Mirror profile and intracavity field profile

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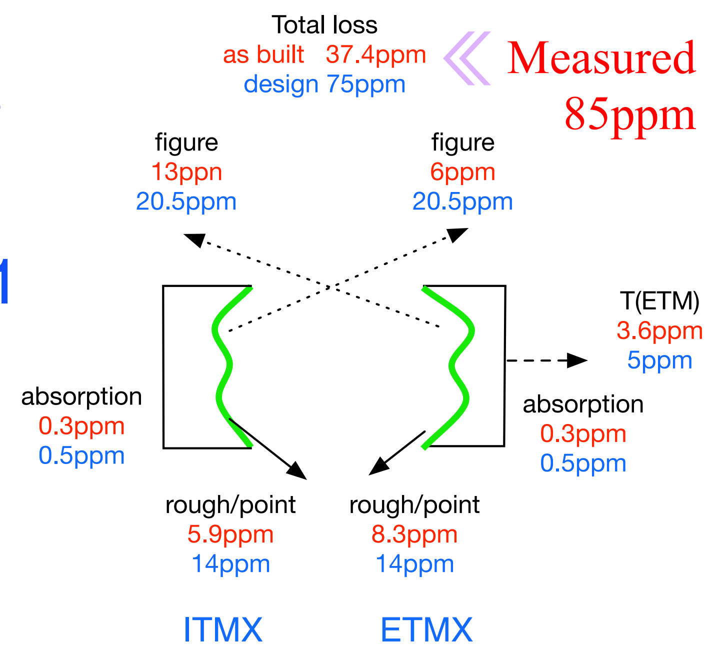
- Introduction
- Mirror spatial frequency and arm loss
- Point scattering and intracavity field
- Spiral patterns on ETMs at L1 and H1
  - » Imbalanced noise by spiral patterns
  - » Direct measurement of the cone scattering by spiral pattern
- Polishing vs coating for the future
- Summary, question to be answered



Mirror surface aberration, reflected field and intracavity field

$$E_{ref} = E^0_{ref}\exp(i\omega t - ikz)\cdot\exp(2ikf(x,y))$$

$$= E^0_{ref}\exp(i\omega t - ikz)(1-2(kf)^2) + E^0_{ref}\exp(i\omega t - ikz)i2kf$$

dF

$$f(x,y) = \sum_{nx,ny} a_{nx,ny}\sin(n_x\omega_x x + n_y\omega_y y + \varphi_{nx,ny})$$

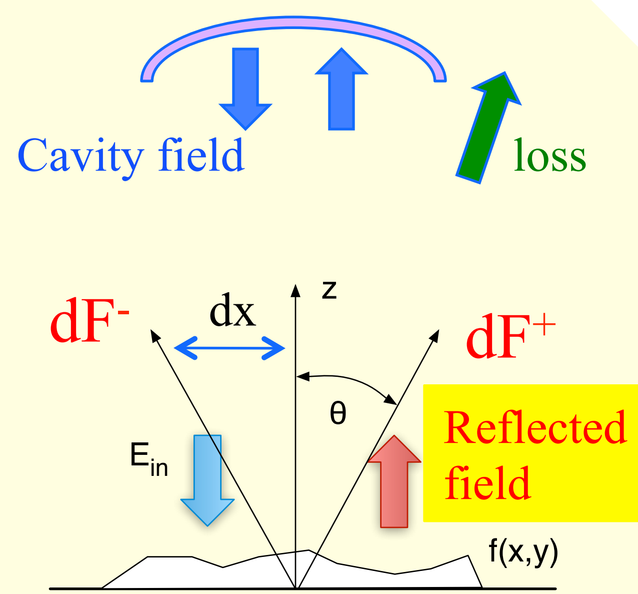
$$dF = E^0_{ref} k \sum_{nx,ny} a_{nx,ny}(\exp(i\Phi^+_{nxny}) - \exp(i\Phi^-_{nxny}))$$

$$\sigma^2 = \frac{\iint dx\,dy f^2}{S}$$

Small size aberration

$$dW = \iint dx\,dy \left|E^0_{ref}\right|^2 4k^2 f^2$$

$$= P^0_{ref}\left(\frac{4\pi\sigma}{\lambda}\right)^2 S$$



Mirror surface aberration

* Periodical aberration scatters to a fixed angle

$$\theta \sim n\sqrt{\omega_x^{\,2} + \omega_y^{\,2}}\,/\,k \sim n\cdot\lambda/a,\ \ dx = L_{cav}\cdot\theta \sim L_{cav}\cdot\lambda/a$$

