Core Optics related loss hierarchy of aLIGO

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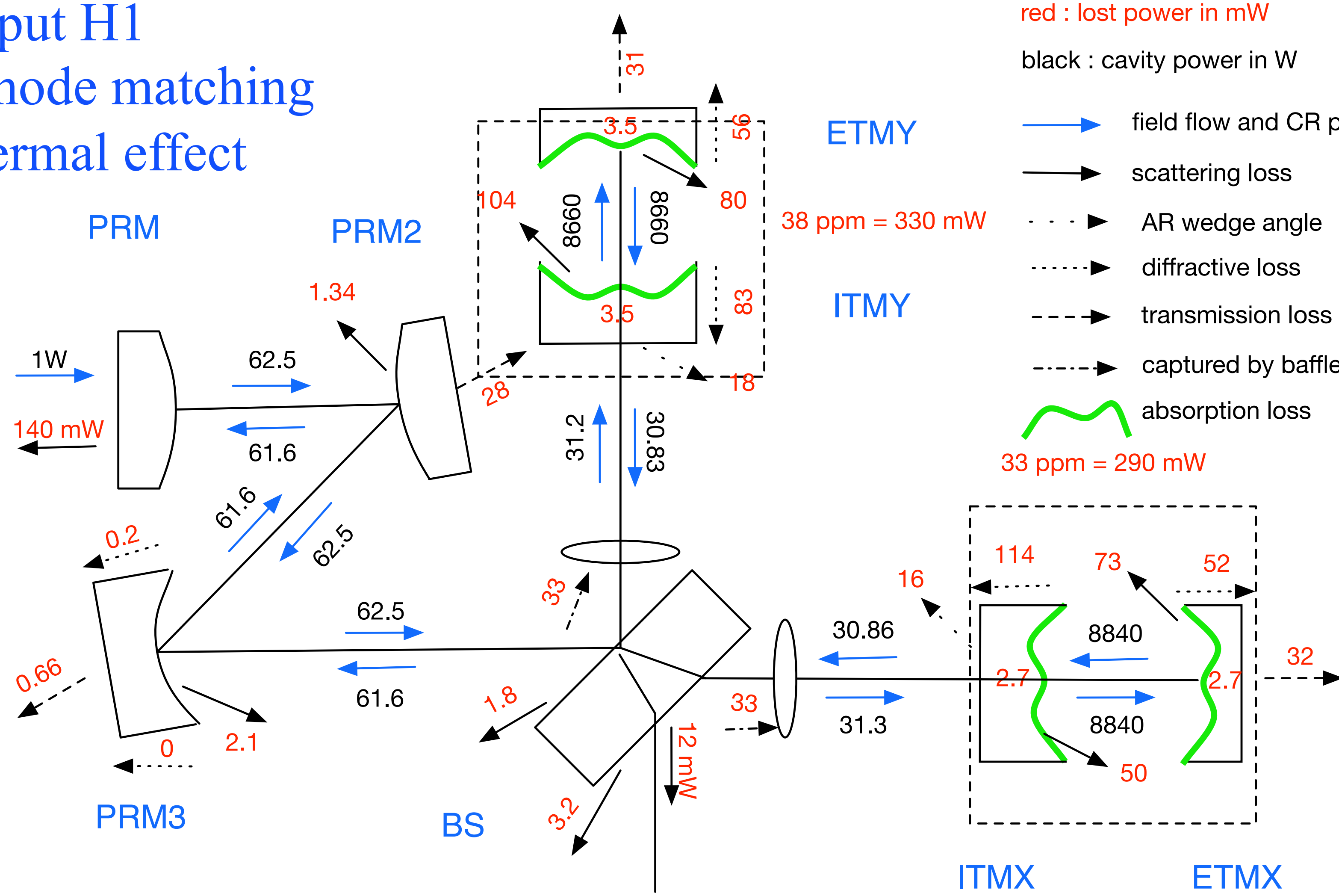
- Introduction
- Loss related to geometry
- Loss related to as-built arms
- Loss related to aberrations
- Loss related to thermal deformations
- Summary

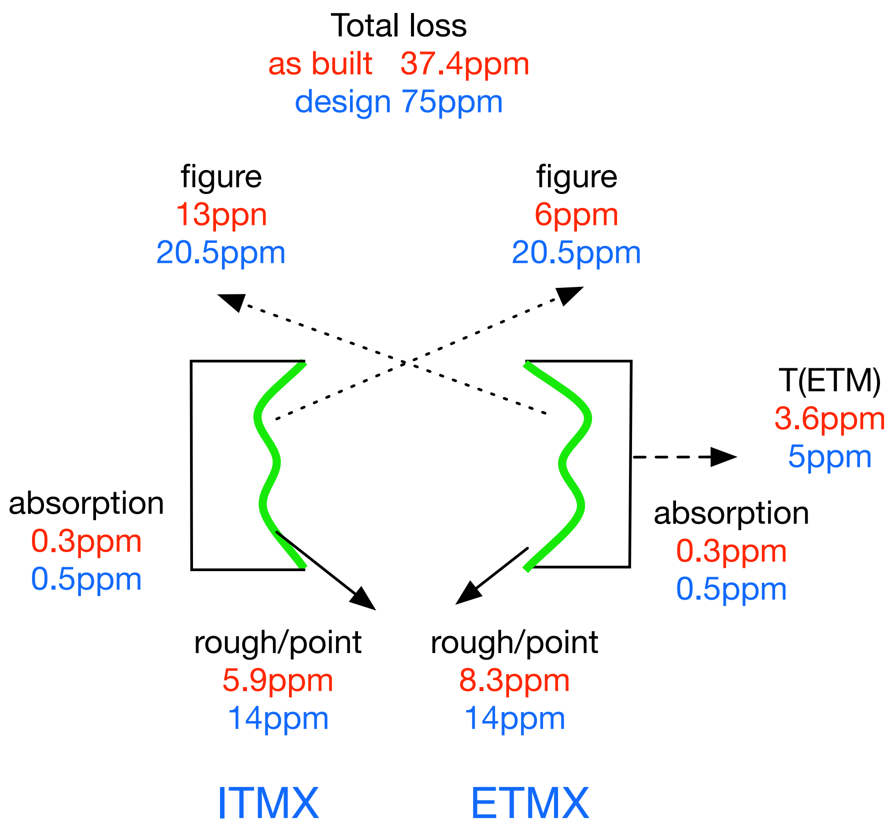
Energy conservation or where the CR power goes

