1,\alpha_1) + P(k_{SB}L_2,\alpha_2)$$
$$= P(-k_{SB}L_1,\alpha_2) + P(-k_{SB}L_2,\alpha_1)$$

modes in the dark port
- back on the envelope -



$$CR00(w = 3.63) = CR00(w = 3.61) + \varepsilon \cdot CR02/20(w = 3.63)$$

$$\varepsilon = \frac{3.63}{3.61} - 1 = 0.006$$

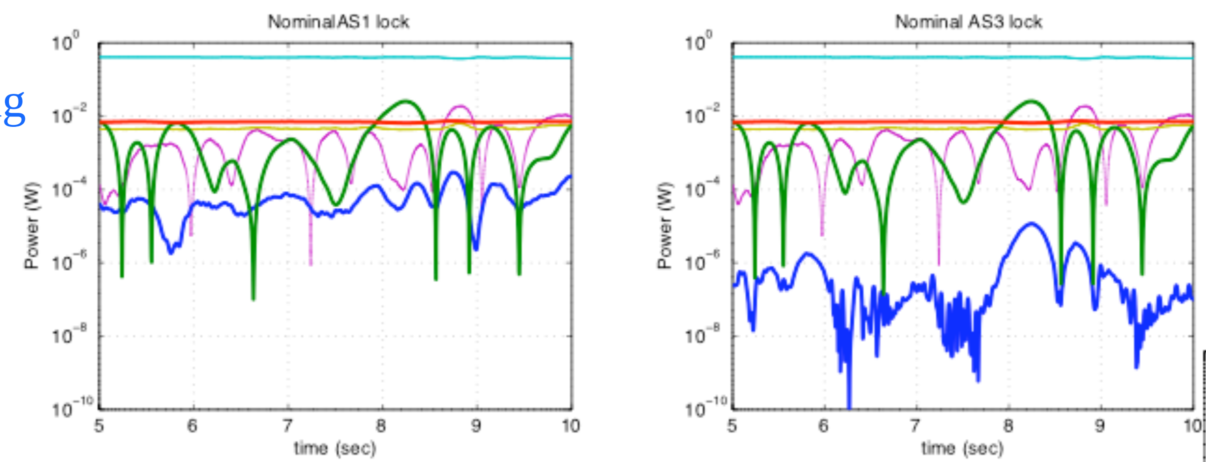
$$\frac{CR02/20}{SB00} = \frac{\varepsilon}{J_1(\Gamma)\cdot\sqrt{0.03}} = 0.15$$

