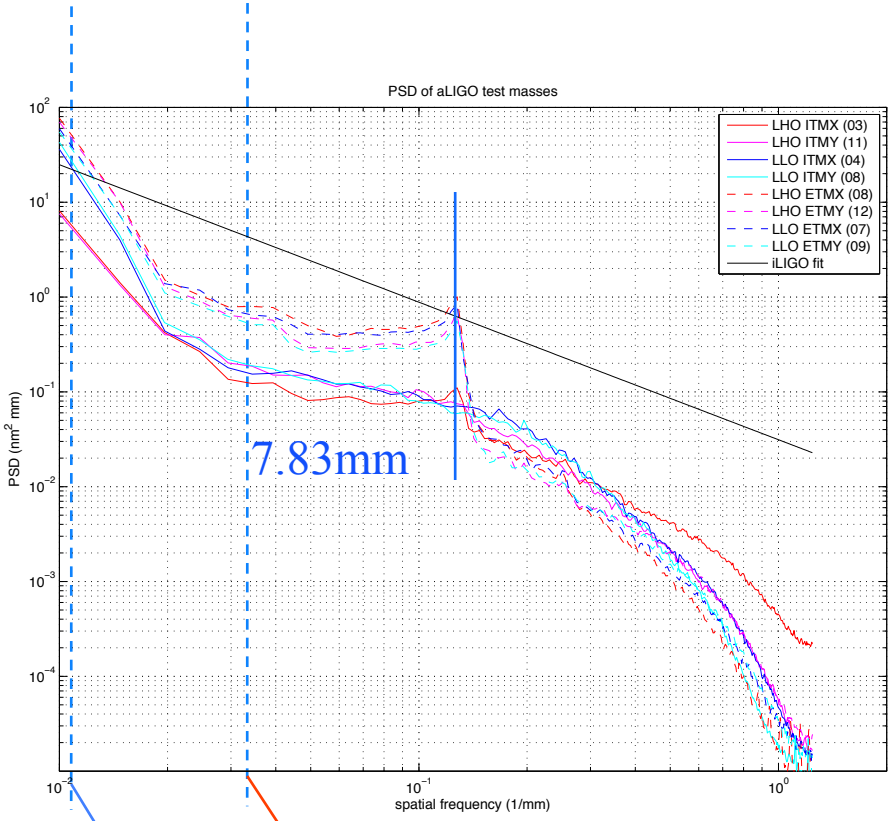
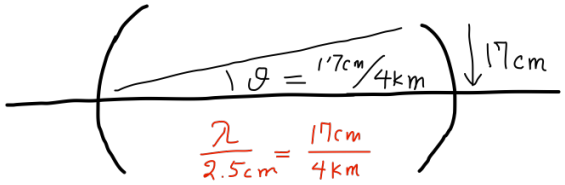
Optical Simulation vs Reality at LLO

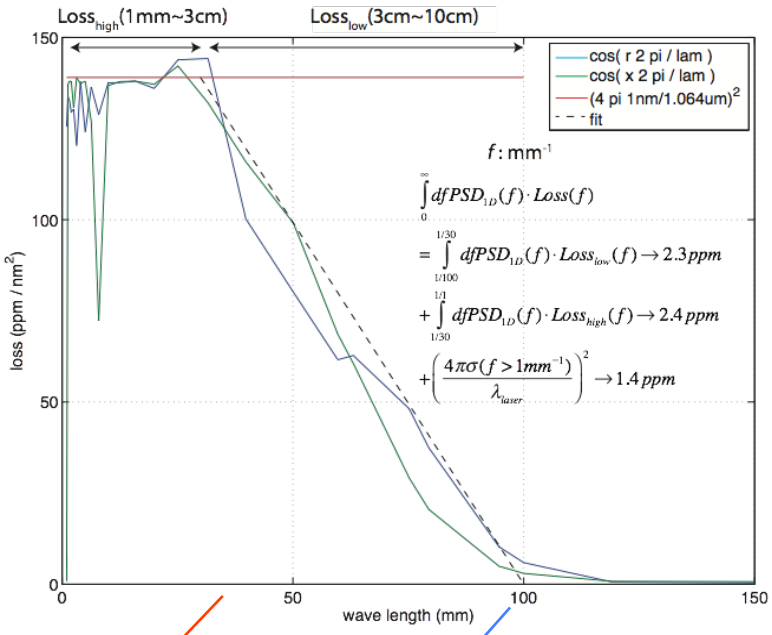
Hiro Yamamoto LIGO lab/Caltech

- Introduction
- Arm loss
  - » Loss by COC data and modeling
  - » Measured loss to total loss
  - » Effect of LMA coating
- Arm modes
  - » Effective RoC and locations of HOM peaks
- Contrast Defect
  - » 400ppm measurement vs 300ppm model
    - – Various sources of CD, what's missing?
  - » ITMY lens and transmission maps, BS maps etc

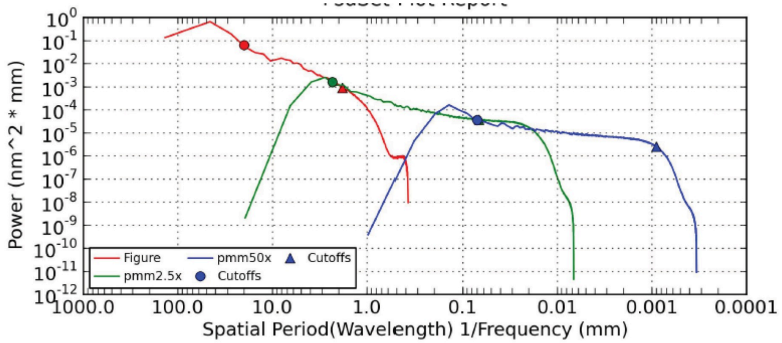
aLIGO optics scattering loss by wavelength







COC data and modeling

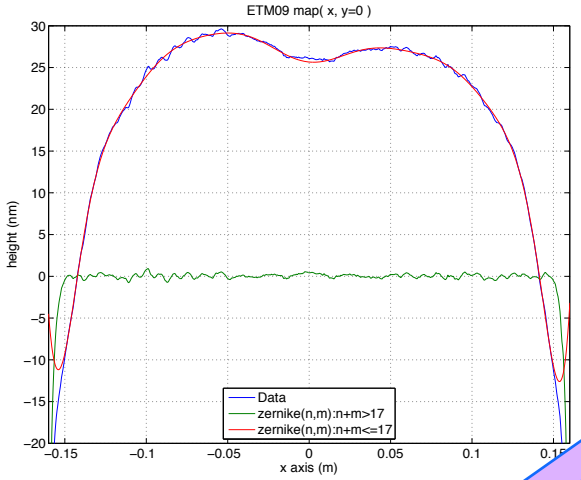


	Spatial resolution	coverage	Main use
Phase map	> 1mm	< 2 x 10^{-4} rad, < 1m at 4km	Field in cavity and near the outer edge of mirror, cavity mode
PSD, RMS	1μm ~ a few mm by PMM, + phase map	~ large angle	Characterization of continuous structure, field scattered at large angle
Integrating sphere	fraction of mm	> 5 degree	Total scattering to all angle, effects of non contiguous structures captured. Hole at forward is covered by others.