1W input H1
Max mode matching
No thermal effect

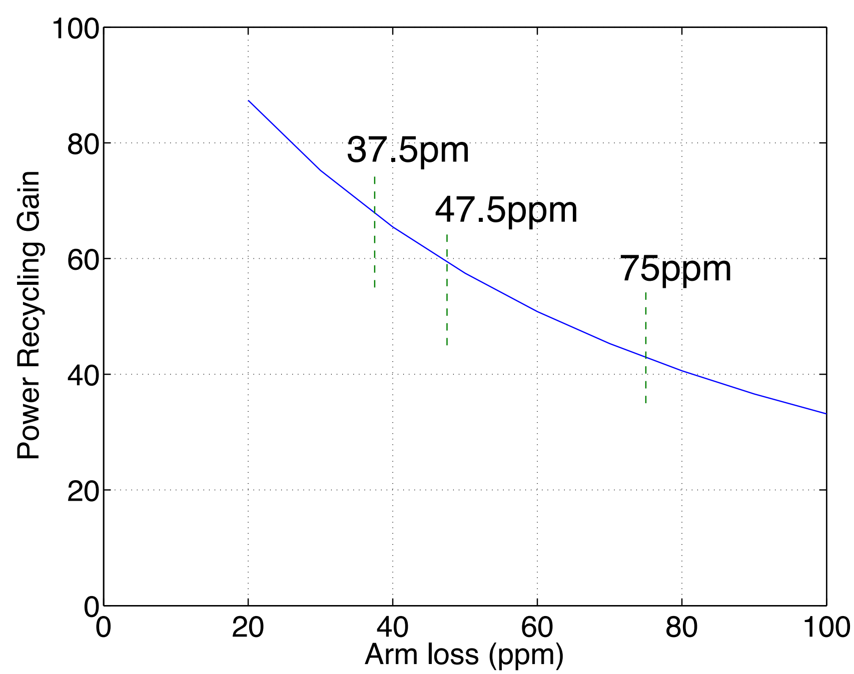


Arm loss
designed vs as-built

Loss in arm : as-built vs design



Power Recycling Gain vs Arm loss

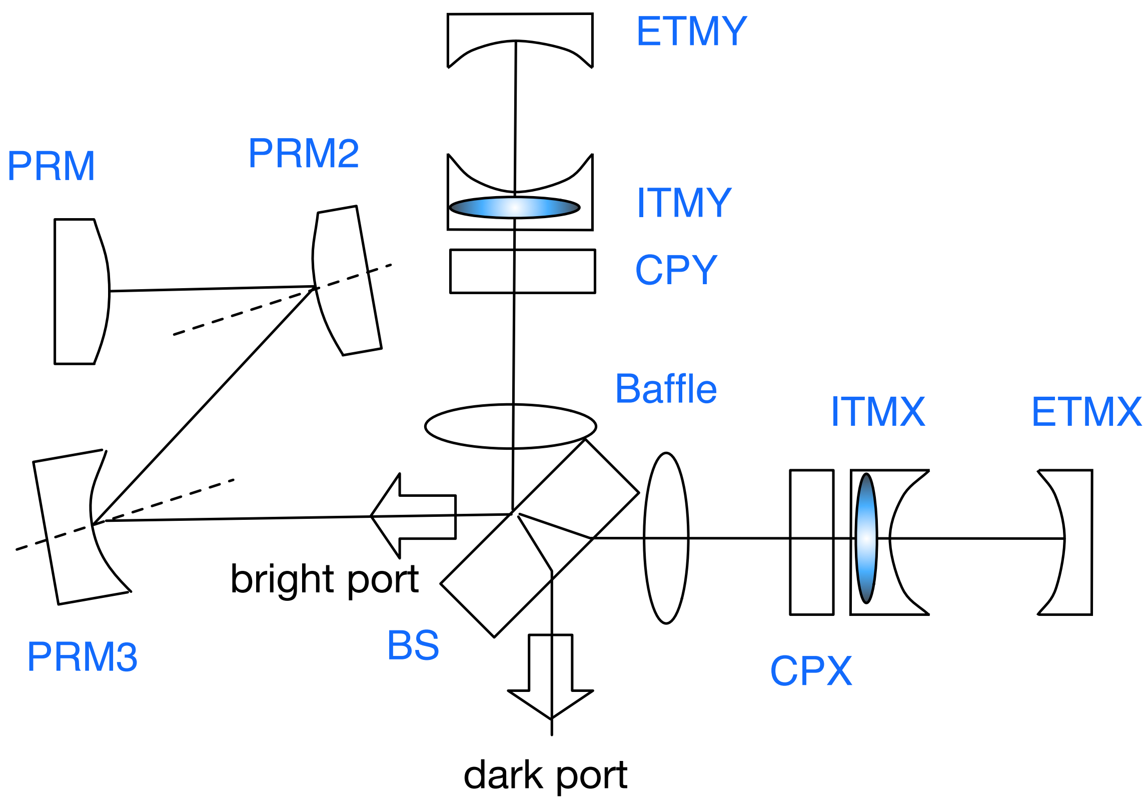


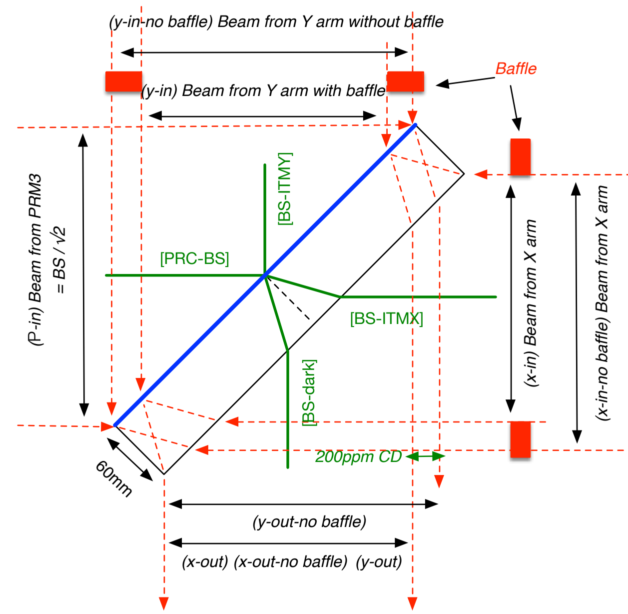
Introduction

now that almost all COCs have been delivered and measured

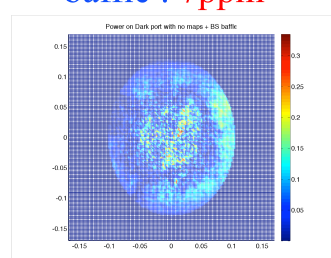
- Purpose of the talk
  - » Understanding the fundamental limitation by COC
- Optics data
  - » Use as built / measured RoC, maps, losses
  - » https://galaxy.ligo.caltech.edu/optics/ and links from this URL
- Simulation tool used
  - » FOGPrime13
    - FFT-based IFO simulation using matlab
    - Modular design to build FP ~ full aLIGO by adding optics and propagators
    - Easy integration with real data files and other matlab tools like COMSOL

