Core Optics related loss hierarchy of aLIGO

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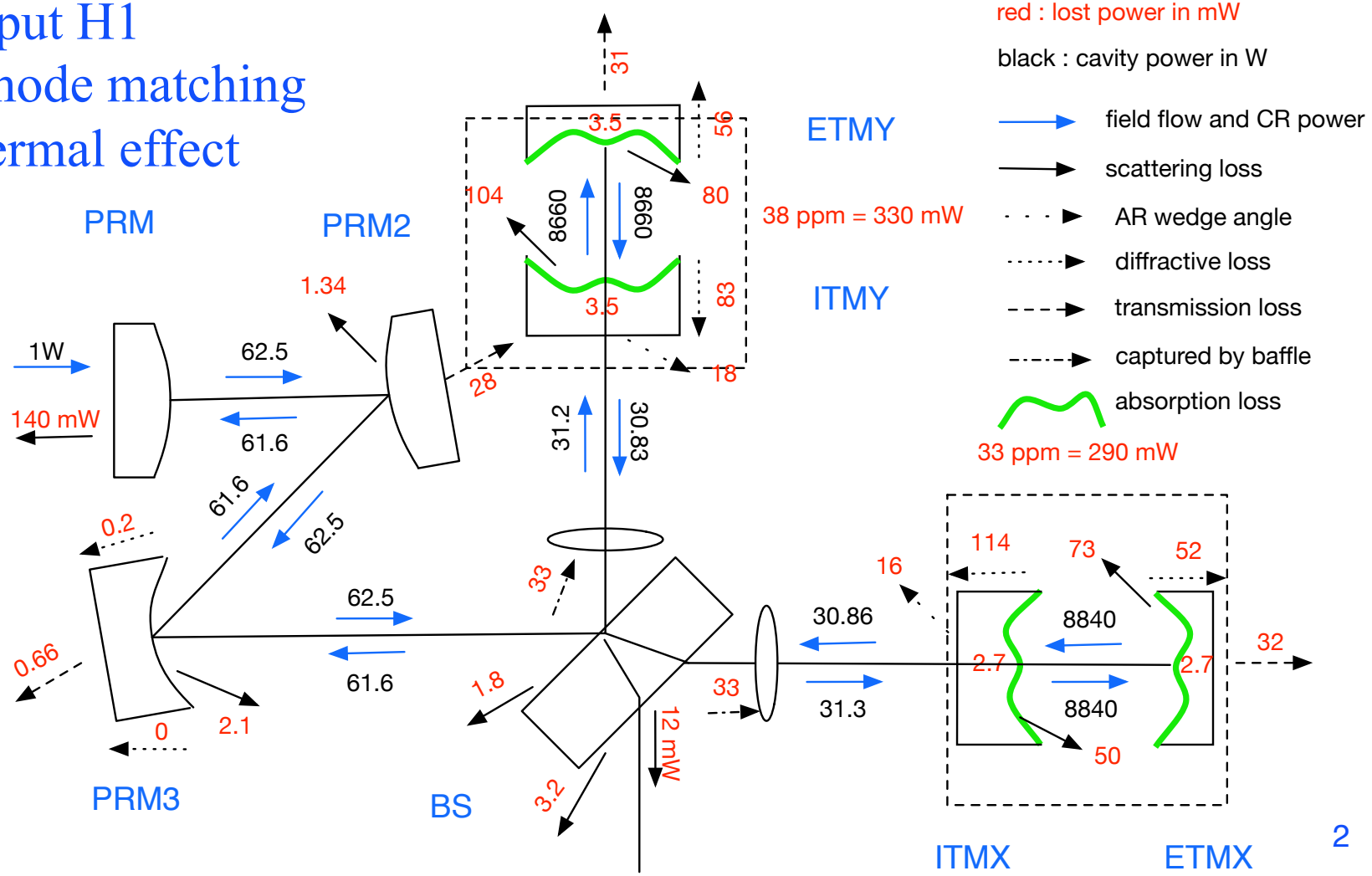
- Introduction
- Loss related to geometry
- Loss related to as-built arms
- Loss related to aberrations
- Loss related to thermal deformations
- Summary

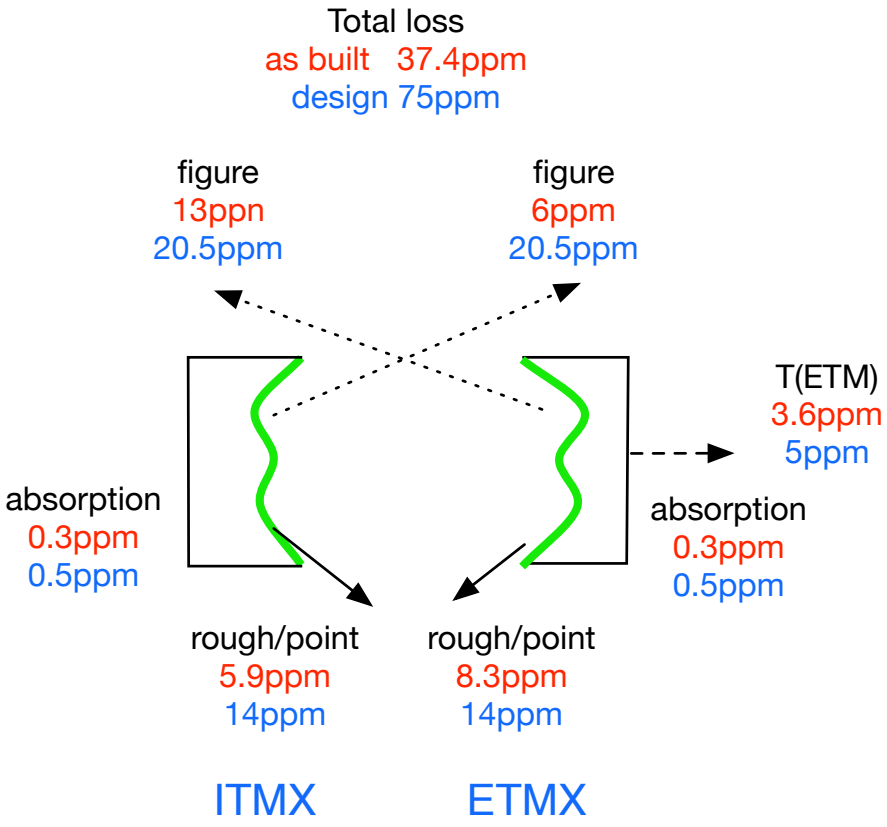
Energy conservation or where the CR power goes