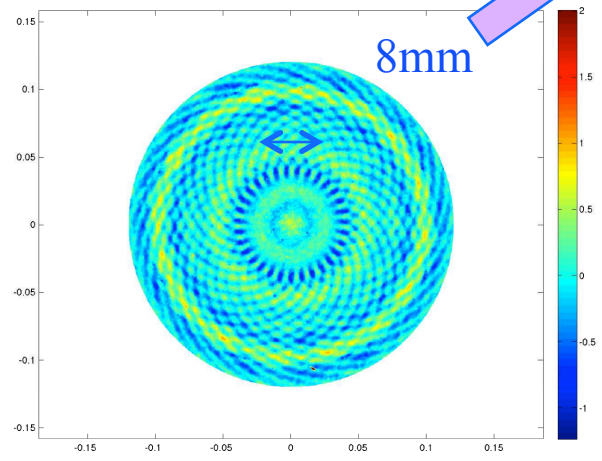
COC data (characteristics of mirror) +
appr. Maxwell eq. with rigorous boundary cond.
⇒ IFO observable

Details of ETM09 spiral effect

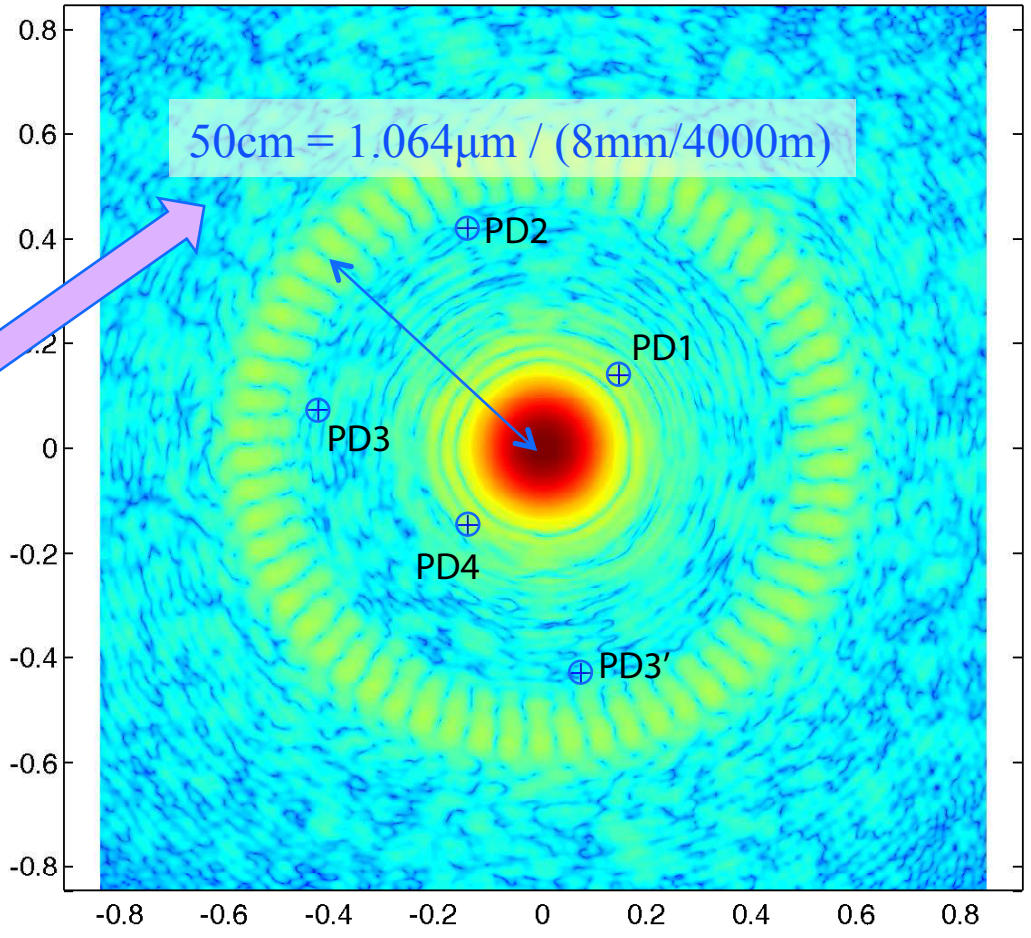
ETM09 map



Spiral component



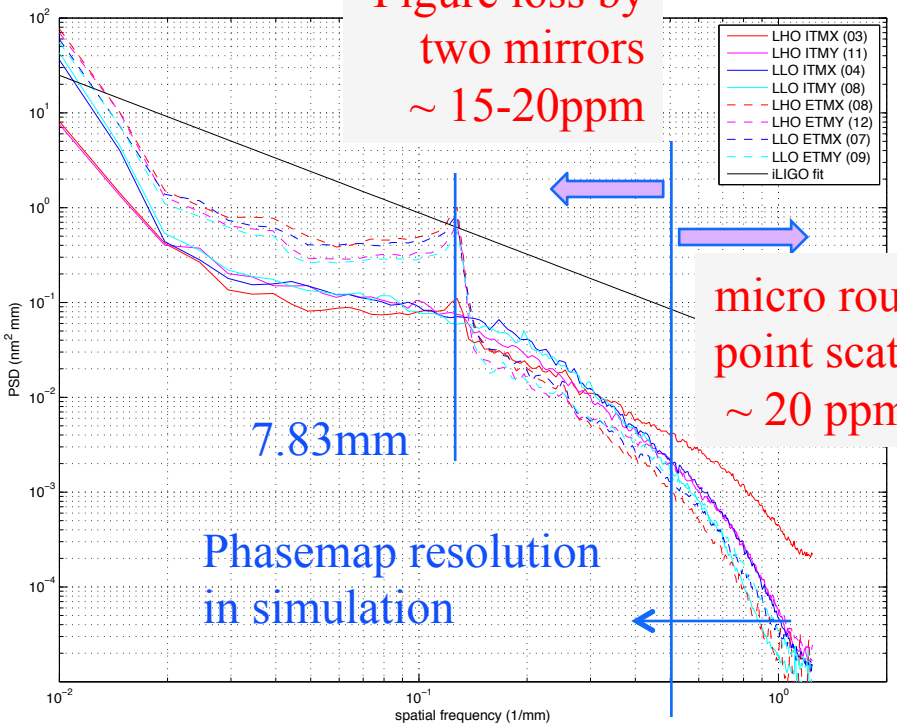
Field going to ITM



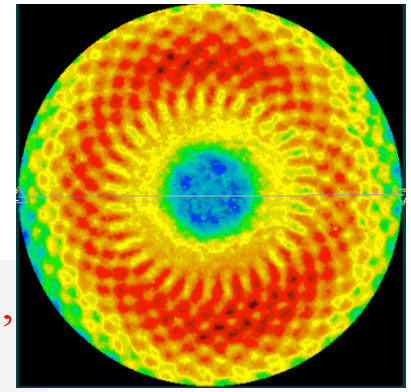
Real PD diameter is ¼ of ○

Noise injection by the spiral pattern on test mass coatings

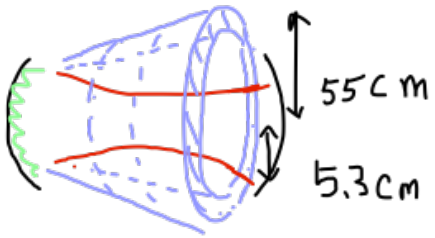
Figure loss by two mirrors ~ 15-20ppm



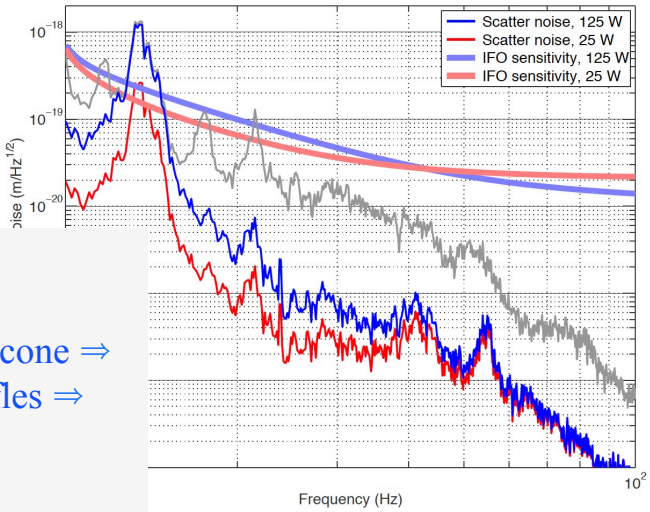
micro roughness, point scattering ~ 20 ppm