$$\frac{SB02/20}{SB00} = \frac{\alpha}{\sqrt{0.03}} \sim 0.1$$

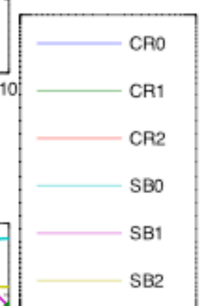
modes in the dark port

- e2e simulation -

common heating
α~0.01
use dark port
signal to lock

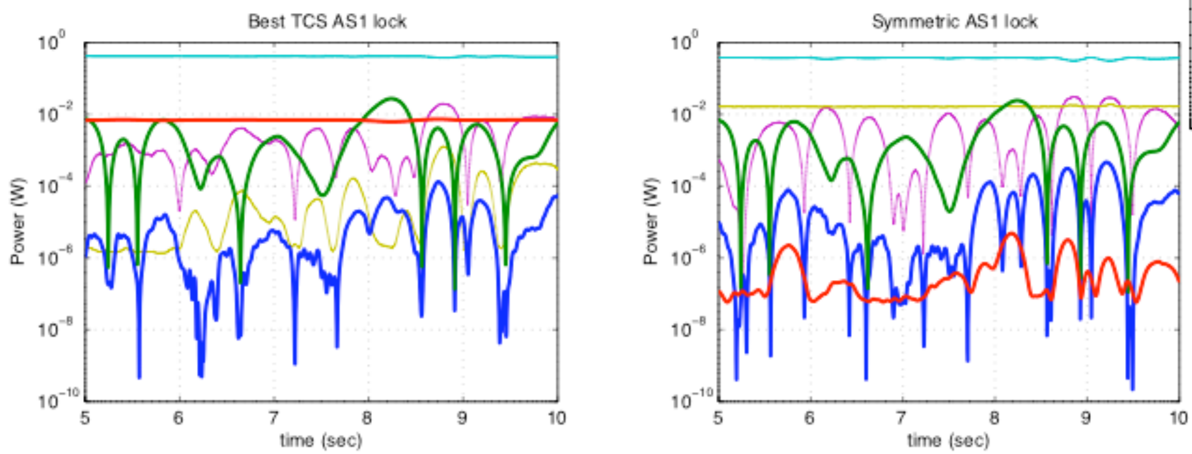


common heating
α~0.01
use OMC output
signal to lock



time evolution of powers of various modes

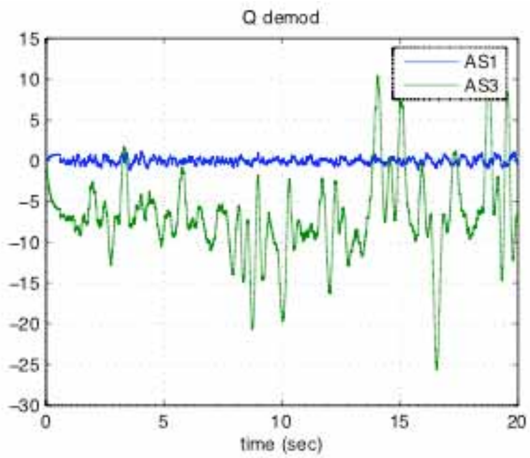
differential
heating
α~0
use dark port
signal to lock