1W input H1
Max mode matching
No thermal effect

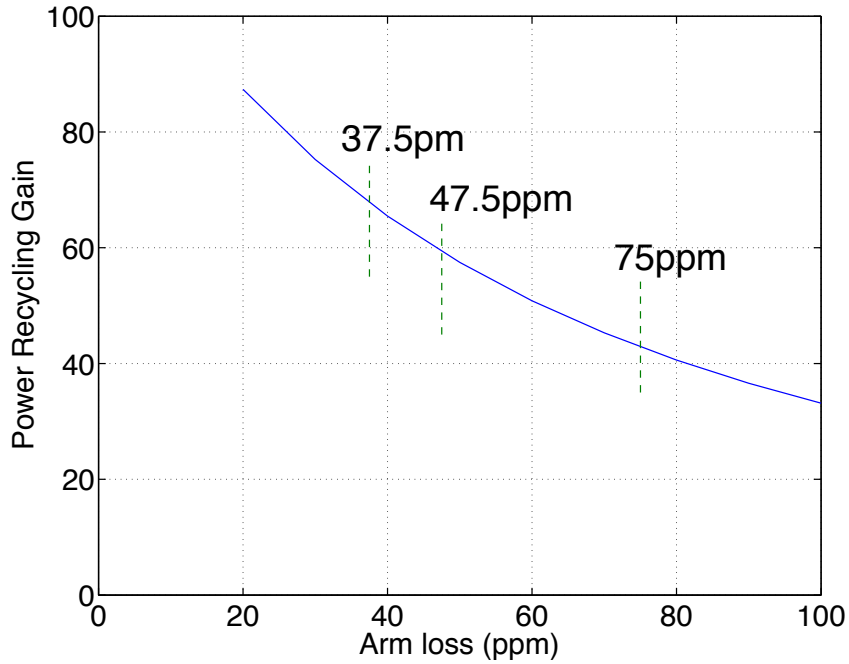


Arm loss designed vs as-built

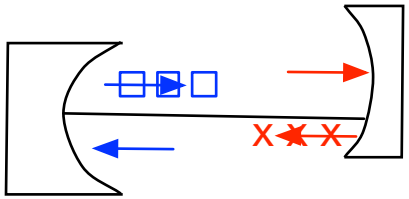
Loss in arm : as-built vs design

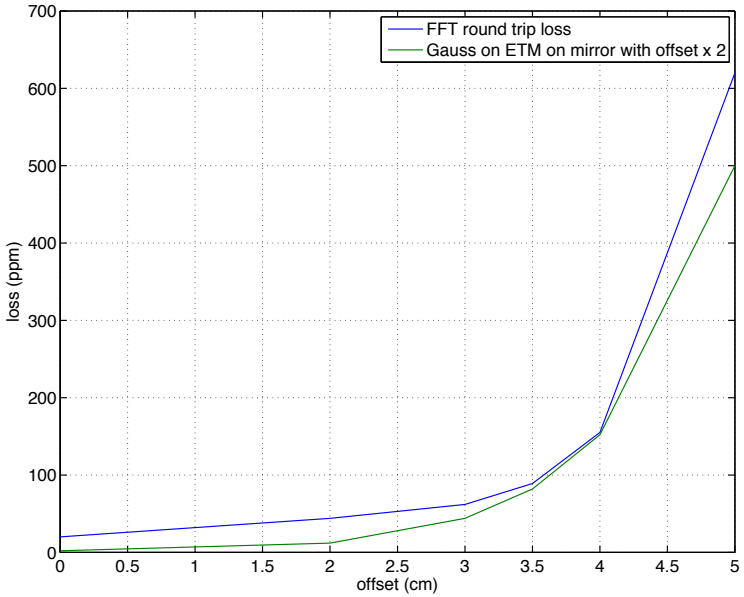


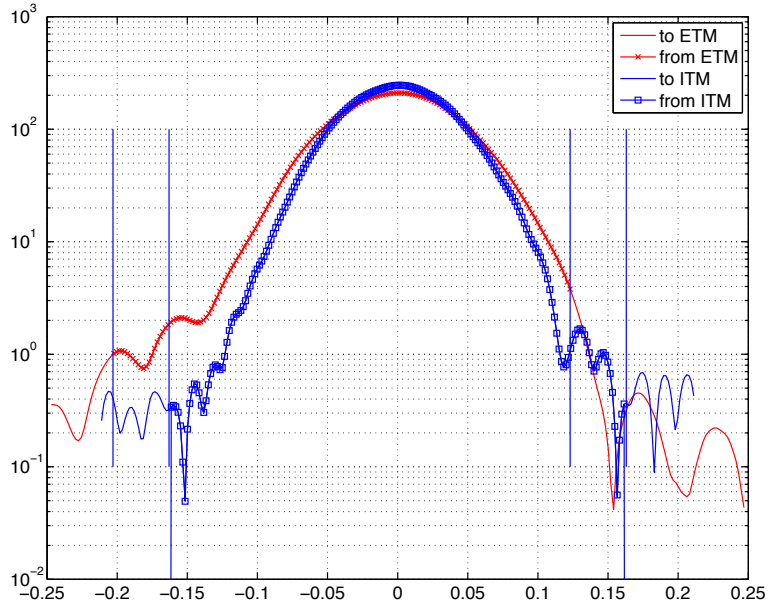
Power Recycling Gain vs Arm loss



Loss by offcentering







Introduction

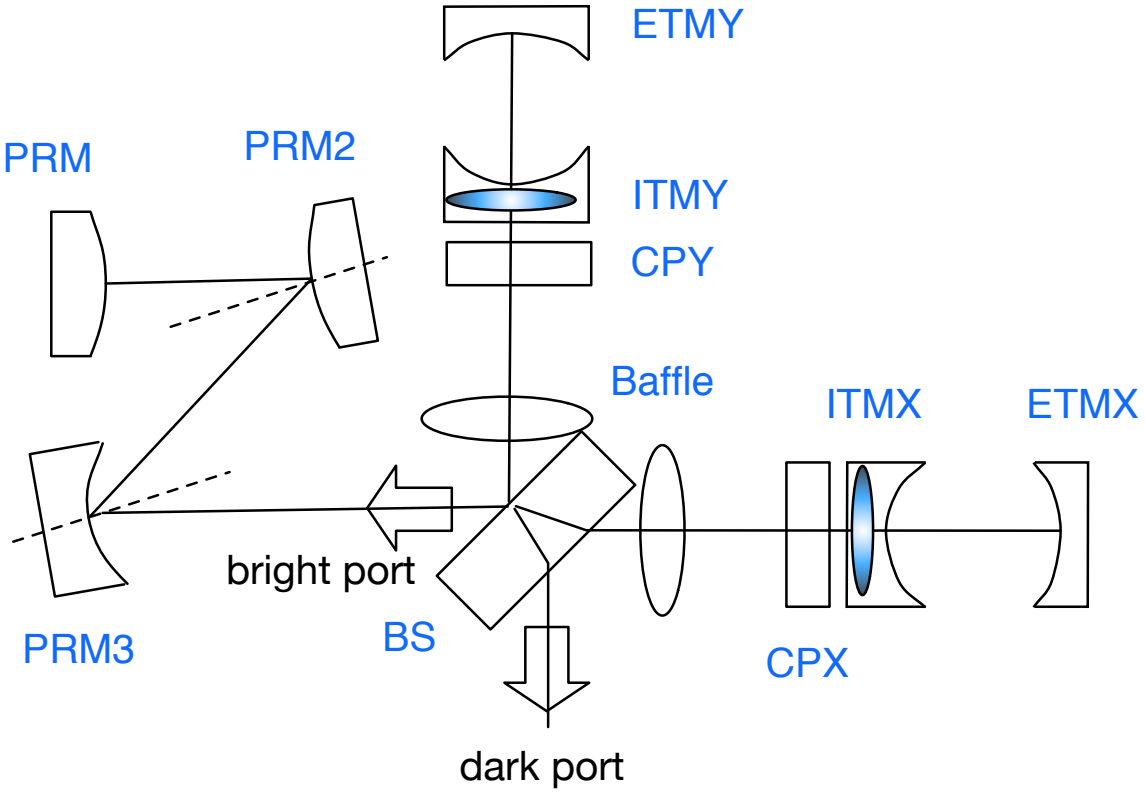
now that almost all COCs have been delivered and measured

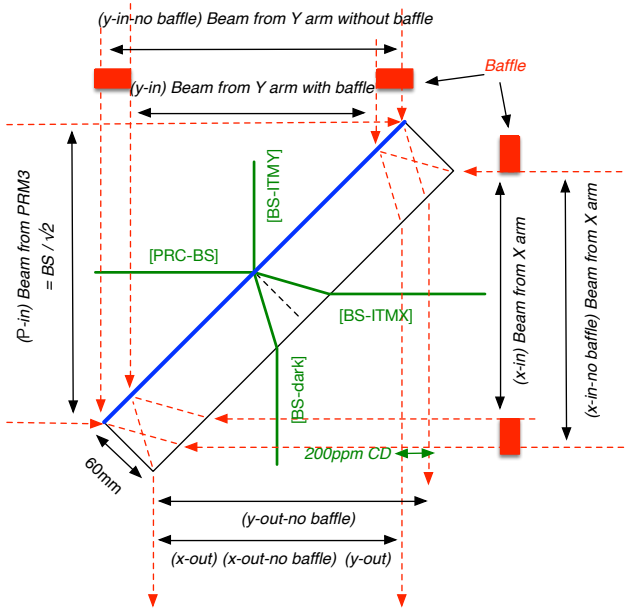
- Purpose of the talk
  - » Understanding the fundamental limitation by COC
- Optics data
  - » Use as built / measured RoC, maps, losses
  - » https://galaxy.ligo.caltech.edu/optics/ and links from this URL
- Simulation tool used
  - » FOGPrime13
    - – matlab program
  - » Documentations, source codes and data files for LLO and LHO available from DCC-T1300942

FOGPrime13

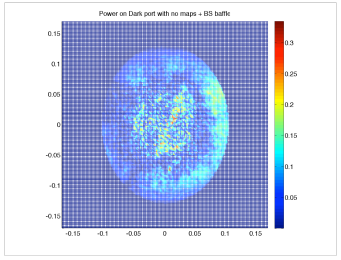
- FOGPrime13
  - » Objet oriented FFT-based IFO simulation and analysis package on matlab
    - – FP to full aLIGO with input and output MCs, transMon
  - » FOGPrime13 = FOG + SIS + e2e + twiddle
    - – FOG as the field calculation engine
    - – SIS as base of the user interface design and support package
    - – e2e as base of the object oriented package infrastructure
    - – twiddle for setting the initial condition of fields, especially for coupled cavities
- Based on matlab
  - » Matlab functions, built-in and user provided, can be easily integrated
  - » Can interact with COMSOL, like thermal deformation
- No setting of Wfft and Nfft
  - » User defines optics quantities and resolution of maps