Loss related to geometry

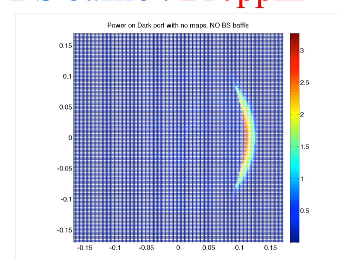




Dark port with BS baffle : 7ppm



Dark port without BS baffle : 210ppm

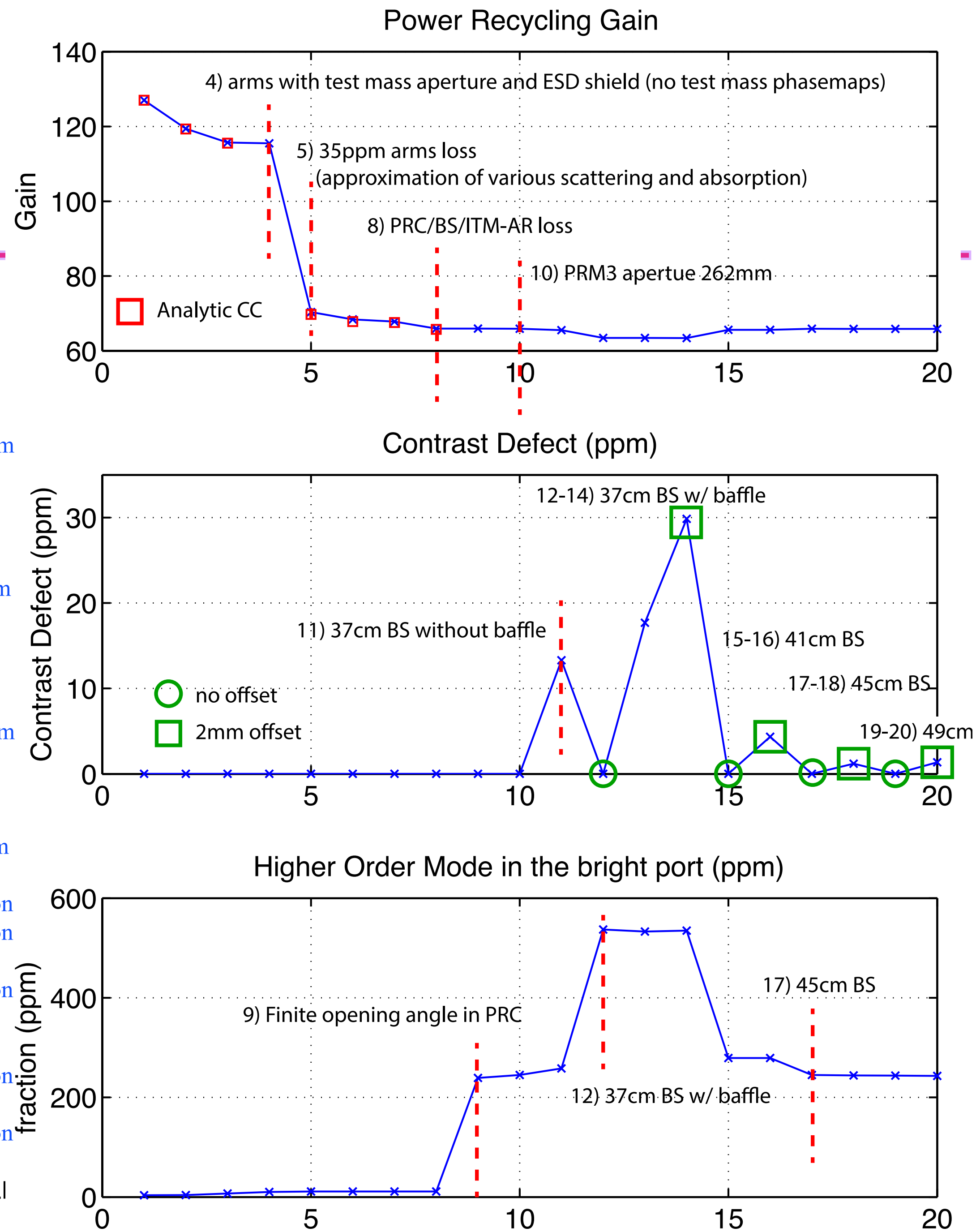


Performance limitation by geometrical design

LLO case

T1400055

1) no loss at all, with large mirrors. A finite HOM (3.7ppm) looks a nice gaussian so probably the base mode parameter is slightly off.
2) 1) + ETM transmittance 3.7ppm
3) 2) + test mass aperture 326mm, round trip loss by the aperture is 1.94ppm (with 340mm, RTL is 0.6ppm)
4) 3) + 266mm ESD aperture, placed using BS baffle (266mmx266mm) in front of BS
5) 4) + 35ppm arm loss
6) 5) + power recycling mirror and beam splitter loss and transmission. Sum of losses + RM2 transmission is 583ppm
7) 5) + ITM AR side loss, (ITMX loss 206ppm, ITMY loss 330ppm)
8) 5) + 6) and 7), i.e., losses and transmission in the PRC, BS and ITM AR
9) 8) + finite opening angles in PRC (0.79° for PRM2 and 0.615° for PRM3). Among the total HOM of 240ppm, major ones are HG(1,0) of 12ppm and HG(0,2) of 210ppm.
10) 9) + PRM3 aperture 262mm
11) 10) + BS 367.1mm/60mm no baffle
12) 11) + BS baffle (210mmx260mm). Total HOM goes up to 540ppm from 260ppm by clipping using BF baffle. The major is HG(4,0) of 170ppm.
13) 12) with BS baffle facing to X arm offset by *1mm* in horizontal direction
14) 12) with BS baffle facing to X arm offset by *2mm* in horizontal direction
15) 10) + BS 410mm/67mm with BS baffle (237mmx260mm)
16) 15) with BS baffle facing to X arm offset by *2mm* in horizontal direction
17) 10) + BS 450mm/73.5mm with BS baffle (260mmx260mm) : no performance impact by the BS baffle
18) 17) with BS baffle facing to X arm offset by *2mm* in horizontal direction
19) 10) + BS 490mm/80mm with BS baffle (260mmx260mm)
20) 19) with BS baffle facing to X arm offset by *2mm* in horizontal direction