ETM07 map



T1300354 by PF,HY

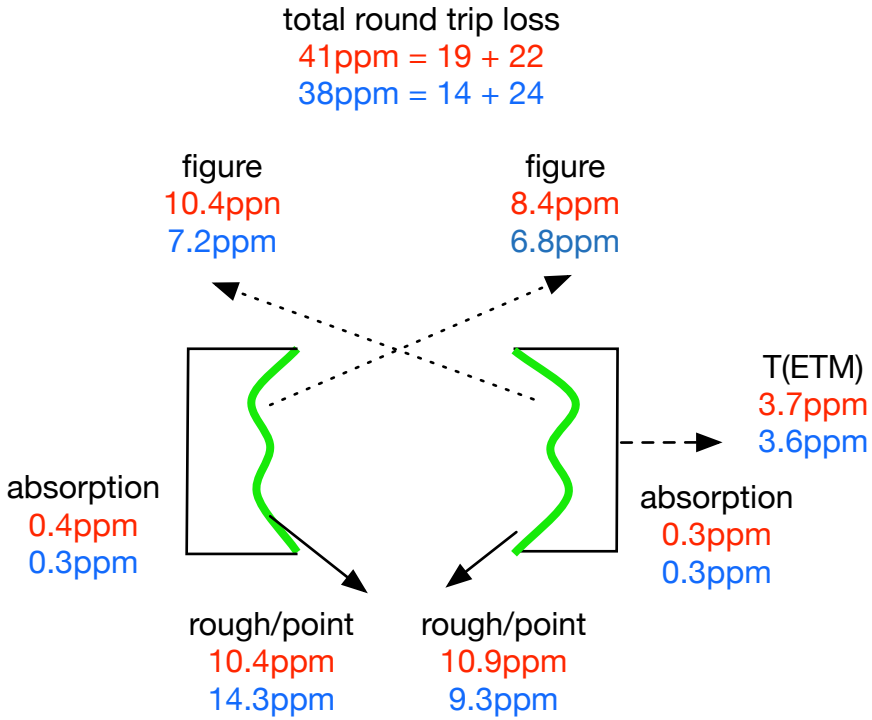


main beam ⇒
ETM reflection ⇒
larger angle scattering into cone ⇒
reflected by beam tube baffles ⇒
back scattered into ETM ⇒
merged into the main beam

Hiro Ya

Loss : measurement vs model with COC data

Phasemap and Caltech/LMA scattering loss measurements

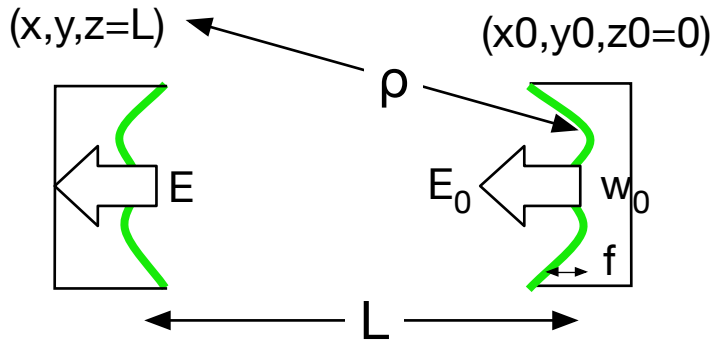


X arm	ITM04	ETM07
Y arm	ITM08	ETM09

- alog13414 ETMY scattering
  - » Total : 36ppm
  - » Point scattering : 18ppm
- alog13769 Best round trip loss 85ppm
  - » Extra 30-40ppm, where???
- COC data + Model
  - » Round trip loss error < 14ppm
  - » Integrated scattering
    - – 7.5ppm by LMA
    - – 9.3ppm by Caltech
  - » Zygo rms ⇒ loss(<1mm) < 1ppm
  - » PSD ⇒ loss(<5mm) < 1ppm

Analytic formula in the forward region

Huygen's integral with Fresnel appr.



$$E(x,y,z) \equiv \frac{i}{\lambda}\iint dx_0\, dy_0 E_0(x_0,y_0,z_0)\frac{\exp(-ik\rho)}{\rho}\cos\theta = F_0 + dF$$

$$\Delta x = x - x_0,\ \Delta y = y - y_0,\ L = z - z_0,\ k = 2\pi/\lambda$$

$$\rho = \sqrt{\Delta x^2 + \Delta y^2 + L^2},\ \cos\theta = \frac{L}{\rho}$$

$$dF(x,y,z) \approx \sqrt{\frac{2}{\pi}}\frac{1}{w_0}\frac{i}{L\cdot\lambda}\iint dx_0\, dy_0\, 2ikf(x_0,y_0)\exp(-ik\frac{\Delta x^2+\Delta y^2}{2L})\exp(-\frac{{x_0}^2+{y_0}^2}{{w_0}^2})$$ small aberration

$$\approx \sqrt{\frac{2}{\pi}}\frac{1}{w_0}\frac{i}{L\cdot\lambda}\exp(-ik\frac{x^2+y^2}{2L})2ik\iint dx_0\, dy_0 f(x_0,y_0)\exp(ik\frac{x\cdot x_0 + y\cdot y_0}{L})$$ Fresnel approx

Tiny source : dF ⇒ const BRDF ⇒ 2π dS / λ^2 x true scattering

PSD to dF : $$|dF[x,y,z]|^2 = \frac{32\pi^2}{w^2\lambda^4L^2}\left|\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Delta[f_u,f_v]\delta\left[f_u-\frac{x}{\lambda L},\varepsilon\right]\delta\left[f_v-\frac{y}{\lambda L},\varepsilon\right]df_u df_v\right|^2$$

Δ : 2D amplitude spectral density, ε~1/a few cm

Baffle PD capturing ETMY scatter

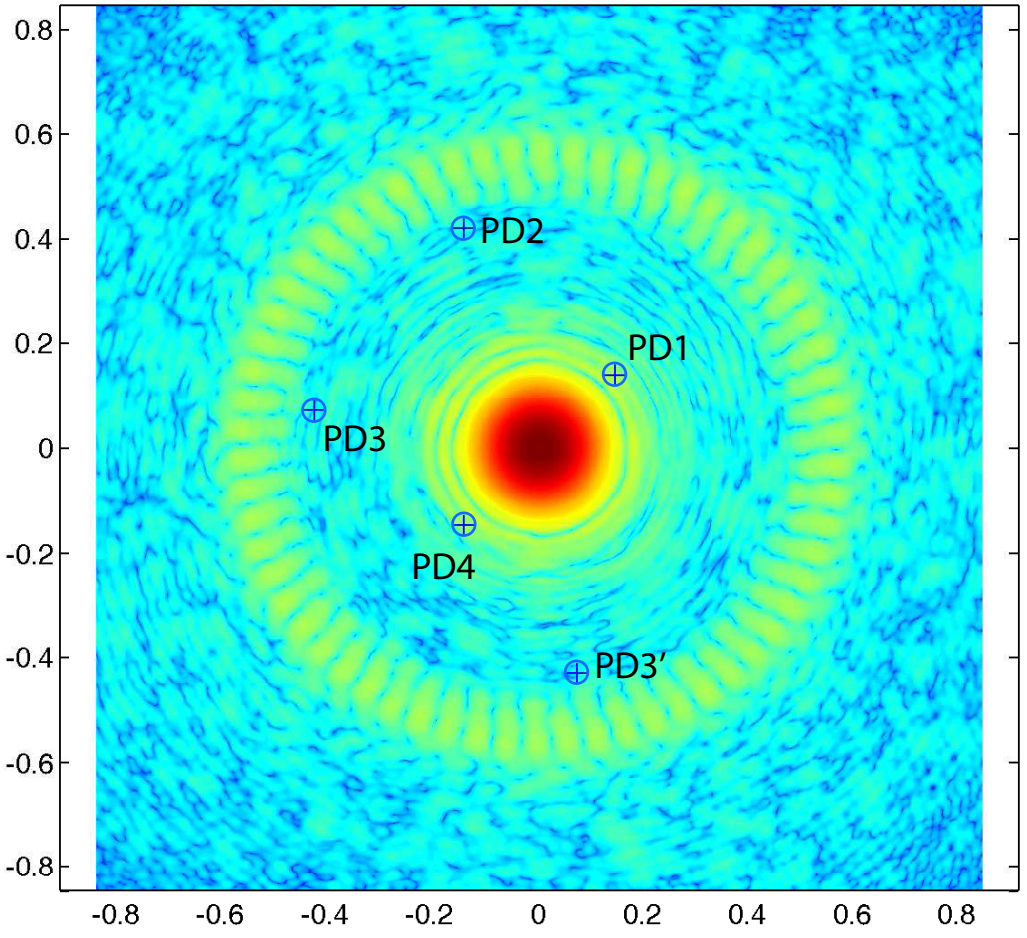
phasemap resolution ~ 2mm ⇒ covers 1m

BRDF on ITMY baffle PD

	PD1	PD2	PD3	PD4
location (mm)	200	438	435	217
data	768	118	48	352
FOGP	863	15	3 (5)	625