* Small size aberration scatters back spherically

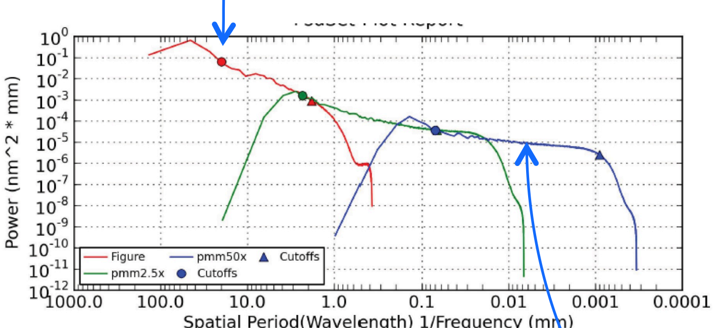
$$loss = (1-(\text{mirror size / cavity length})^2)\bullet dW$$

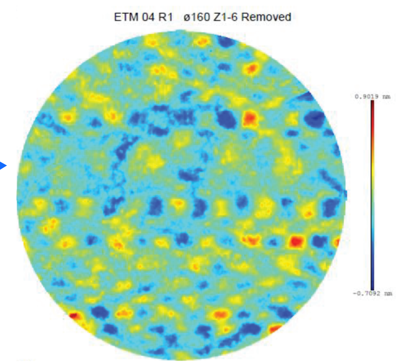
Measured mirror profile and intracavity field

Mirror profile	Spatial resolution	Field angle	Cause and effect in cavity
Phase map	> 1mm	< 2 x 10^{-4} rad, < 1m at 4km	Intracavity fields and near the edge of mirror, cavity modea
PSD, RMS, BRDF	1µm ~ a few mm by PMM, + phase map	~ large angle	Characterization of continuous structure, field scattered out to large angle
Integrating sphere	fraction of mm	> 5 degree	Total scattering to almost all angle, effects of non contiguous (point) structures captured. Near backward is covered by others.

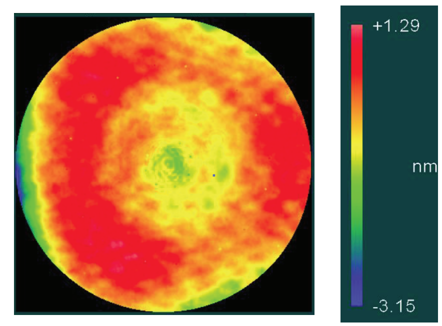
COC mirror data (characteristics of mirror) +
appr. Maxwell eq. with rigorous boundary cond.
⇒ IFO observable

Raw data of mirror profiles

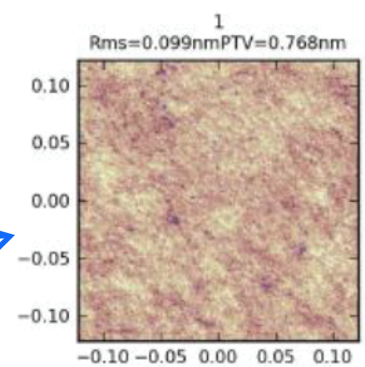




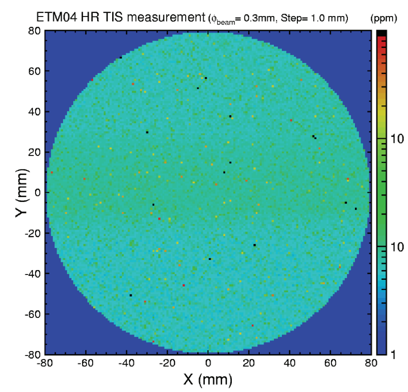
(1) Surface after polishing by ASML
Aperture size 160mm
RMS = 0.1732nm, PV=1.611nm



(2) Surface after multilayer coating by ison spattering
Aperture160mm
RMS = 0.563nm, PV=4.436nm



(3) Surface after polishing measured by PMM(phase measuring microscope) with magnification of 50.
0.25mm x 0.25mm square near center.
RMS = 0.099nm, PV=0.768nm