Hiro Yai

Arm performance
only aberrations in arms included

- Low arm loss (70 ppm design to 35-50 ppm expected)
- High power recycling gain and high arm power
- High (~0.15) reflected power
- High higher order mode content in the bright port

	LHO **TITM=1.39%,1.42%**	**LLO** **TITM=1.48%,1.48%**	**LLO (no maps)**
CD	29 ppm	48 ppm	44 ppm
PRG	63	61	74
Arm power	8800 W (1W input)	8100	9900
HOM in bright	1900	1600	520
HOM in x/y arm	95 / 114 ppm	97 / 113	38 / 62
Round trip loss	33 / 37 ppm	40 / 38	23 / 26

Noise injection by the spiral pattern on test mass coatings

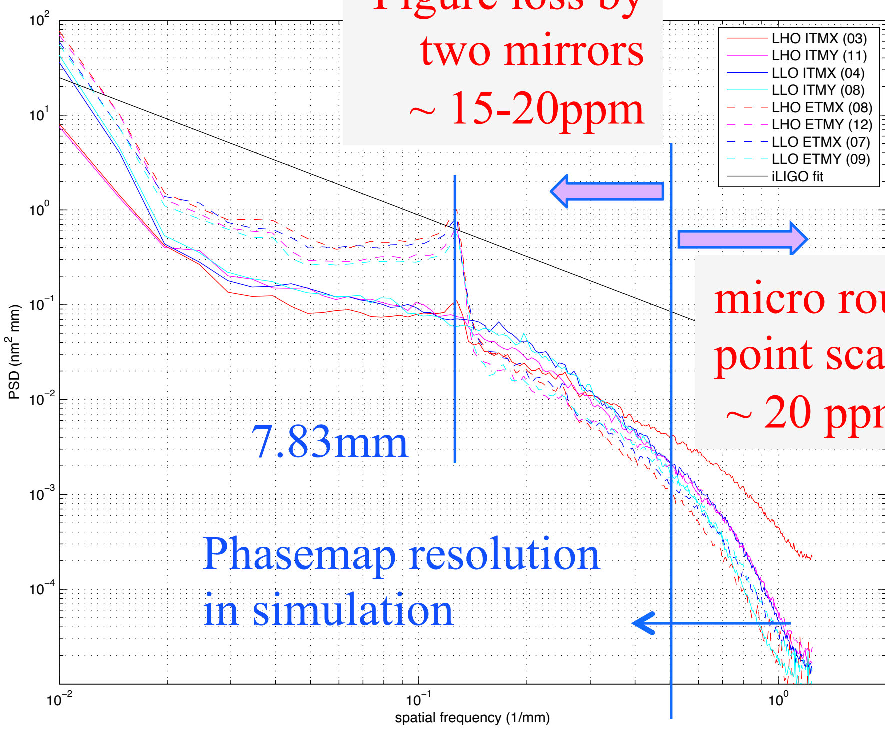
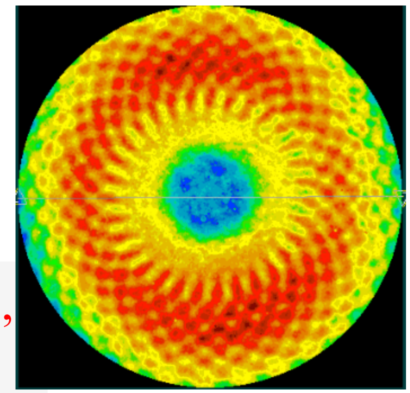


Figure loss by two mirrors ~ 15-20ppm

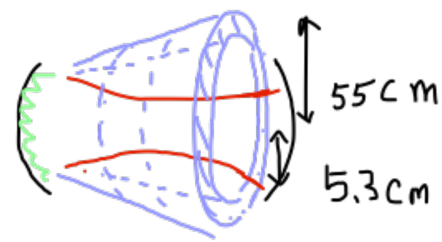
micro roughness, point scattering ~ 20 ppm

7.83mm

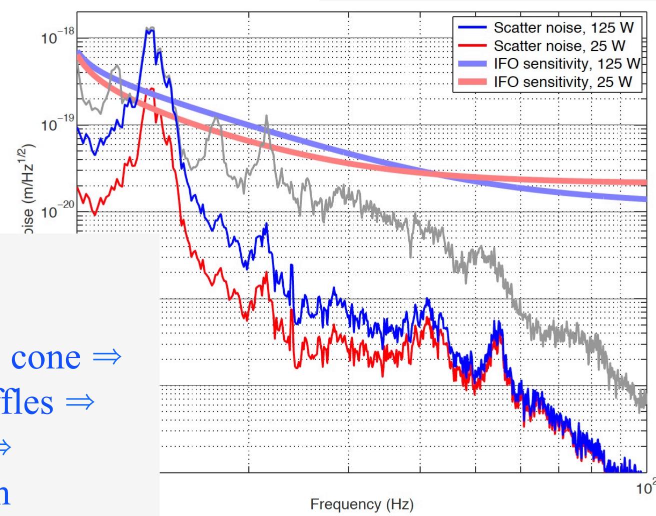
Phasemap resolution in simulation



ETM07 map

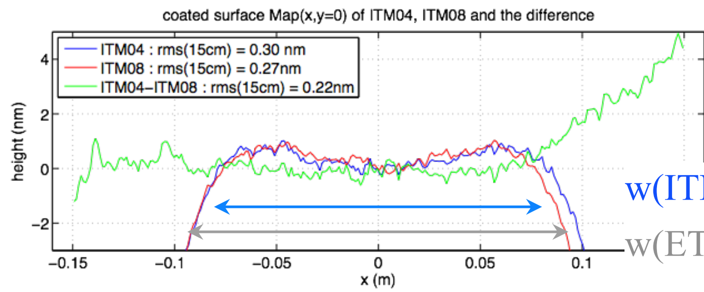


T1300354 by PF,HY



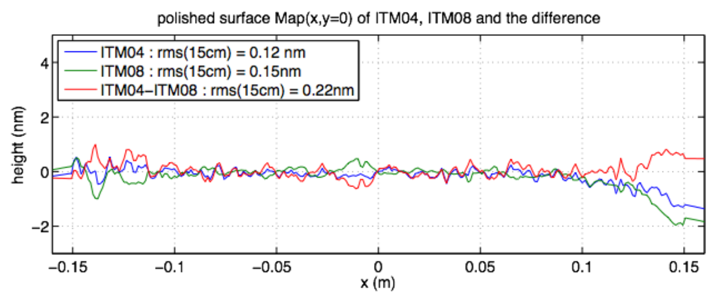
main beam ⇒
ETM reflection ⇒
larger angle scattering into cone ⇒
reflected by beam tube baffles ⇒
back scattered into ETM ⇒
merged into the main beam