Loss related to geometry

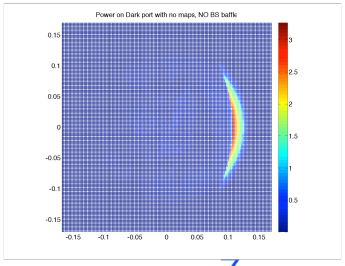




With BS baffle
7ppm



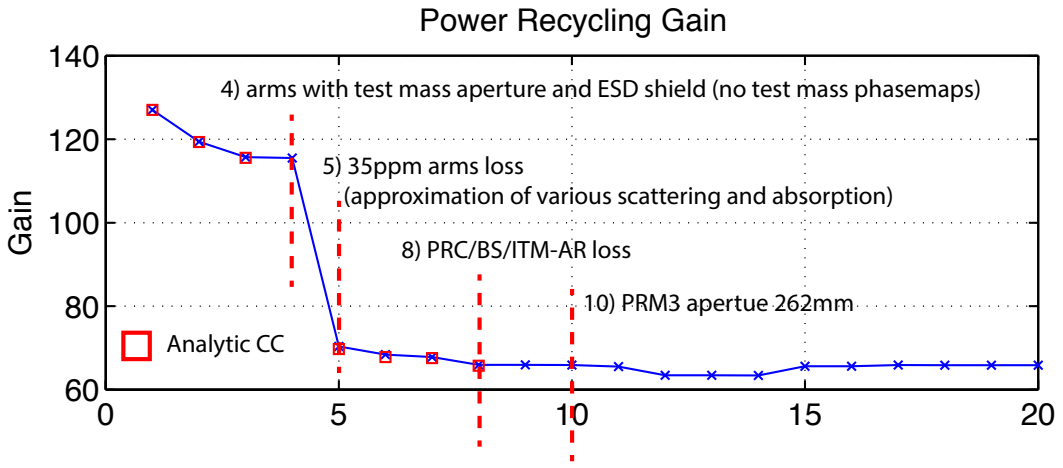
Without BS baffle
210ppm

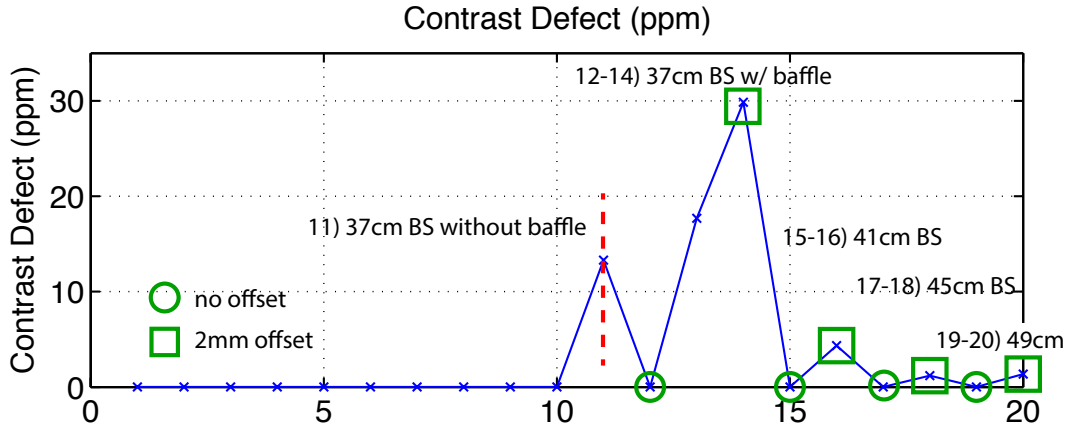


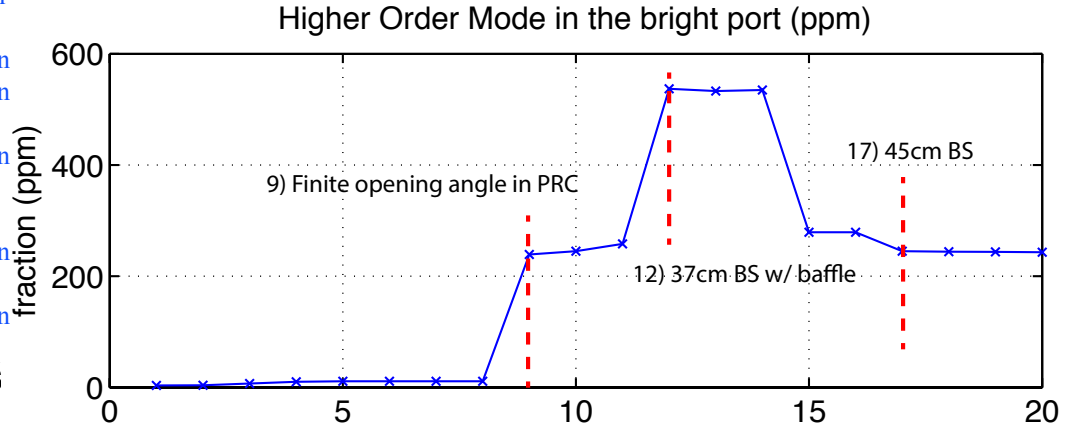
Performance limitation by design
LLO case

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 Y

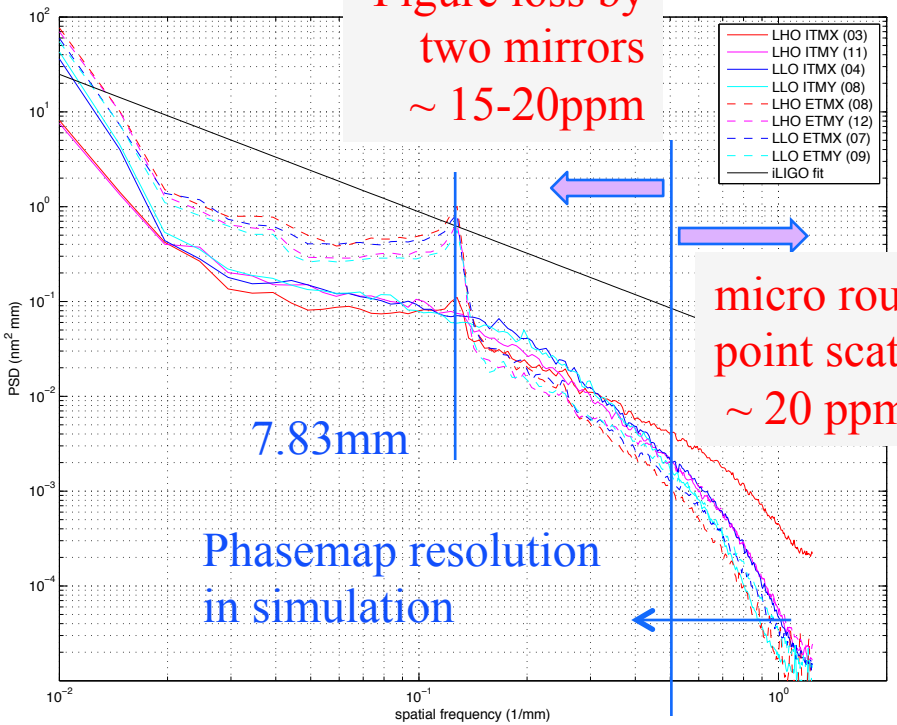
Arm performance
only aberrations in arms included

- 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

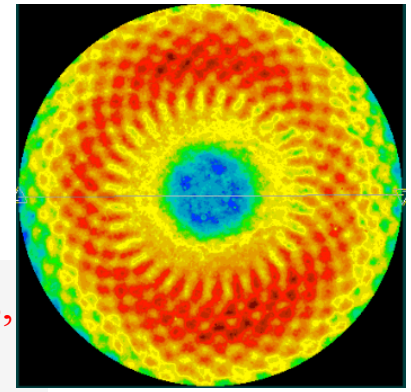
	LHO TITM=1.39%,1.42%	LLO TITM=1.48%,1.48%	LLO (no maps)
CD	29 ppm	48 ppm	44 ppm
PRG	63	61	74
Arm power	8800 W (1W input)	8100	9900
HOM in bright	1900	1600	520
HOM in x/y arm	95 / 114 ppm	97 / 113	38 / 62
Round trip loss	33 / 37 ppm	40 / 38	23 / 26

Noise injection by the spiral pattern on test mass coatings

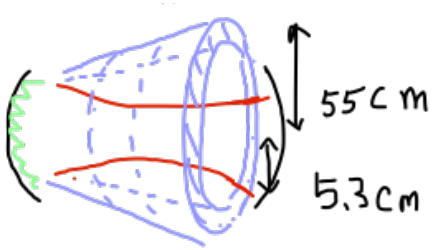
Figure loss by two mirrors ~ 15-20ppm



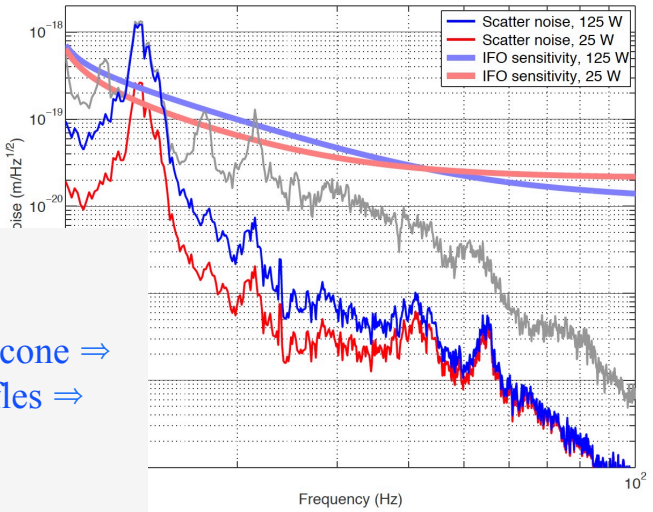
micro roughness, point scattering ~ 20 ppm