PSD(f)=2500 f(m)$^{-2}$ nm^2 mm
⇒ BRDF = 20 (big error) at 45cm
by using Huygen+Fresnel

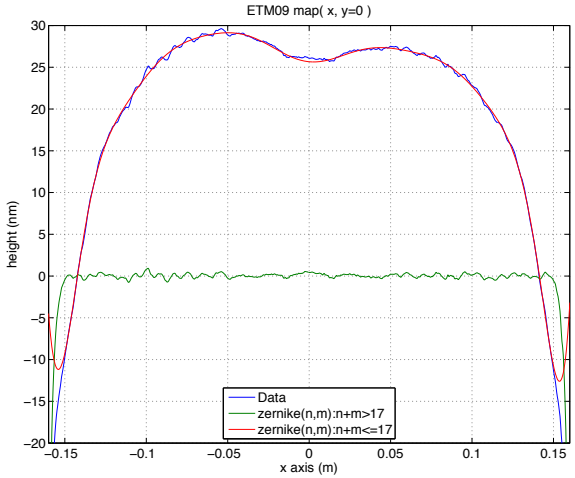
Field going to ITM

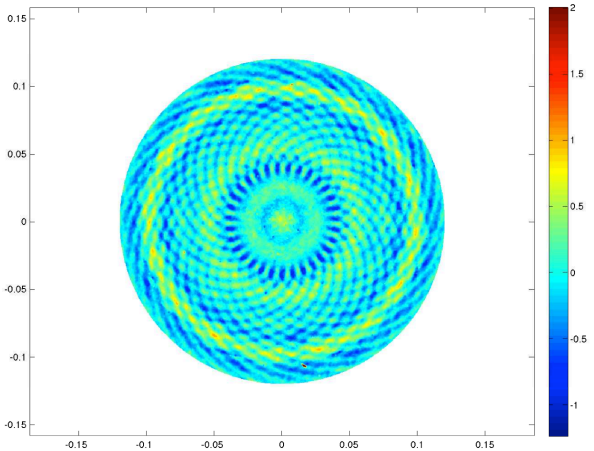


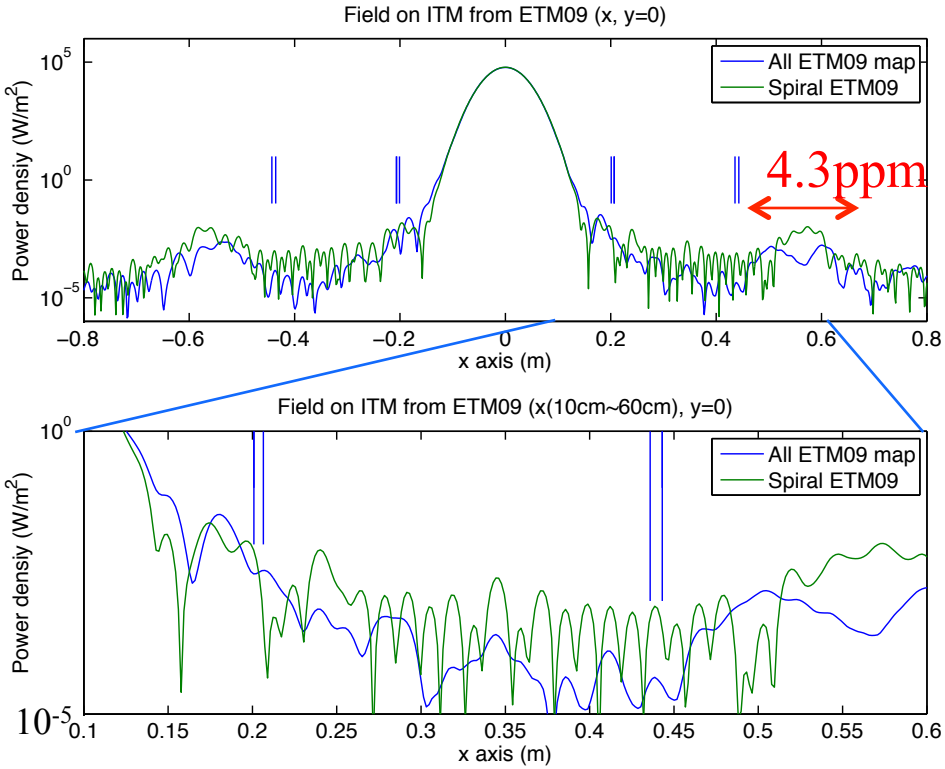
Real PD diameter is ¼ of ○

Details of ETM09 spiral effect

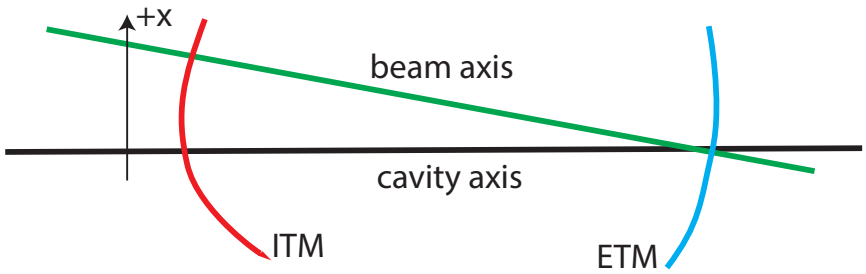
PD1,4 edge of central peak, PD 2,3 edge of 50cm ring