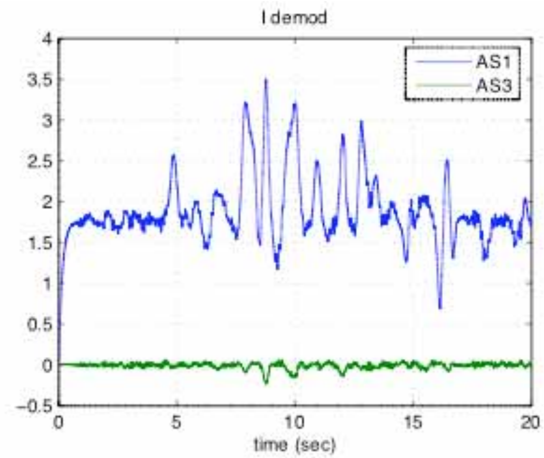


Symmetric arm
common heating
α~0.01
dark port signal

OMC and ASQ and ASI
(1) nominal matching

use dark port signal to lock common heating α~0.01



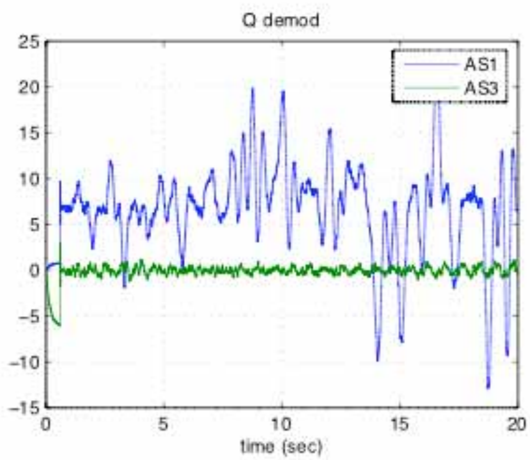


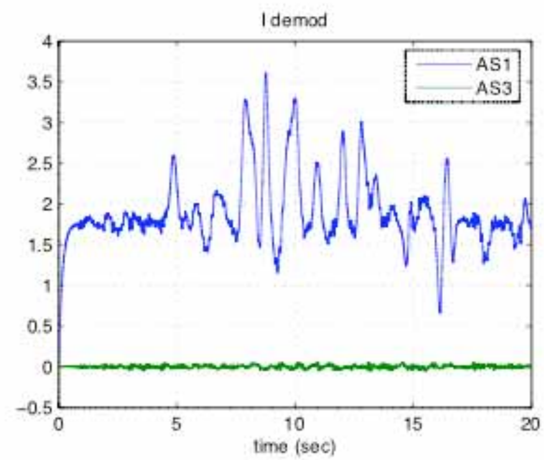
Q-demod

I-demod

AS1: dark port
AS3: OMC output

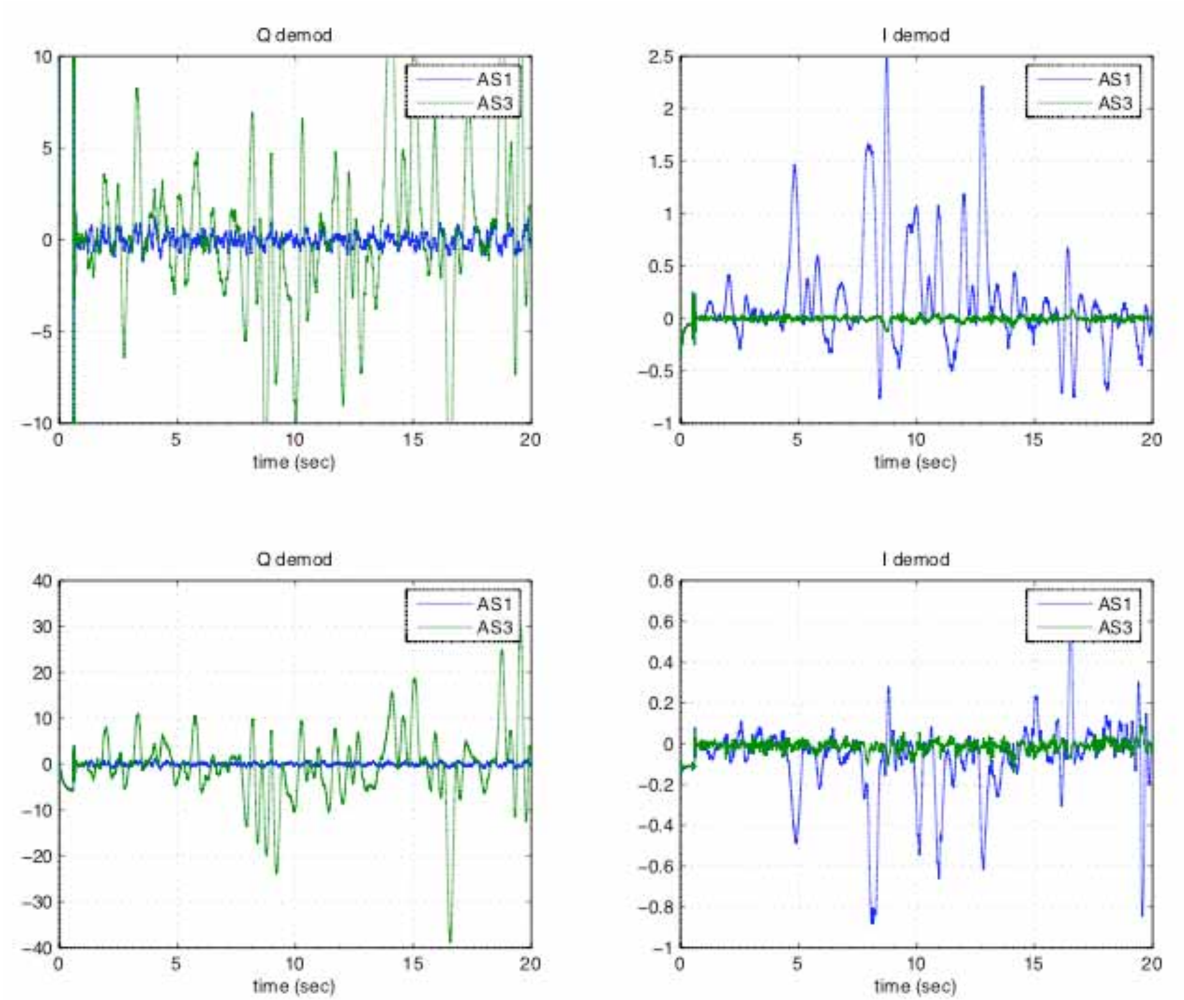
use OMC output signal to lock common heating α~0.01





OMC and ASQ and ASI
(2) better matching

differential
heating
α~0
use dark port
signal to lock



Symmetric arm
common heating
α~0.01
dark port signal

Effect on length DOF