ETM07 map

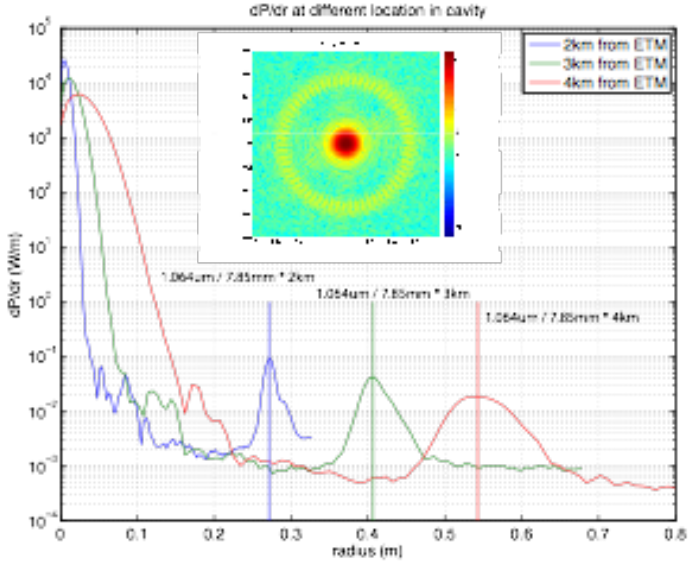


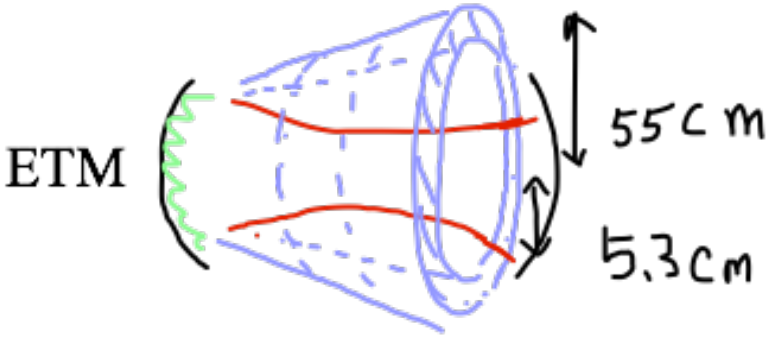
T1300354 by PF,HY

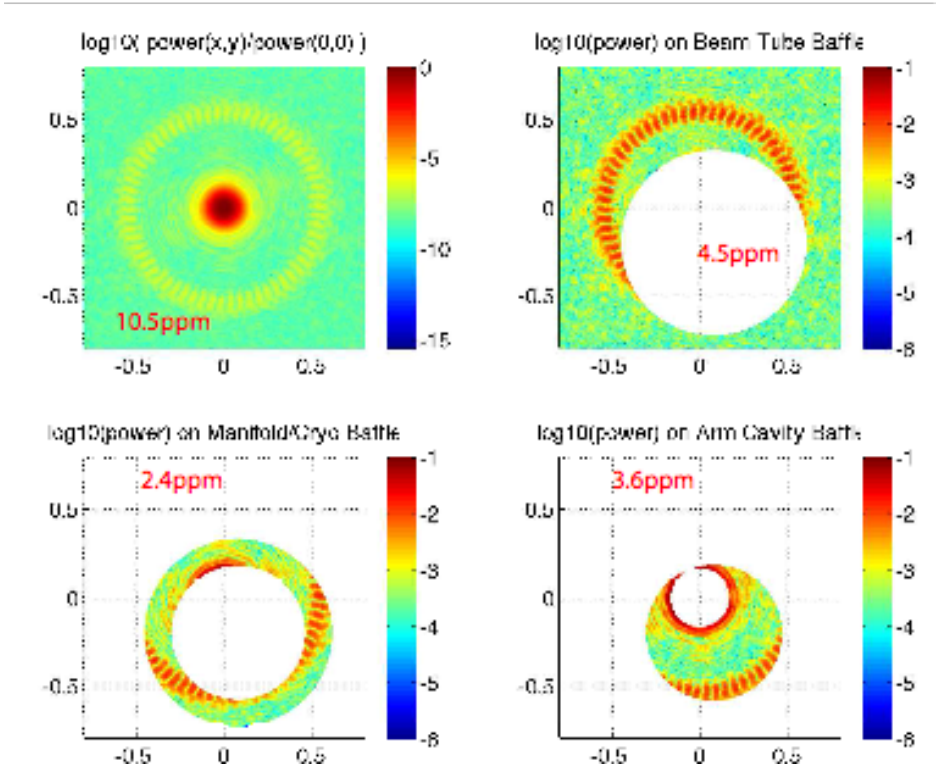


main beam ⇒
ETM reflection ⇒
larger angle scattering into cone ⇒
reflected by beam tube baffles ⇒
back scattered into ETM ⇒
merged into the main beam

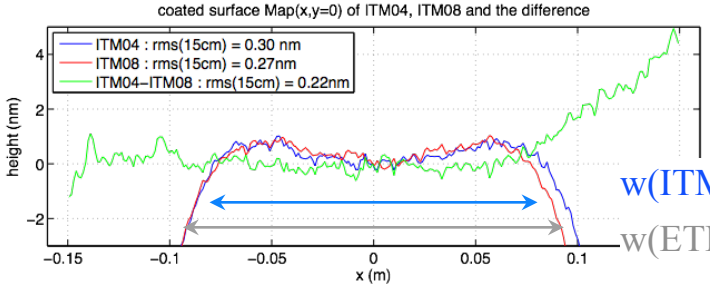
Scattered light ring pattern





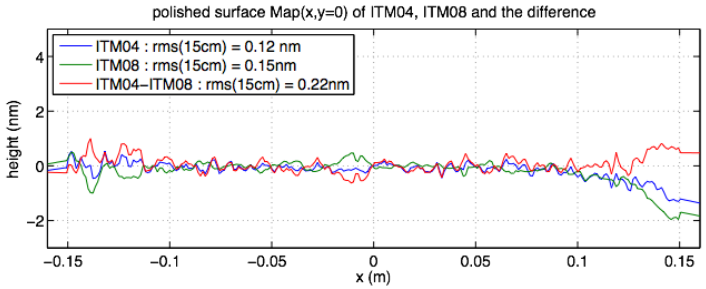


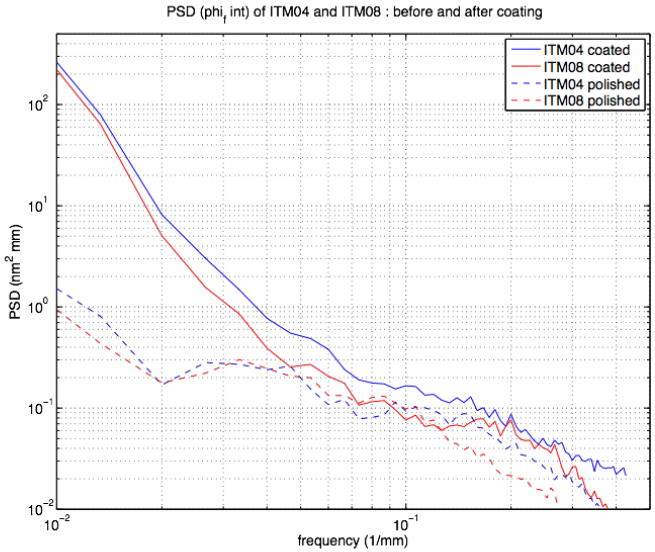
Higher order mode due to imperfect test mass coating figures



w(ITM)x1.5 : good

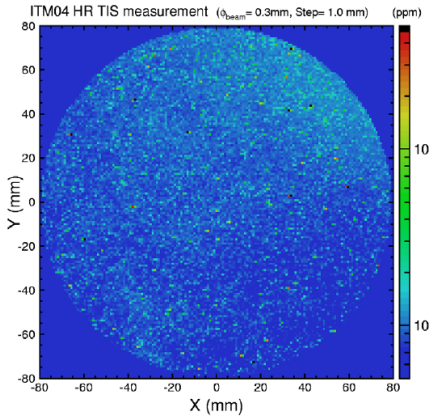
w(ETM)x1.5 : NG





		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

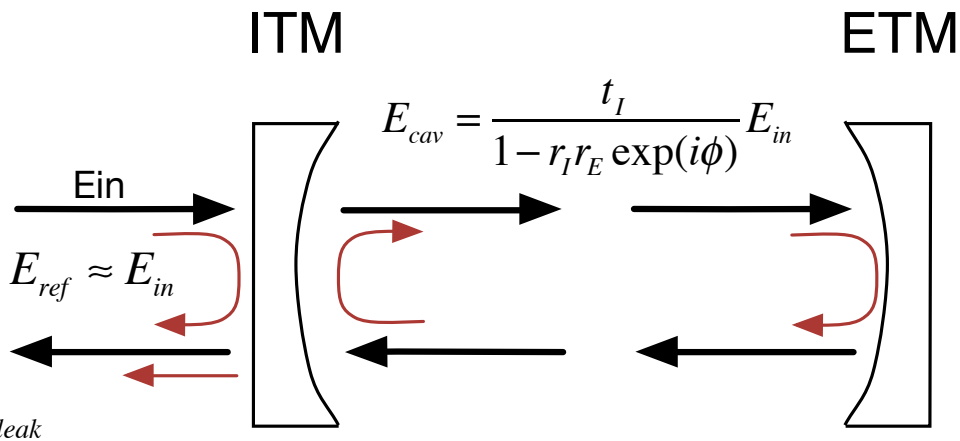
Table 1 Cavity quality factors



Caltech : 10ppm

LMA : 4.5ppm

The sign flip basic



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

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

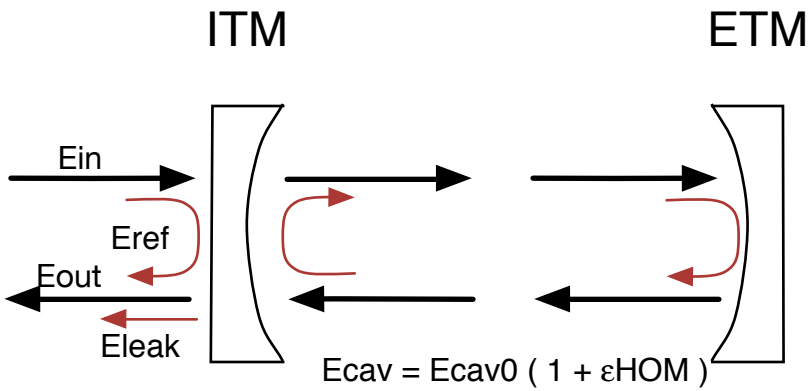
$$E_{out} = E_{ref} + E_{leak}$$

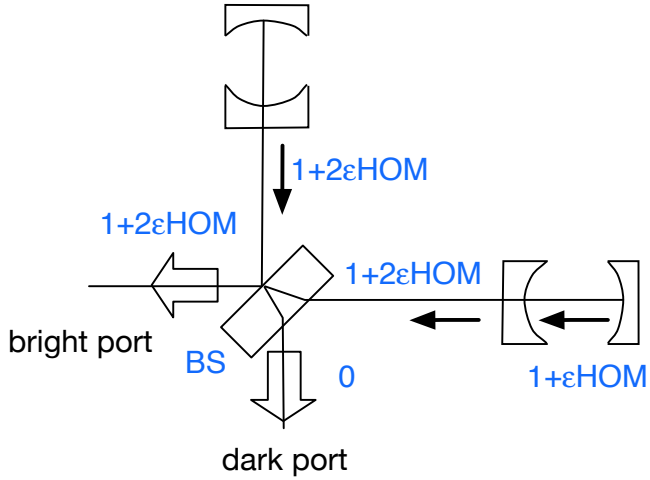
$$= \left\{ \begin{array}{c} -1 \\ 1 \end{array} \right\} E_{in} \qquad E_{leak} = \left\{ \begin{array}{c} -2 \\ t_I^2 / 2 \end{array} \right\} Ein$$