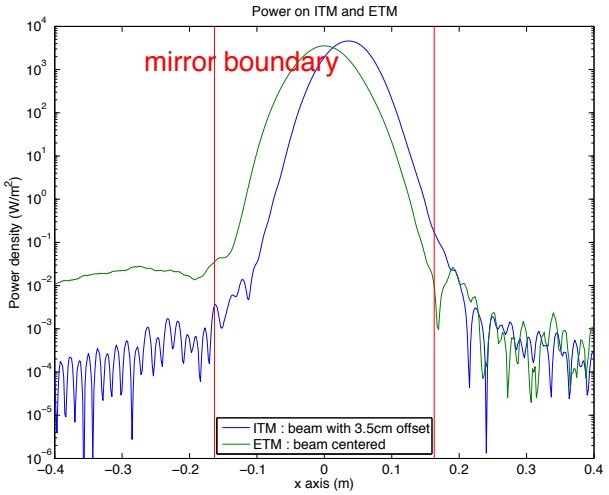


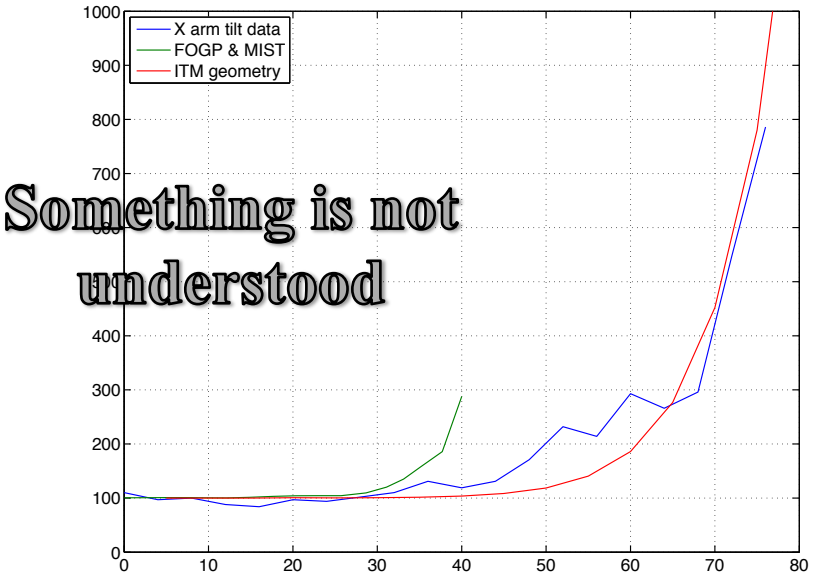




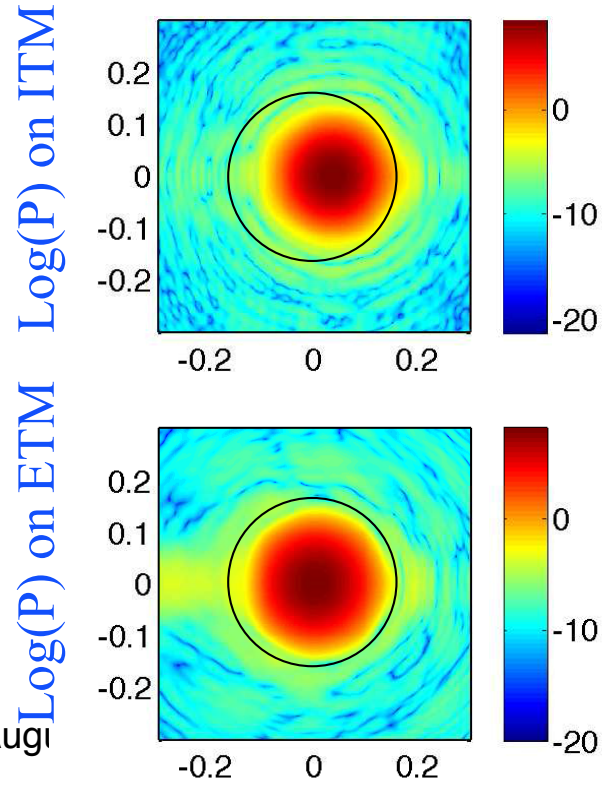
Loss vs ITM tilt
alog14171





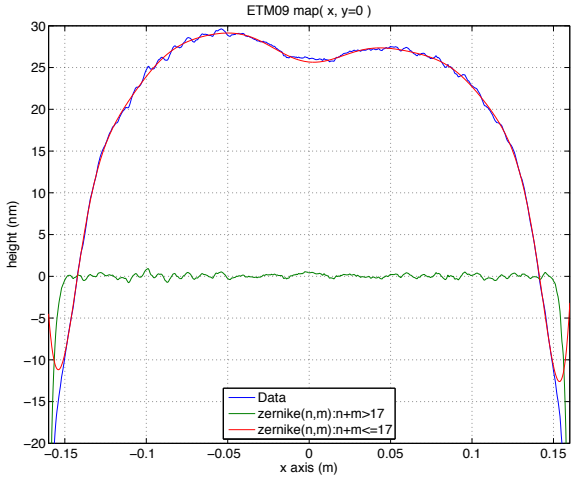


Something is not understood

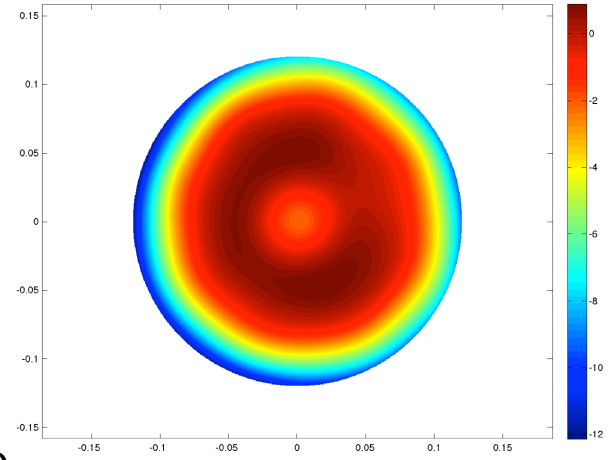


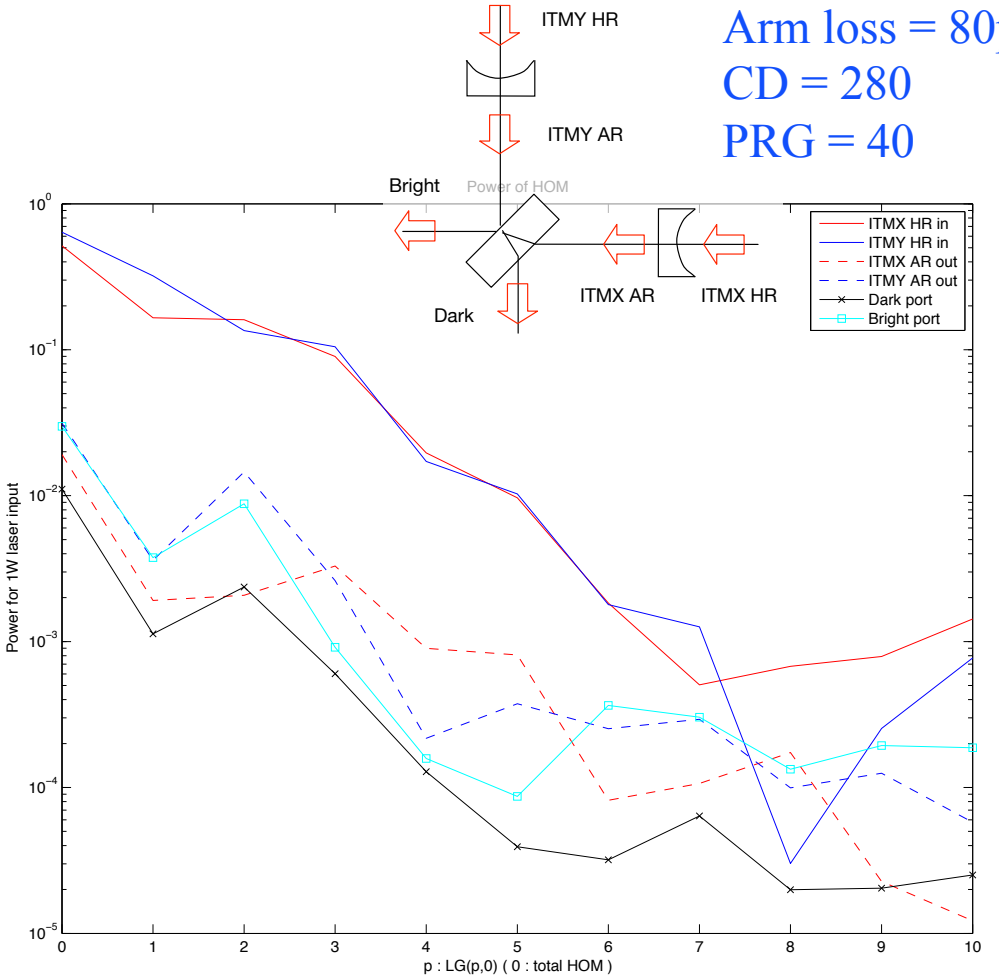
LMA coating and arm modes

ETM09 map



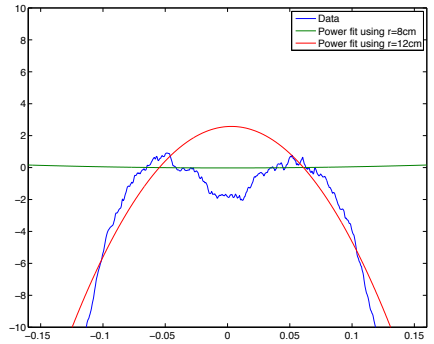
Zernike(n+m≤17)