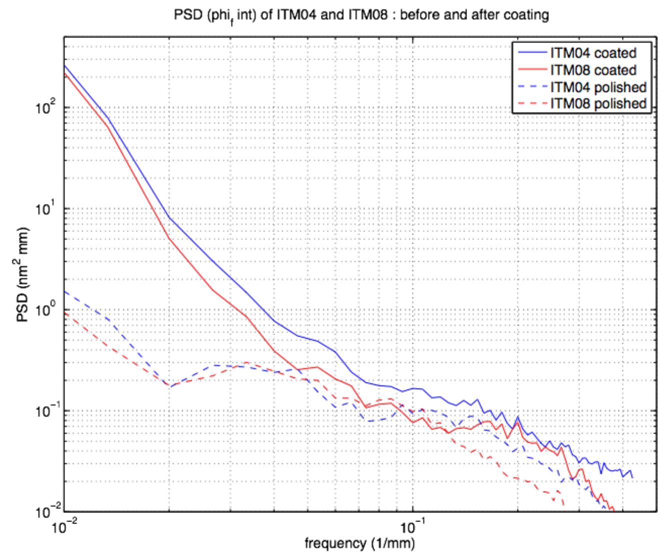
Higher order mode due to imperfect test mass coating figures

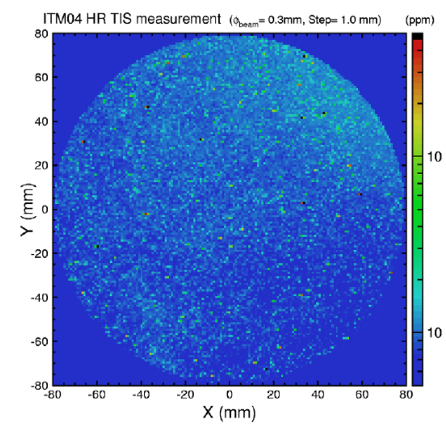


w(ITM)x1.5 : good

w(ETM)x1.5 : NG







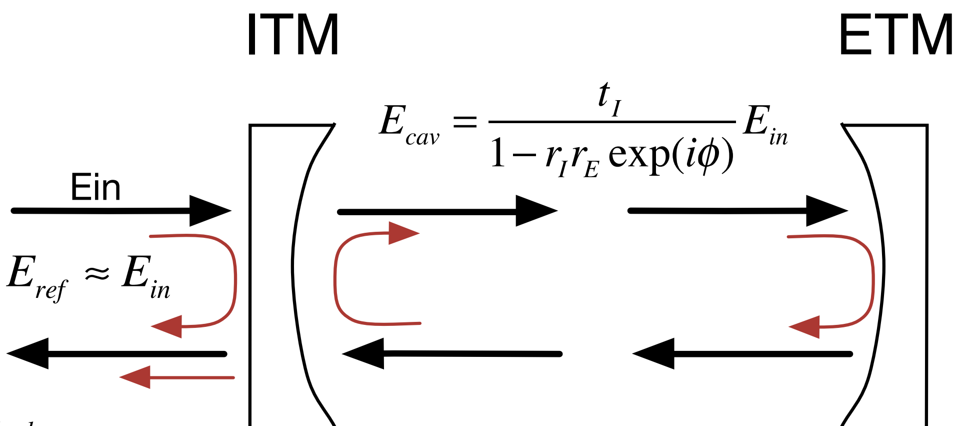
Caltech : 10ppm

LMA : 4.5ppm

		Round trip loss (ppm)	Non 00 mode in cavity (ppm)	LG20 mode in cavity (ppm)
polished	ITM04	2.9	3.2	0
	ITM08	3.0	3.5	0
coated	ITM04	2.7	8.8	2.8
	ITM08	3.0	9.0	4.9

Table 1 Cavity quality factors

The sign flip basic



$$E_{cav} = \frac{t_I}{1 - r_I r_E \exp(i\phi)} E_{in}$$

$$E_{ref} \approx E_{in}$$

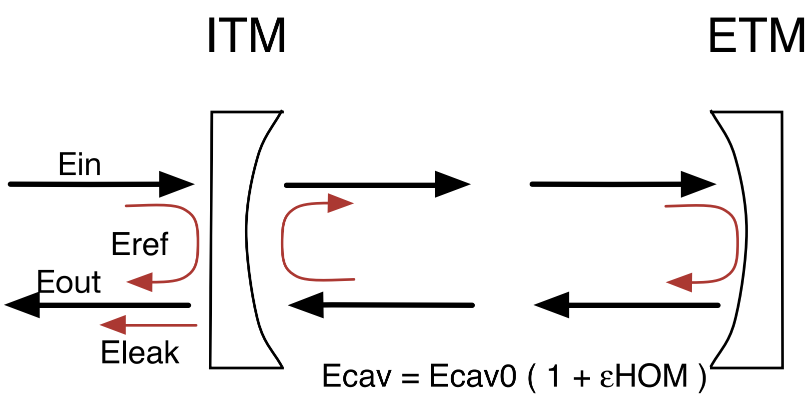
$$E_{out} = E_{ref} + E_{leak}$$

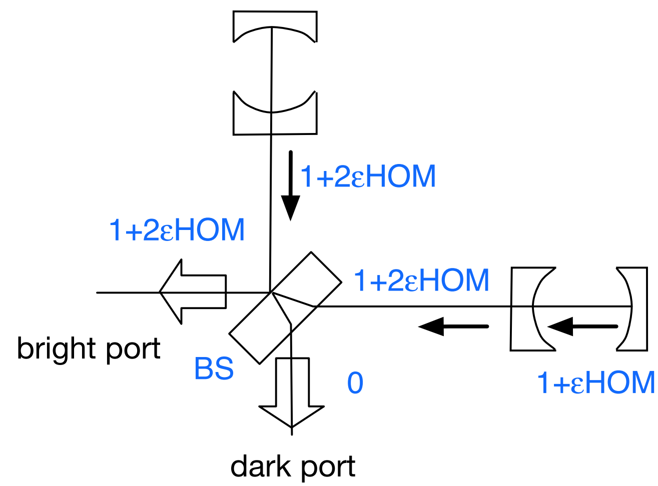
$$= \left\{ \begin{matrix} -1 \\ 1 \end{matrix} \right\} E_{in} \qquad E_{leak} = \left\{ \begin{matrix} -2 \\ t_I^2 / 2 \end{matrix} \right\} Ein$$