field resonant in cavity

field non-resonant in cavity

HOM amplification





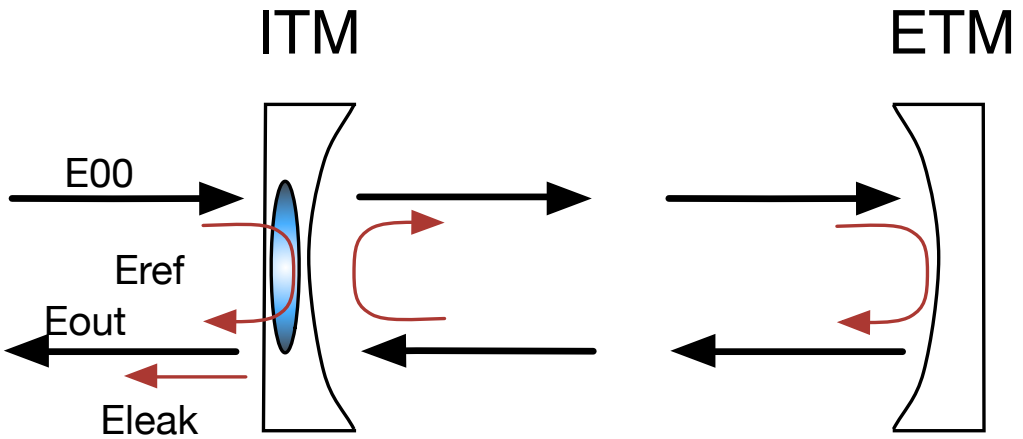
$$Eref = Ein$$
$$Eleak = -2Ein(1+\varepsilon HOM)$$
$$Eout = -Ein(1+2\varepsilon HOM)$$
$$HOM(arm) = \varepsilon HOM^2$$
$$HOM(bright) = 4\varepsilon HOM^2$$
$$HOM(dark) = 0$$

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

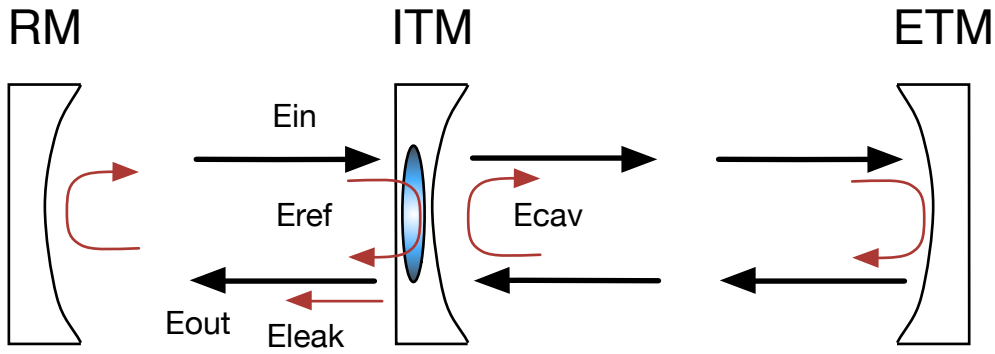
- CR (Eout) : don't see
- SB (Eref) : see
- Signal SB (Eleak) : see



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

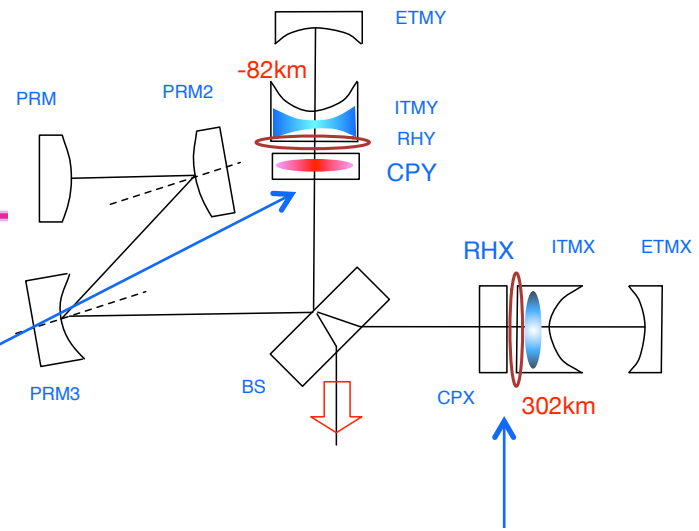
$$E_{leak} = \exp(i\phi)\begin{Bmatrix} -2 \\ 0 \end{Bmatrix} Ein \qquad E_{tot} = \begin{Bmatrix} \exp(2i\phi) \\ \exp(i2\phi) \end{Bmatrix} E_{00} + \begin{Bmatrix} -2\exp(i\phi) \\ 0 \end{Bmatrix} E_{00} \approx \begin{Bmatrix} -1+O(\phi^2) \\ 1+i2\phi \end{Bmatrix} E_{00}$$

Cavity mode



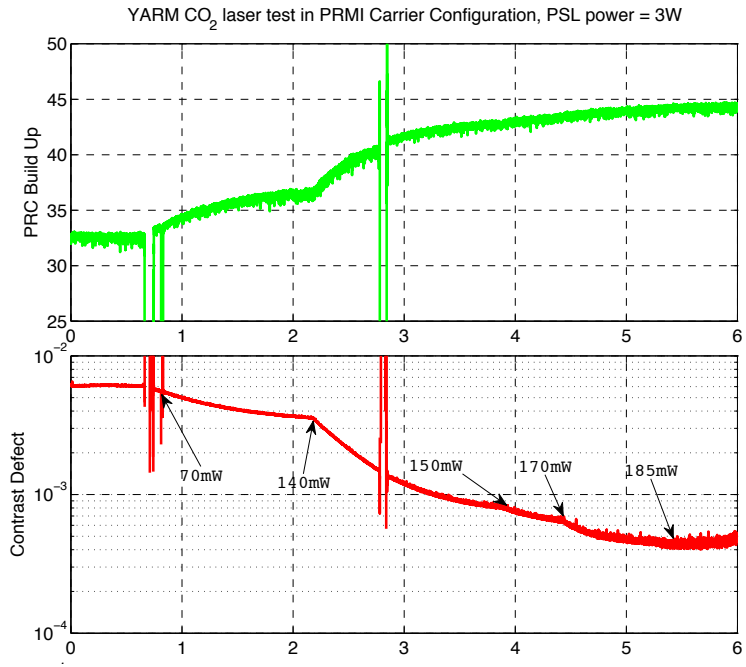
- Recycling cavity mode is defined by RM HR reflection and ITM reflection, Ein to Eout, not Ein to Eref, just the same as length DOF case
- Optimal coupling is mode(Eref) = mode(Eleak), which makes mode(CR in RC) = mode(SB in RC)
- When thermal lens changes, mode(CR in RC) does not change in the first order, but the mode(SB in RC) changes in the first order