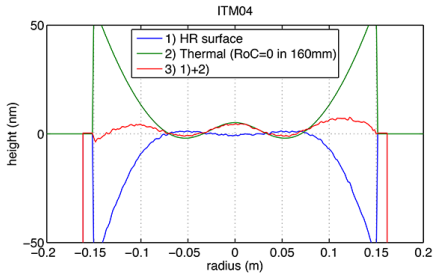


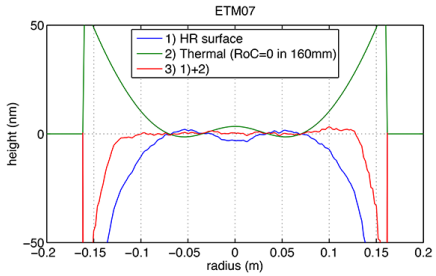


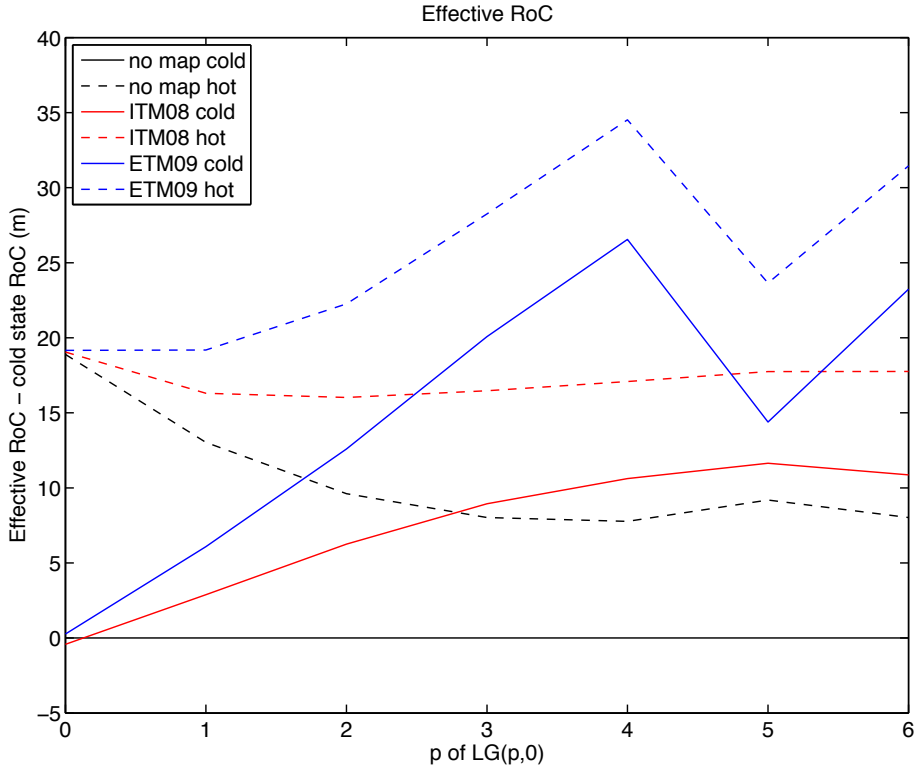
Arm loss = 80ppm
CD = 280
PRG = 40

Effective RoC and modes

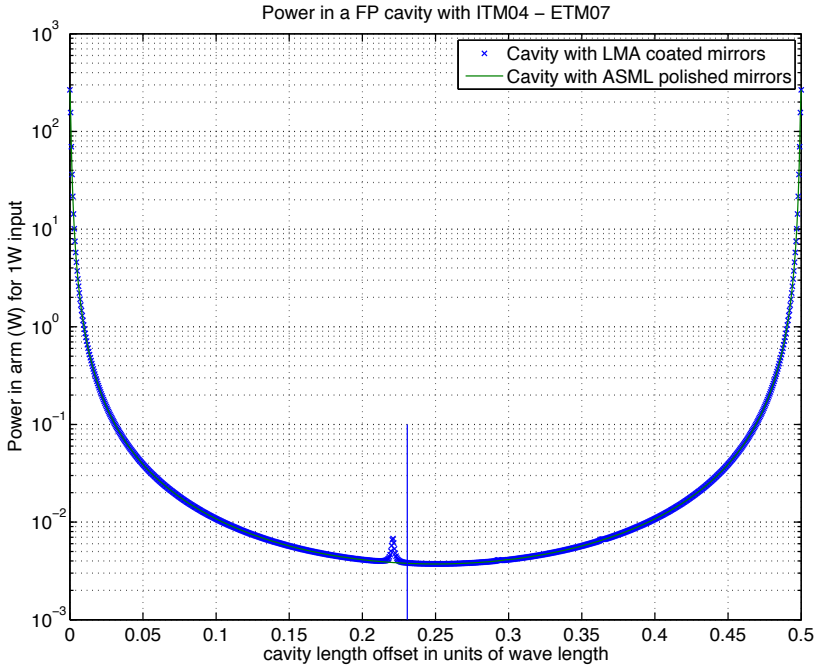


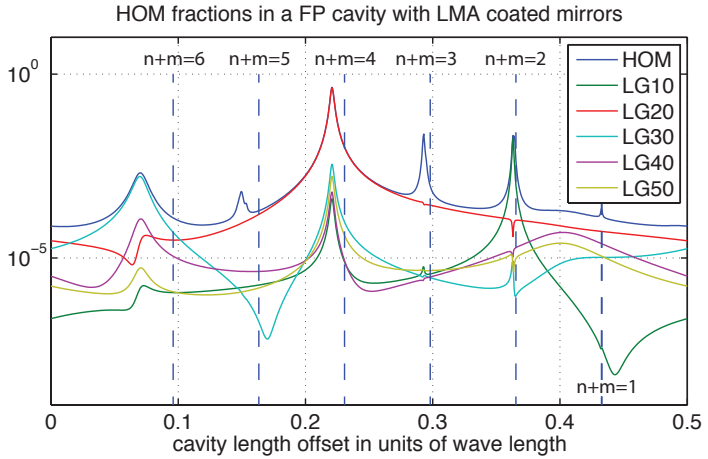


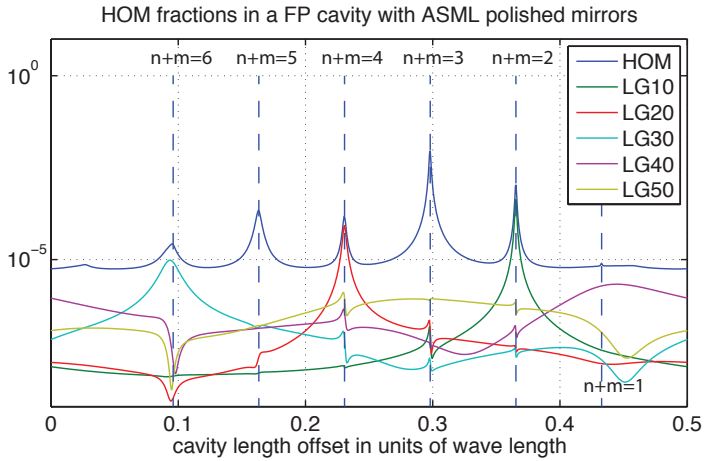




HOM peak and effective RoC

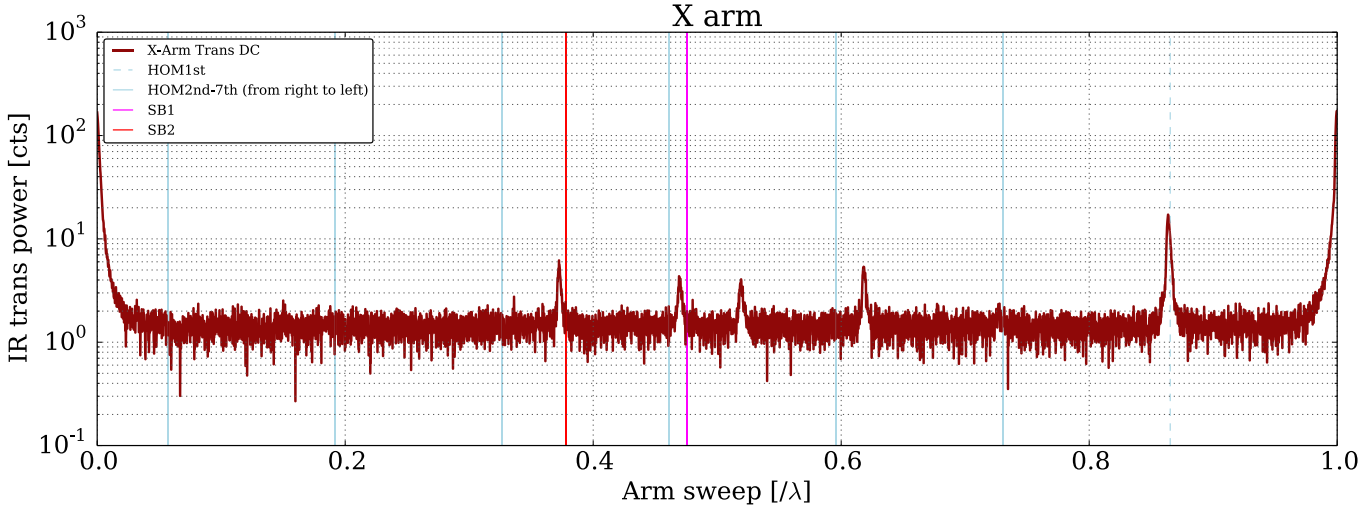


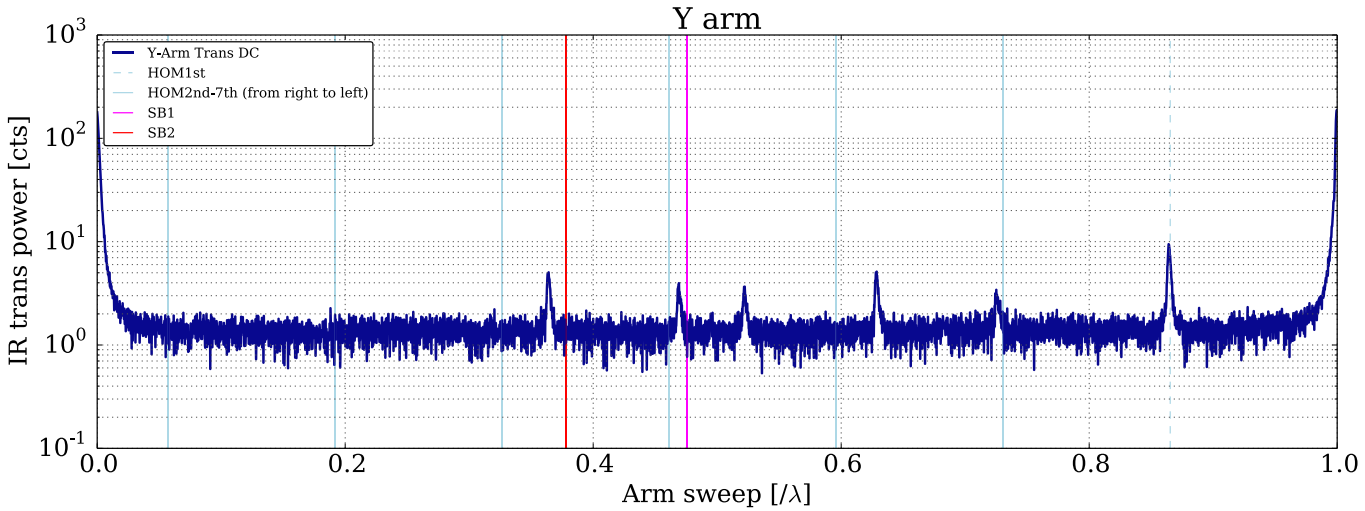




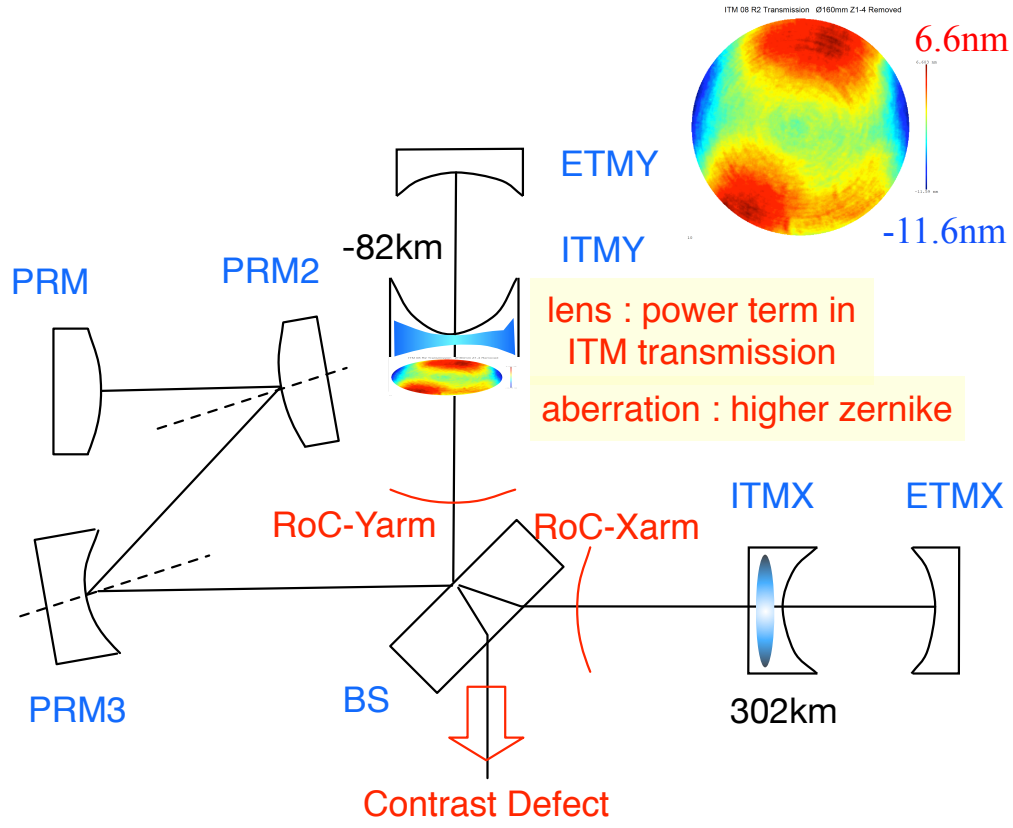