field resonant in cavity

field non-resonant in cavity

HOM amplification





$$Eref = Ein$$

$$Eleak = -2Ein(1+\varepsilon HOM)$$

$$Eout = -Ein(1+2\varepsilon HOM)$$

$$HOM(arm) = \varepsilon HOM^2$$

$$HOM(bright) = 4\varepsilon HOM^2$$

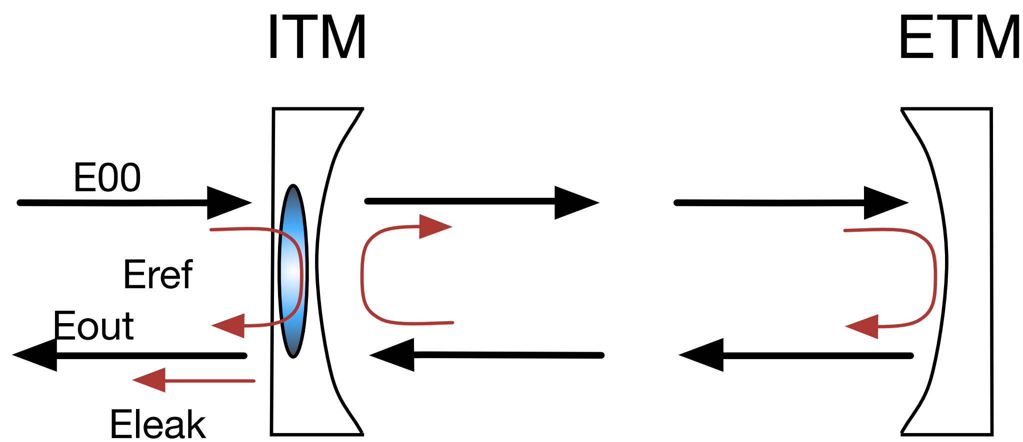
$$HOM(dark) = 0$$

Higher order mode power fraction (H1)

	ITMX	ITMY	BS bright
LG10	26	43	83
LG20	40	38	890
LG30	7.8	9.9	47

ITM lens
some sees, some not

- CR (Eout) : don’t see
- SB (Eref) : see
- Signal SB (Eleak) : see

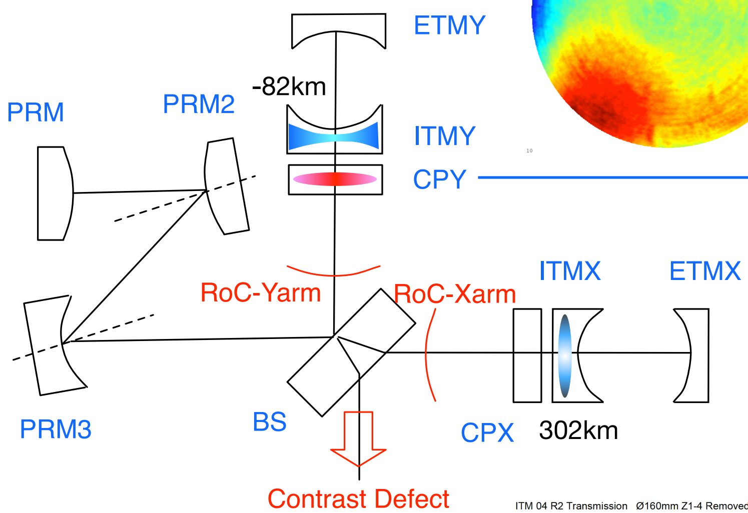


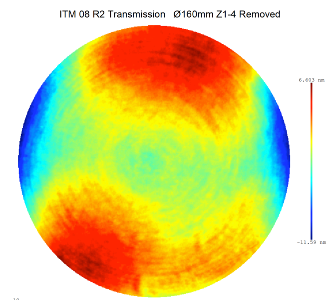
$$E_{ref} \approx \exp(i2\phi)E_{00}$$

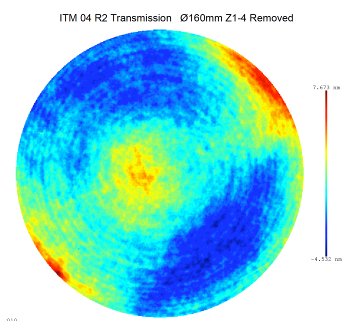
$$E_{leak} = \exp(i\phi)\begin{Bmatrix} -2 \\ 0 \end{Bmatrix} Ein$$

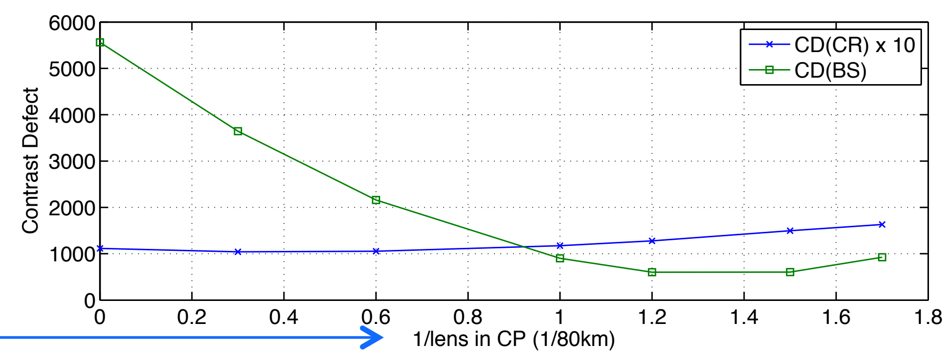
$$E_{tot} = \begin{Bmatrix} \exp(2i\phi) \\ \exp(i2\phi) \end{Bmatrix} E_{00} + \begin{Bmatrix} -2\exp(i\phi) \\ 0 \end{Bmatrix} E_{00} \approx \begin{Bmatrix} -1+O(\phi^2) \\ 1+i2\phi \end{Bmatrix} E_{00}$$