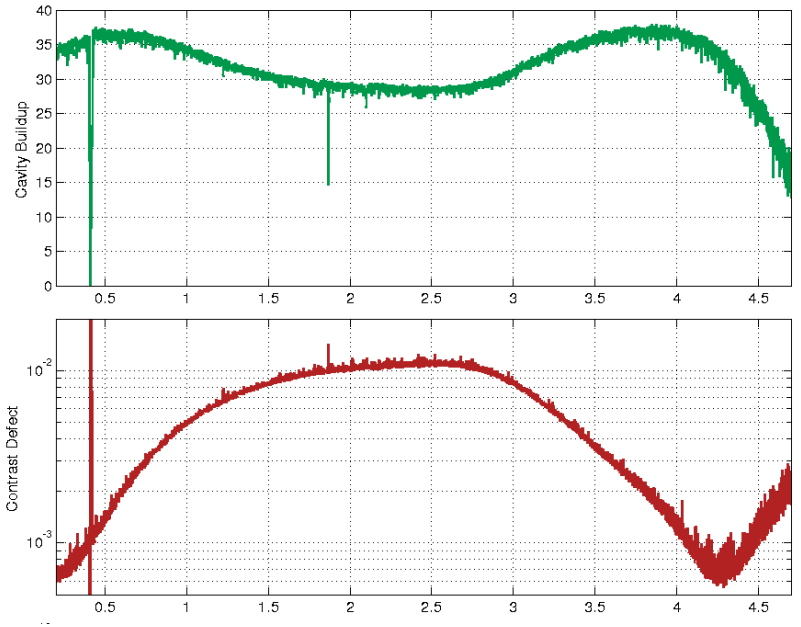
TCS corrections for LLO PRMI



RH optimal lens = n(SiO2) x 82km = 1/0.84 x10^{-5}

CP optimal lens = 82km = 1/1.22 x10^{-5}



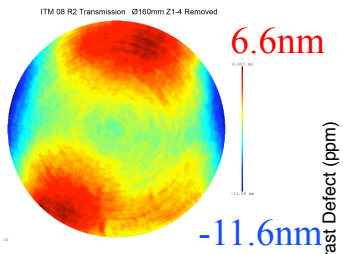


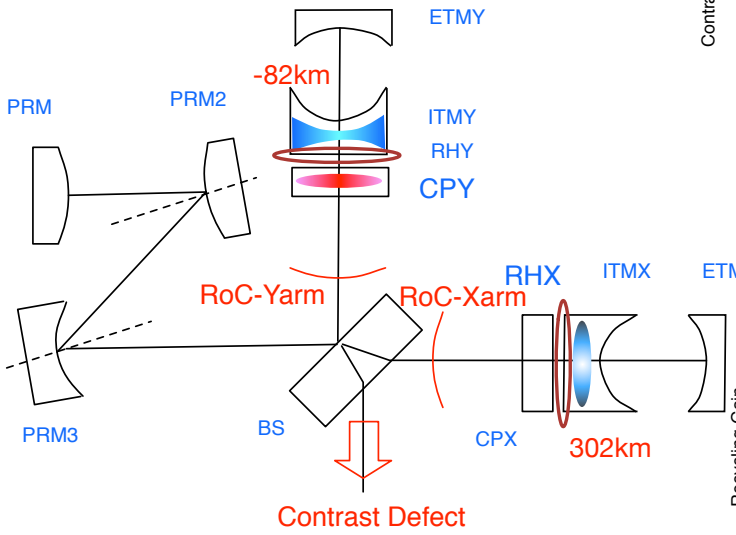
log11140 CD~400ppm, PRG~45

log#9733 CD~600ppm, PRG~35

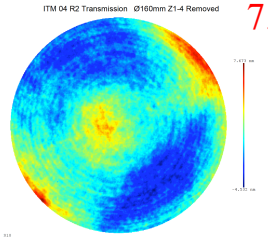
(In)Sensitivity on ITM SPTWE + CP lens

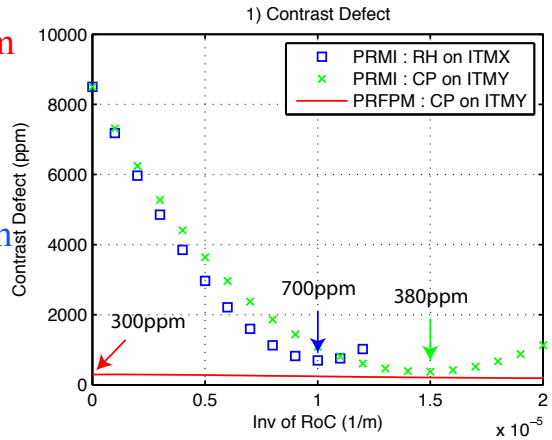
ITM08 / ITMY transmission map in 160mm w/o power