Arm scan : alog 14022

To do : calibrate the VCO linearity and refine (and add errors to) the data analysis. VCO sweep was not completely nice and linear.





Contrast Defect
412ppm : alog13916

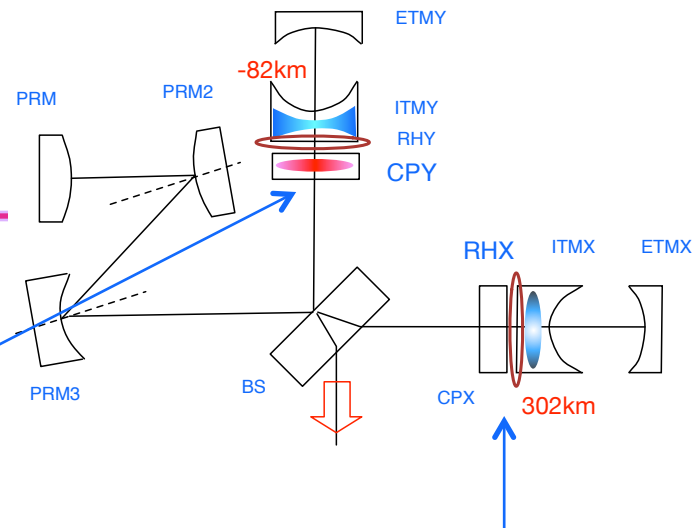


CR only CD, no TCS

	No BS aperture	BS02	BS05
no lens no abr	44	200	82
lens abr	165	280	300
lens no abr	120	260	230
no lens abr	60	200	100

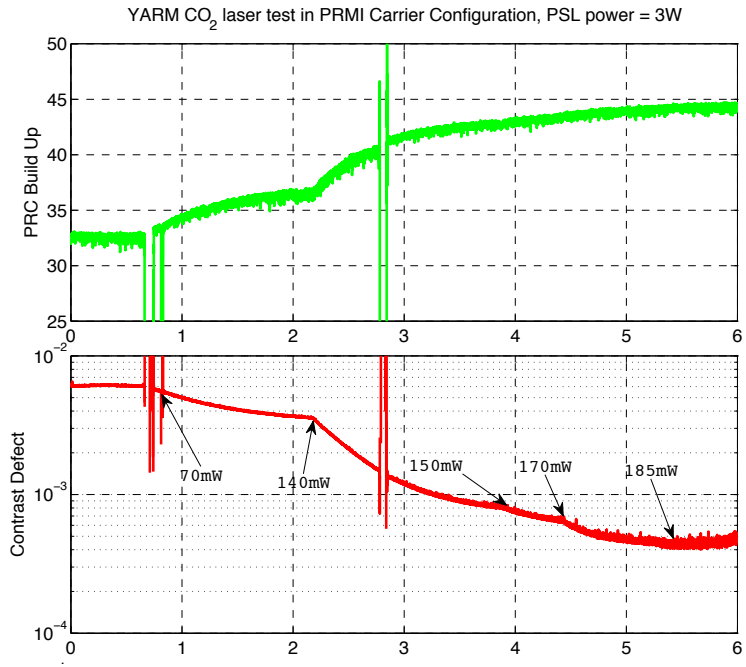
Beam center mismatch $\Rightarrow (a / 2w)^2 = 100$ppm for a=1mm