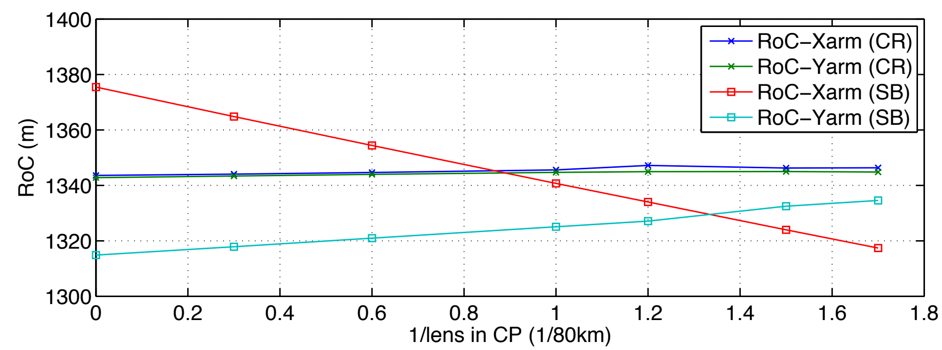
(In)Sensitivity on ITM SPTWE + CP lens



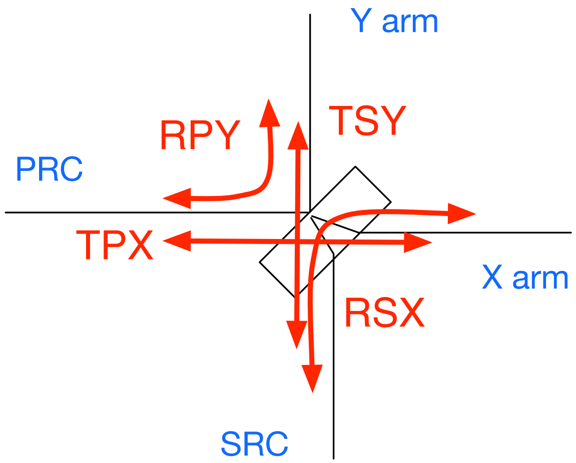


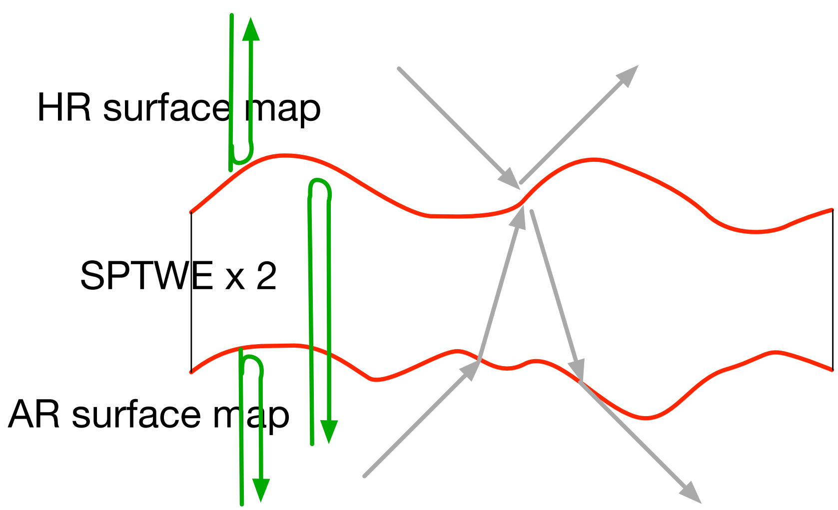


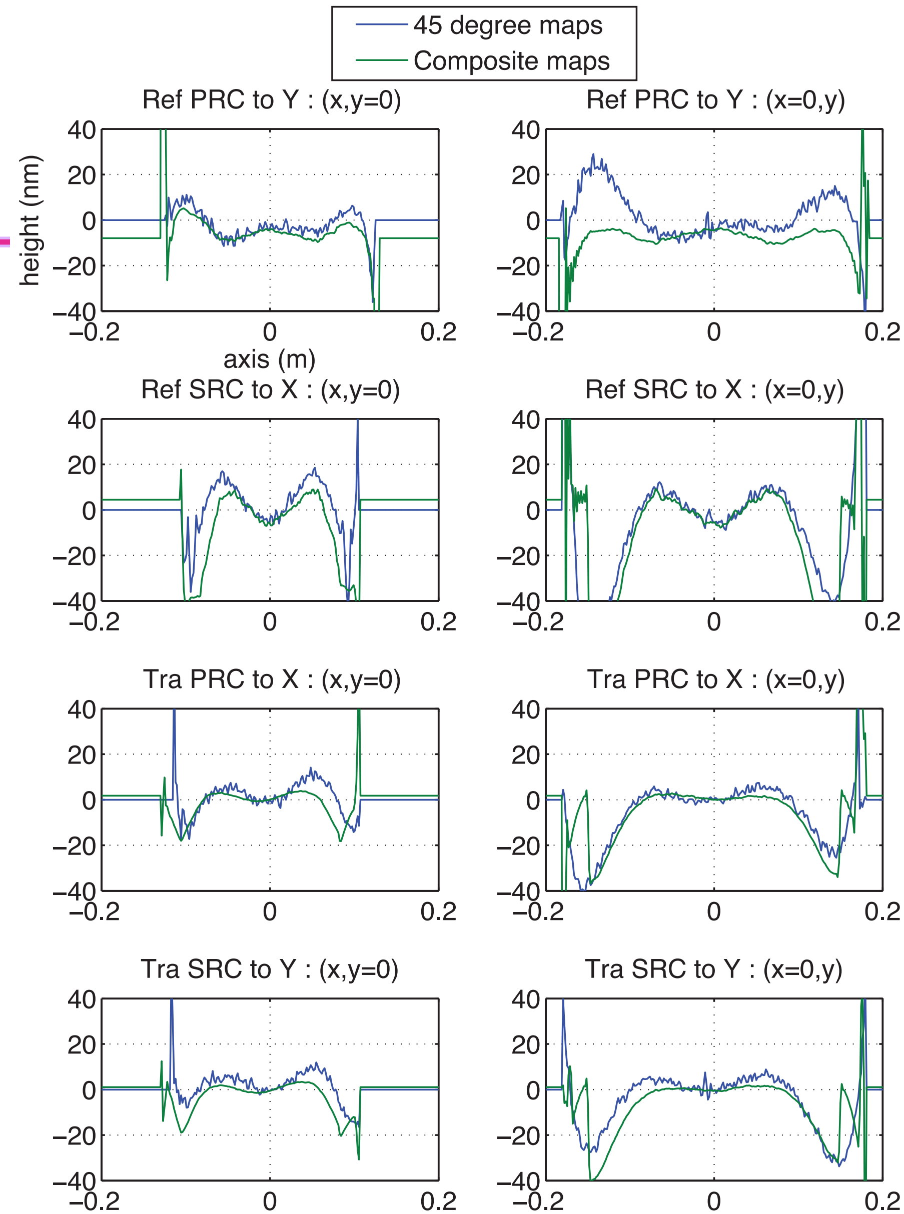




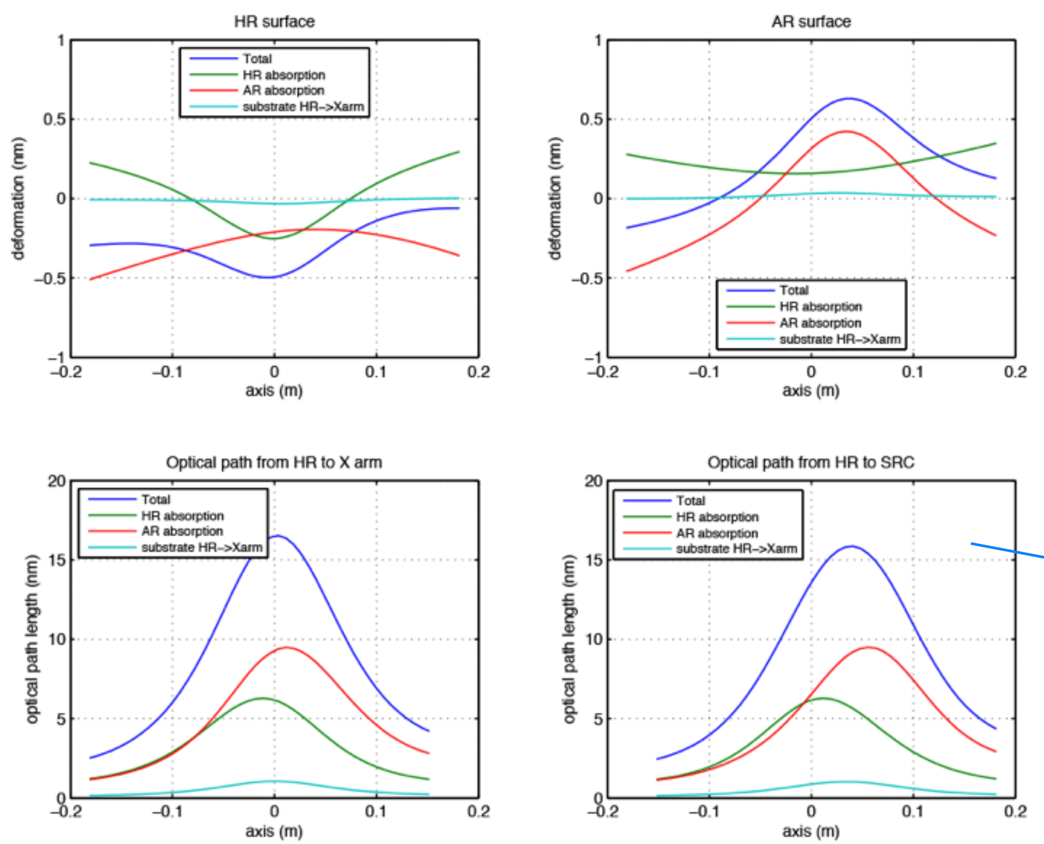
LIGO BS, not quite well measured

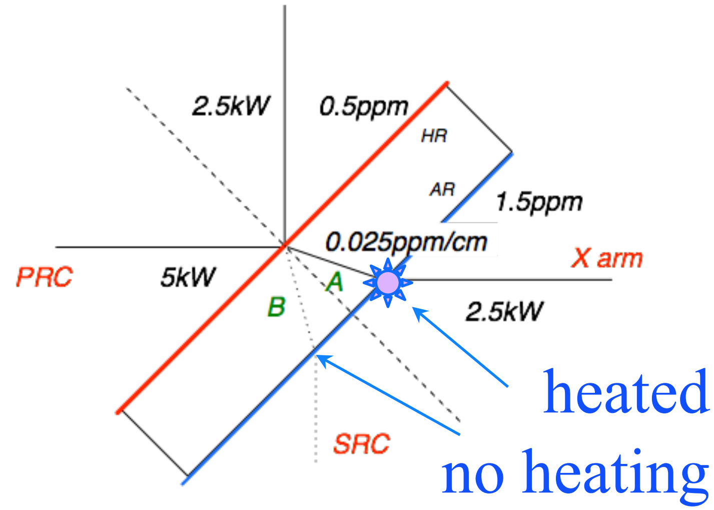


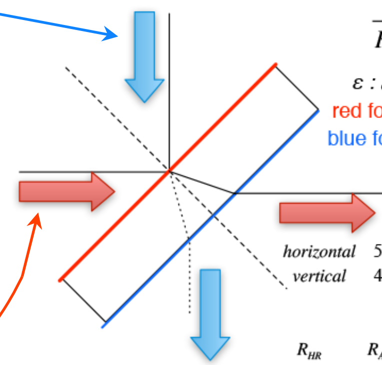




BS Thermal distortion







$$\frac{1}{R_{BS}} = \frac{\varepsilon_{HR}}{R_{HR}} + \frac{\varepsilon_{AR}}{R_{AR}}$$

ε : absorption of coating in ppm

red for ε_{HR}=0.5ppm, ε_{AR}=1.5ppm

blue for ε_{HR}=0.5ppm, ε_{AR}=1.8ppm

	R_{HR}	R_{AR}	R_{BS}	
horizontal	500km	1000km	400km	360km
vertical	420km	870km	340km	307km

	R_{HR}	R_{AR}	R_{BS}	
horizontal	500km	5000km	770km	735km
vertical	440km	1530km	470km	430km

θ(nrad)=26 ε_{HR} + 38 ε_{AR} 70 nrad

LIGO

Summary with maps, BS and thermal

abs(ITMX)-abs(ETMX)
abs(ITMY)-abs(ETMY)

With miracle TCS

		PRC				X arm			Y arm		
		CD ppm	PRG	HOM (BS)	Refl	Power	HOM (ppm)	Round trip loss	Power	HOM (ppm)	Round trip loss
H1	BS06	190	62	1380	0.14	8840	98	33	8660	115	38
	No BS	139	63	1380	0.14	8850	98	33	8670	115	38
	BS thermal	288	50	1330	0.06	7130	98	33	6990	115	38
	0.3-0.3 0.4-0.4	7	61.7	2400	0.14	8730	81	37	8550	137	37
	0.3-0.3 0.3-0.5	23	58.7	2900	0.11	8300	81	37	8110	151	45
L1	BS05	112	61	1165	0.15	8090	98	41	8090	111	38
	No BS	64	61	980	0.15	8120	98	41	8100	110	38