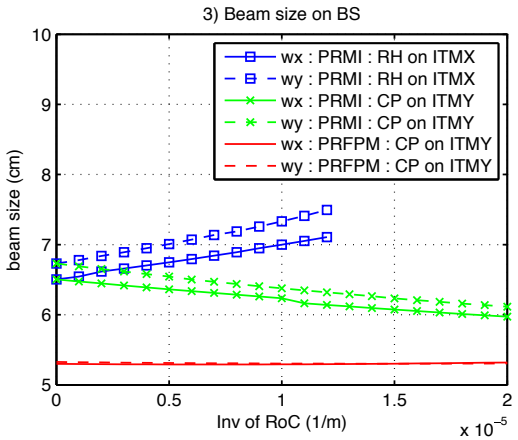


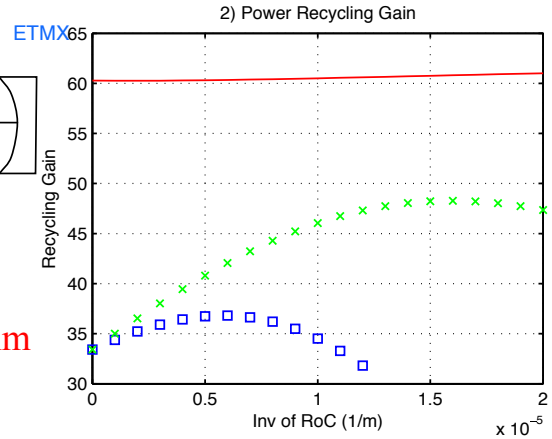


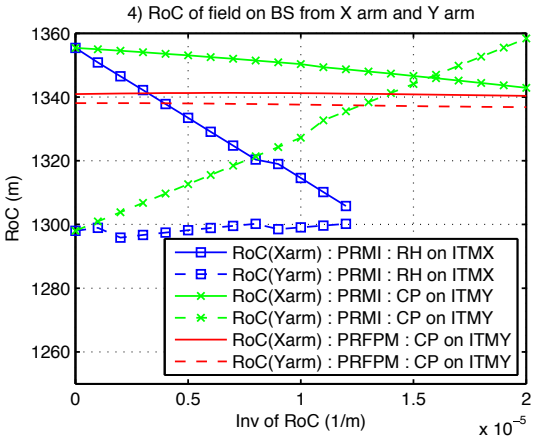
ITM04 / ITMX









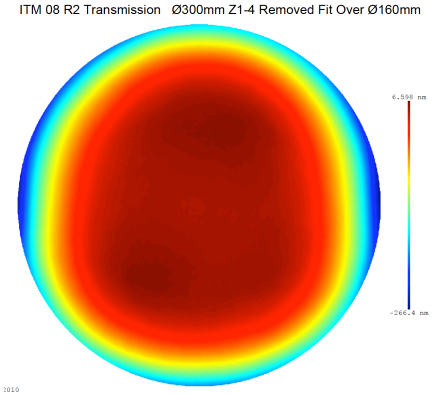


ITM transmission maps

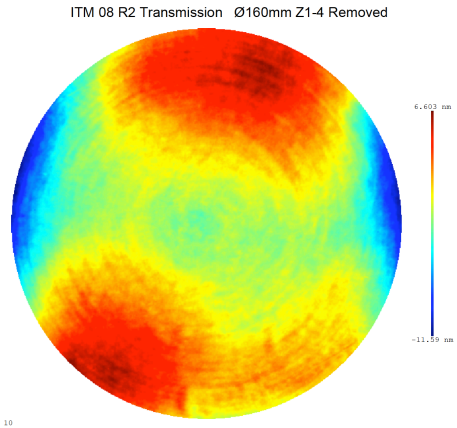
not the large lens effect imbalance

ITM08 / ITMY

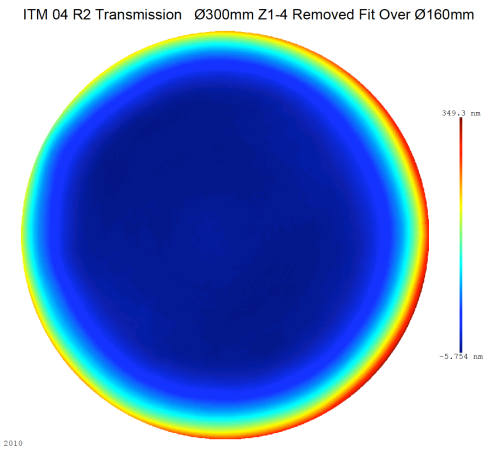
ϕ=300mm

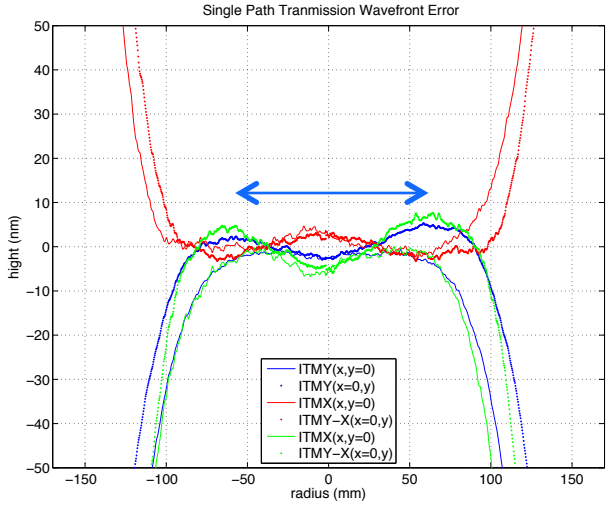


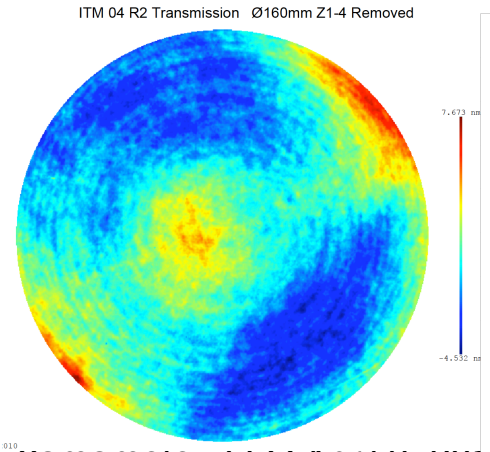
ϕ=160mm



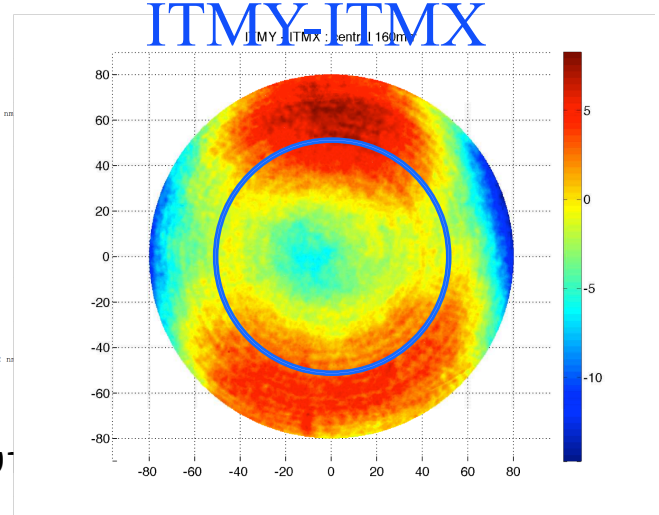
ITM04 / ITMX



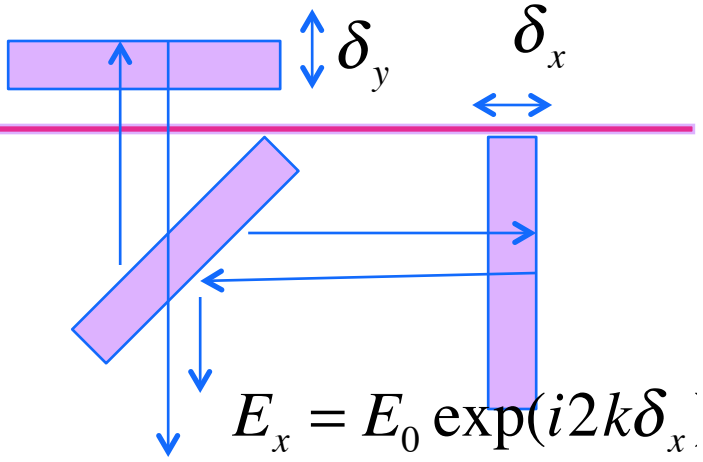




ITMY-ITMX



Back of the envelope vs FFT

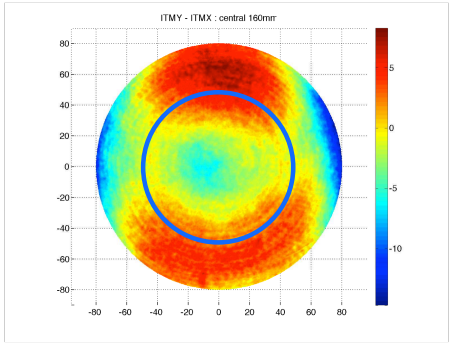


$$CD = Power(E_x - E_y) / Power(E_x + E_y)$$

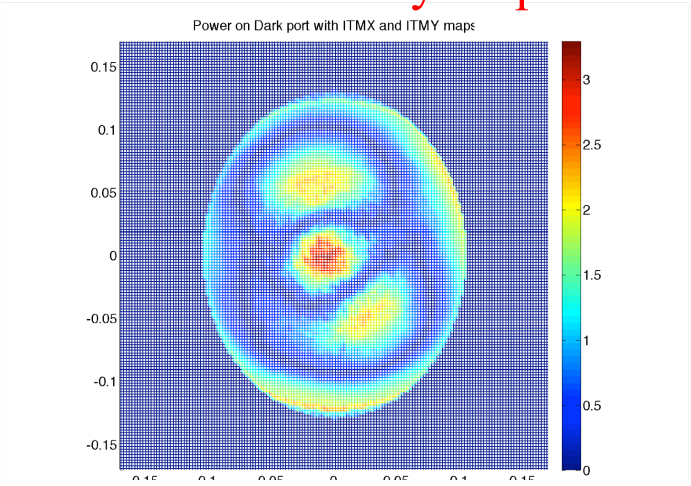
$$= \int dx\,dy (2k)^2 \frac{2}{\pi w^2} \exp(-2\frac{r^2}{w^2})(\delta_x(x,y) - \delta_y(x,y))^2 / 4$$

	W=7cm ITMX	W=7cm ITMY	W=7cm ITMX&Y	W=5.3 ITMX&Y
simple	1200	1900	5500	440
FFT	~~320 ppm~~	~~570~~	~~1370~~	~~120~~

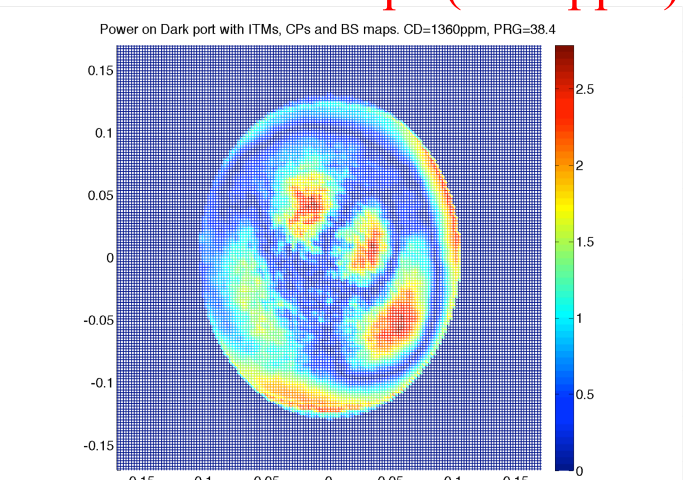
$\delta_y - \delta_x$



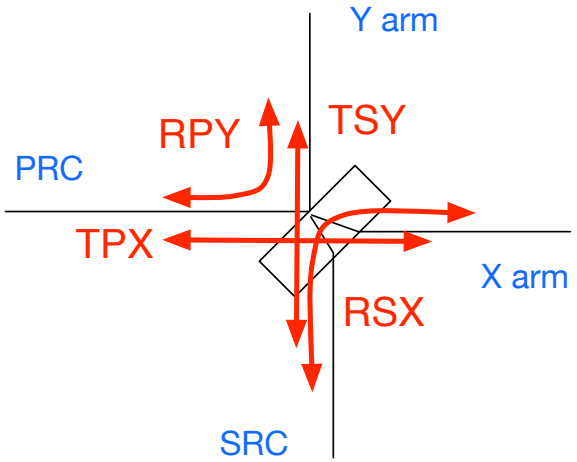
FFT w/ ITMx/y maps



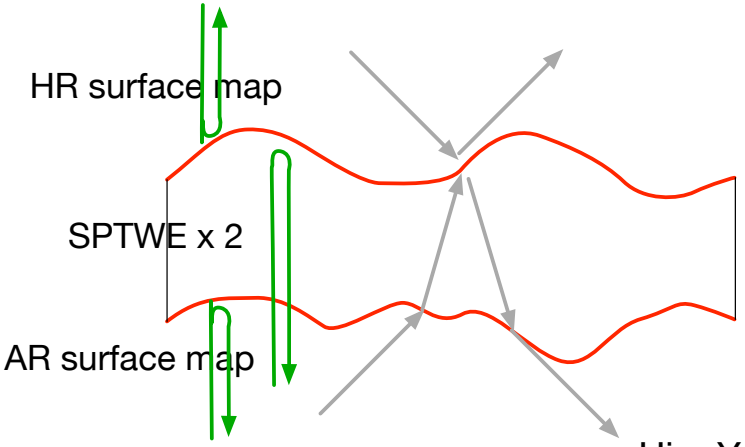
FFT with all maps (1300ppm)