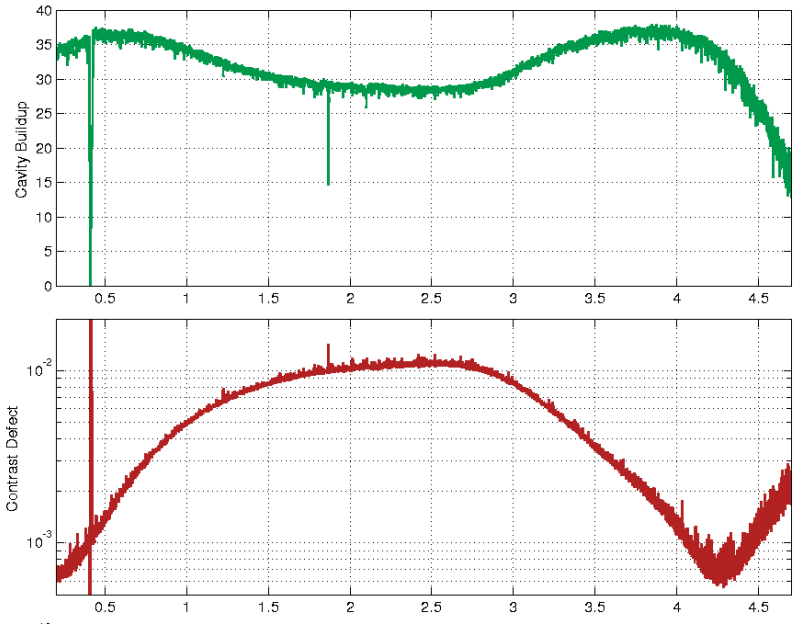
TCS corrections for LLO PRMI



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

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



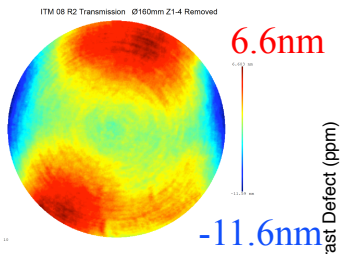


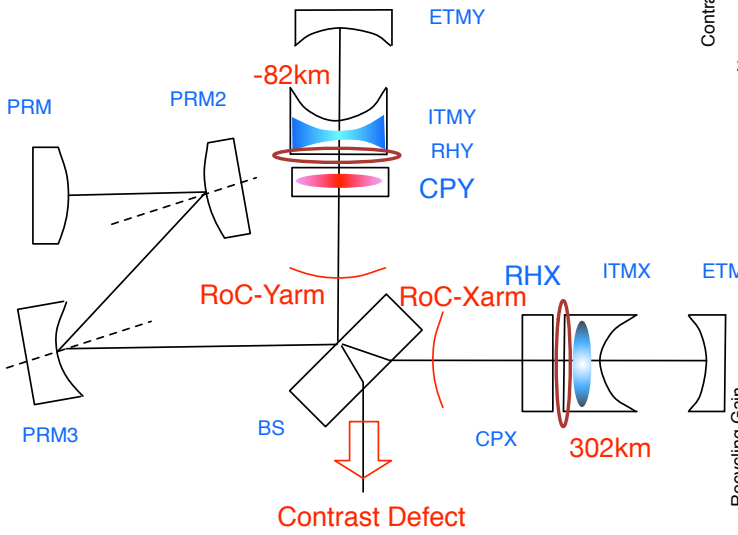
log11140 CD~400ppm, PRG~45

log#9733 CD~600ppm, PRG~35

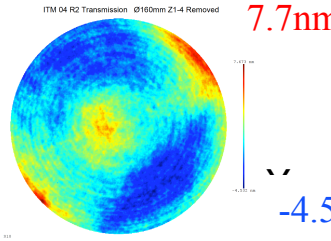
(In)Sensitivity on ITM SPTWE + CP lens

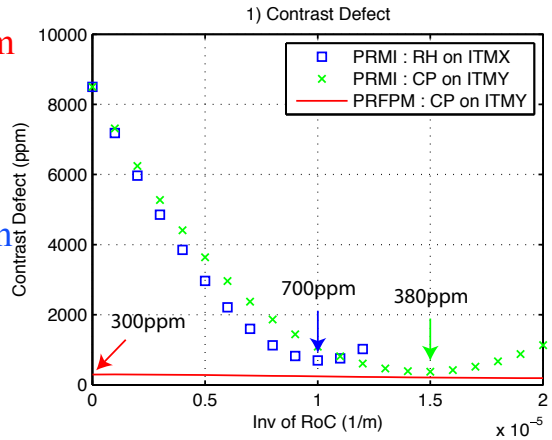
ITM08 / ITMY transmission map in 160mm w/o power

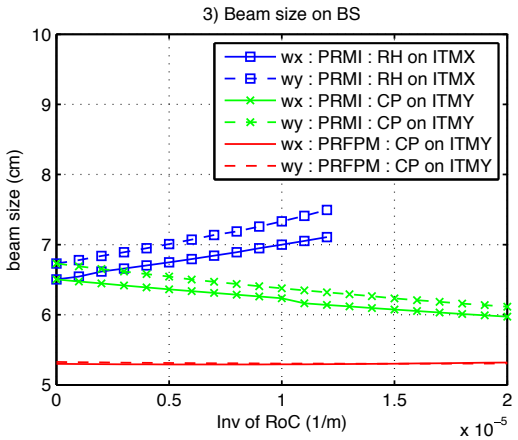


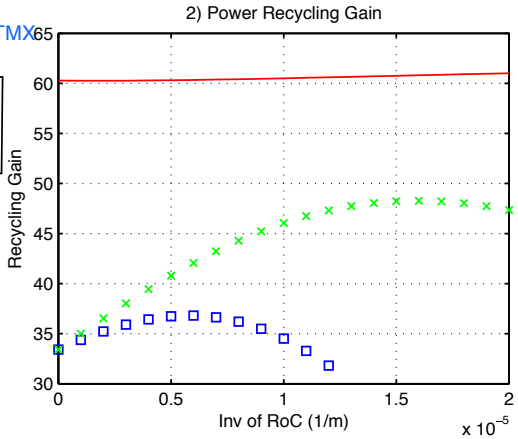


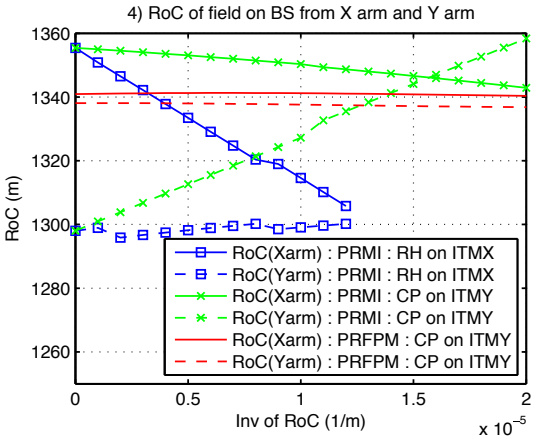
ITM04 / ITMX



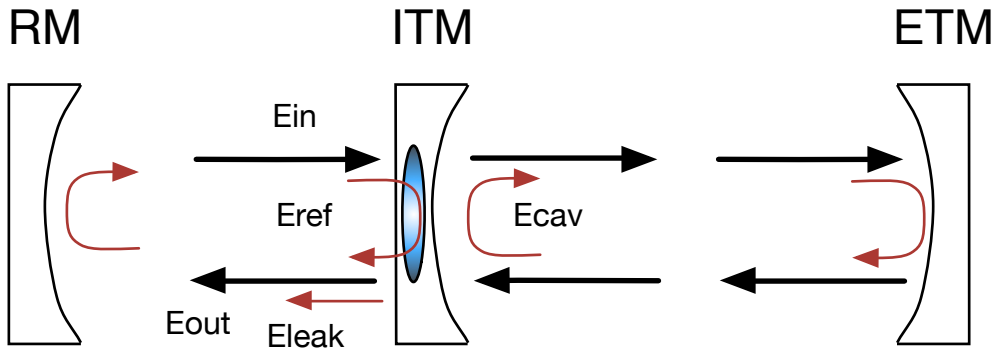








Cavity mode



- Recycling cavity mode is defined by RM HR reflection and ITM reflection, Ein to Eout, not Ein to Eref, just the same as length 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
- But, CR suffers in the second order