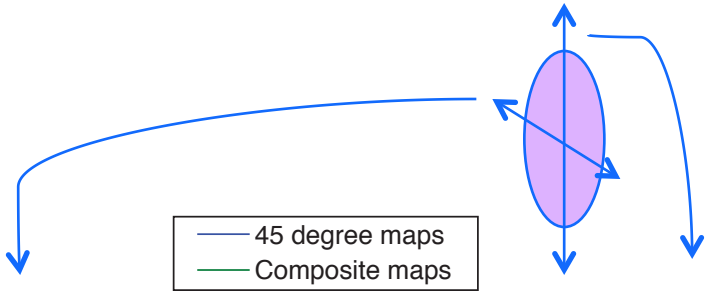


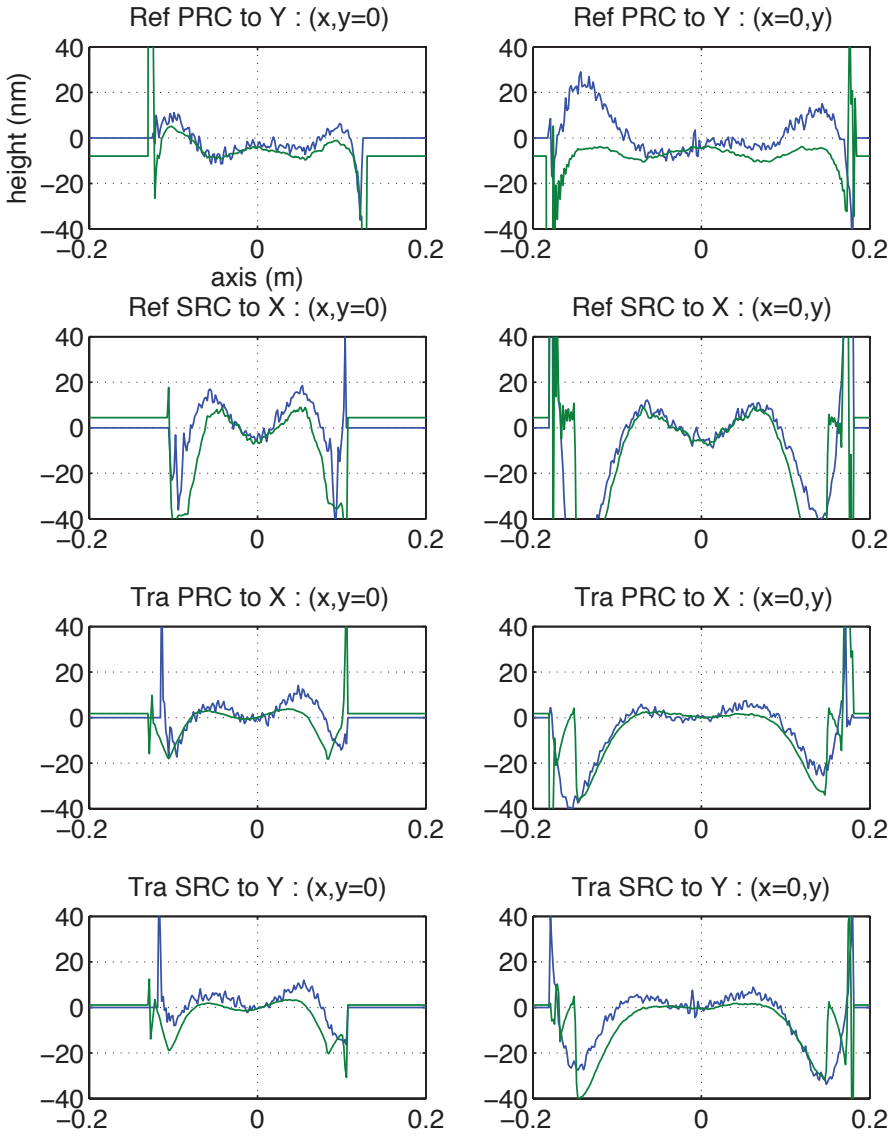
LIGO BS, not quite well measured



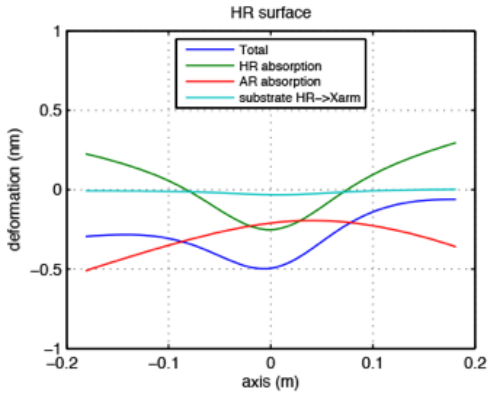
Composite map

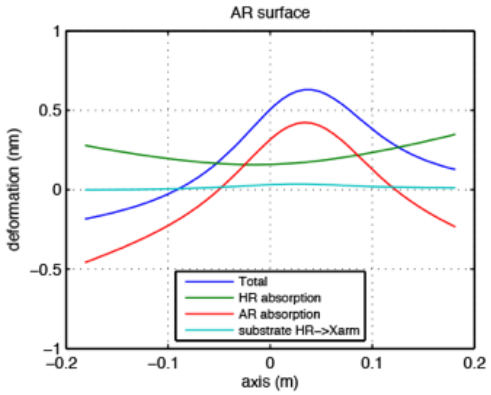


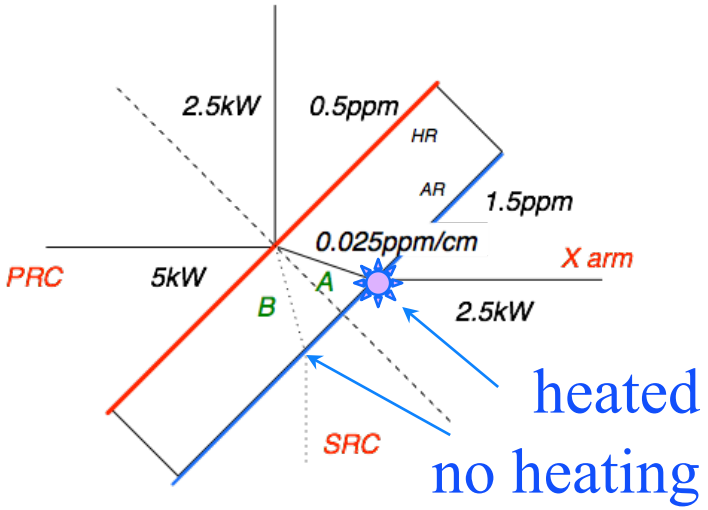


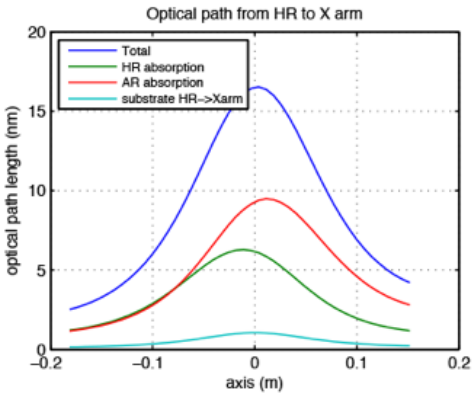


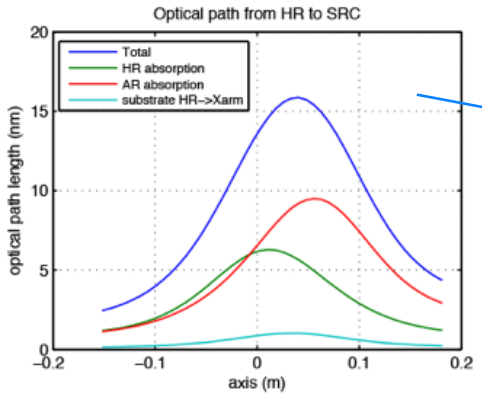
BS Thermal distortion

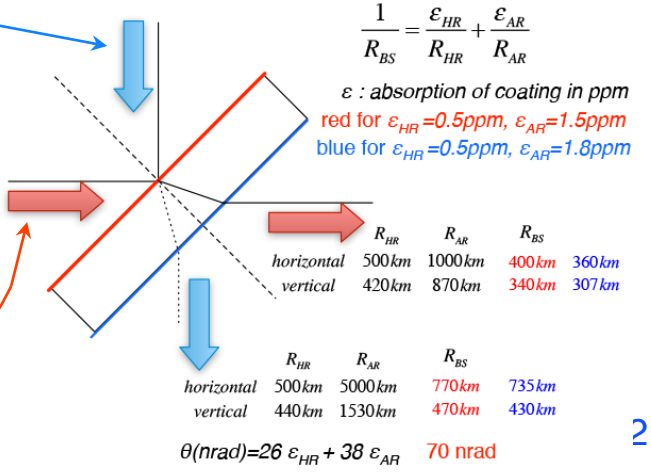




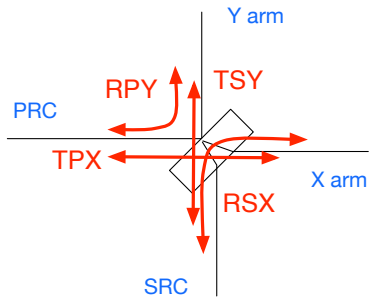


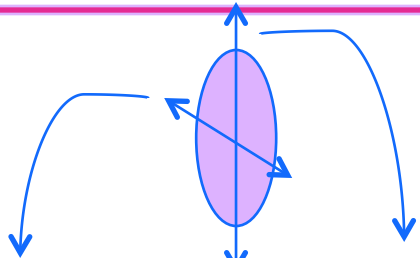


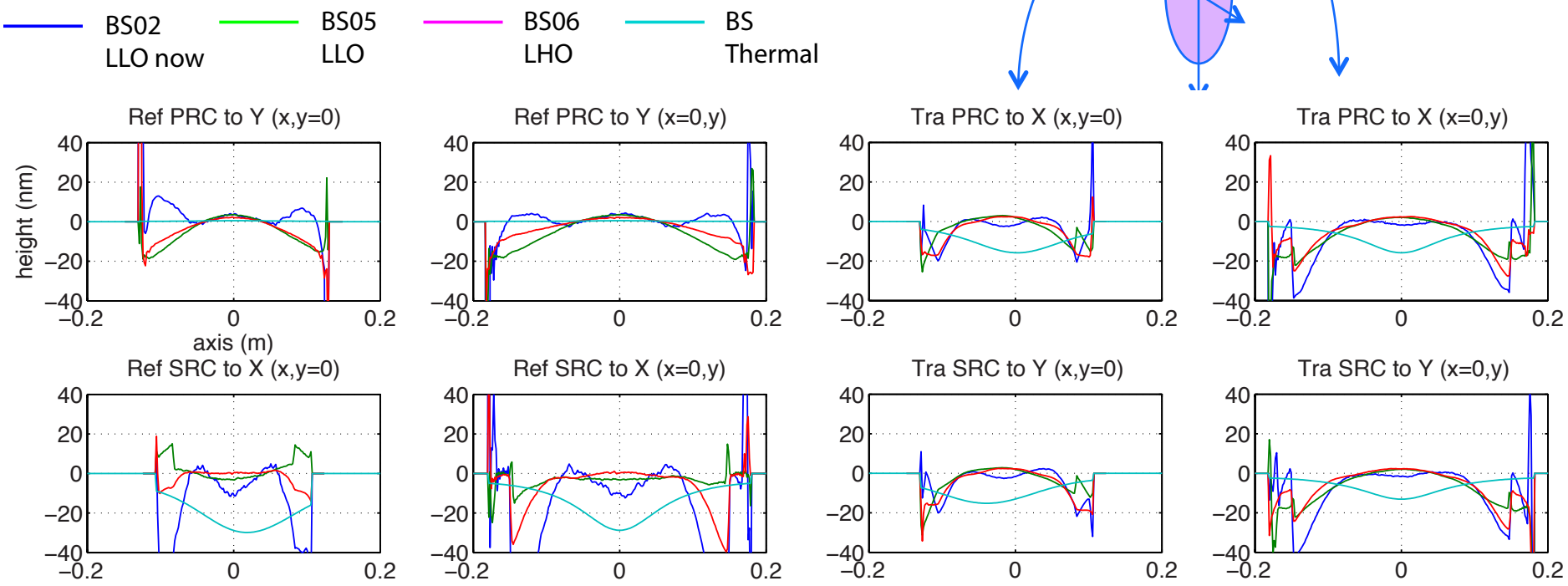




BS : Three maps and Thermal distortion







Reflections

Transmissions

Summary

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

with maps, BS and thermal

		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	63	1390	0.14	8860	97	33	8680	115	37
	No BS	139	63	1380	0.14	8870	97	33	8690	115	37
	BS thermal	147	63	1460	0.14	8860	97	33	8670	114	37
With miracle TCS	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

Coating + Thermal = flat

770kW in LLO X arm, 0.3ppm absorption