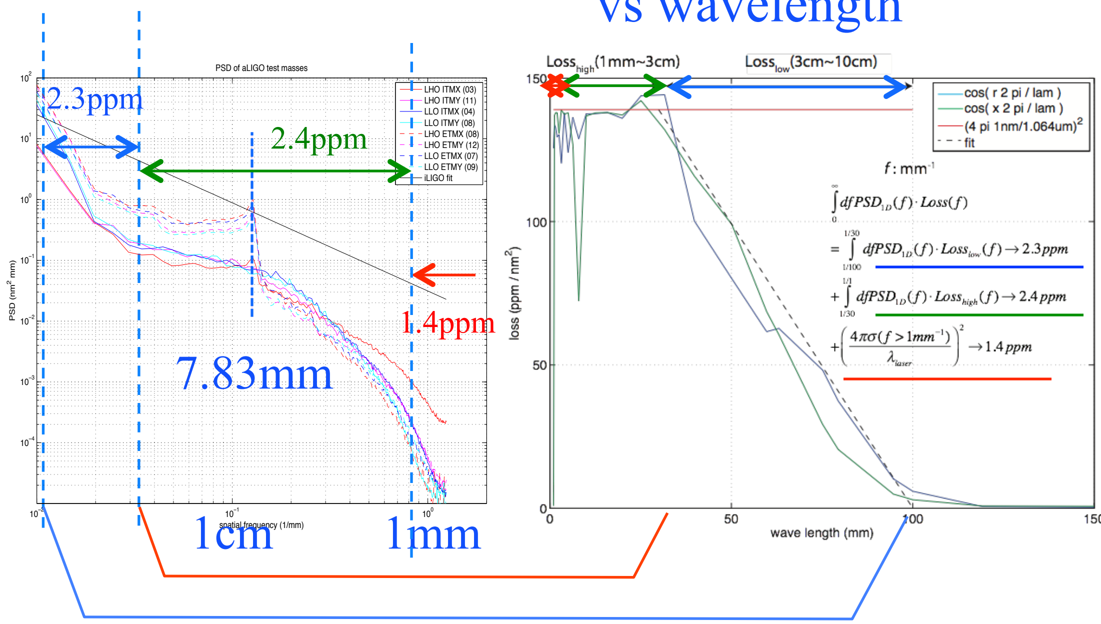


(4) Reflectance measured by an integrating sphere with the scattering angle larger than 1°. The size of the laser is 0.3mm, with spacing 1mm.
RMS using all data points is 98ppm. RMS is 20ppm after excluding 15 points with reflectance > 1000ppm

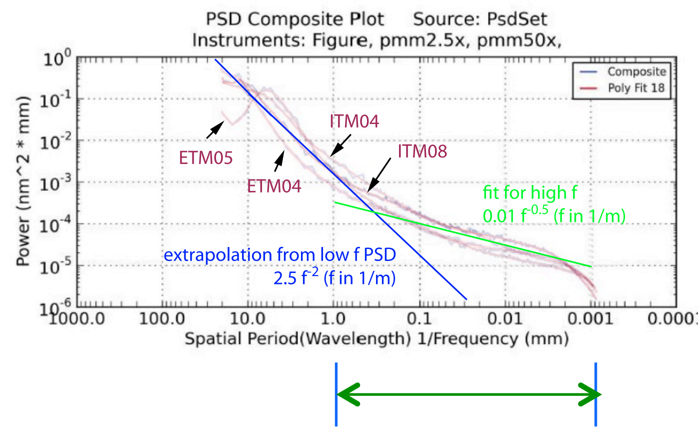
aLIGO cavity scattering loss by wavelength

Mirror surface profile

Loss of intracavity field vs wavelength



Not so simple PSD

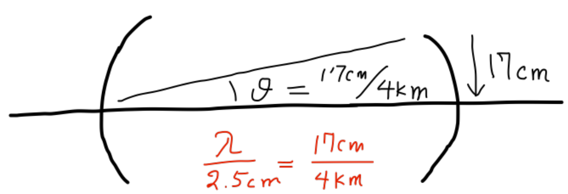


$$\sigma(1mm \sim 1\mu m)^2 = \int_{1/1mm}^{1/1\mu m} PSD(f)df = (0.14nm)^2$$

$$\left(\frac{4\pi\sigma(1mm \sim 1\mu m)}{\lambda}\right)^2 = 3ppm$$

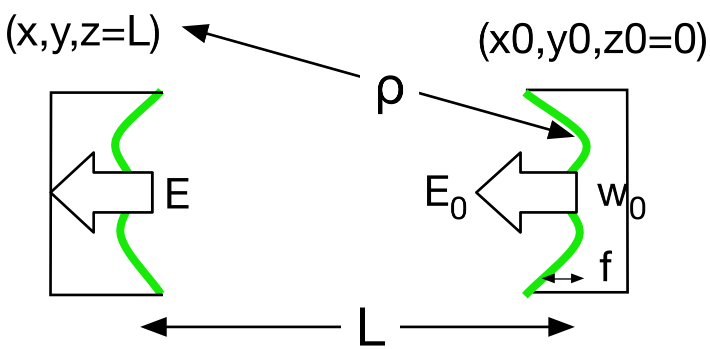
$$\left(\frac{\sigma(3mm \sim 1mm)}{\sigma(1mm \sim 1\mu m)}\right)^2 = \frac{1}{40}$$

Geometrical acceptance



Far field structures

field PSD(θ) ≠ mirror PSD(f), const BRDF⇒wrong loss



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

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

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

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

Point source : dF ⇒ const BRDF ⇒ $2\pi\, dS / \lambda^2$ x true scattering

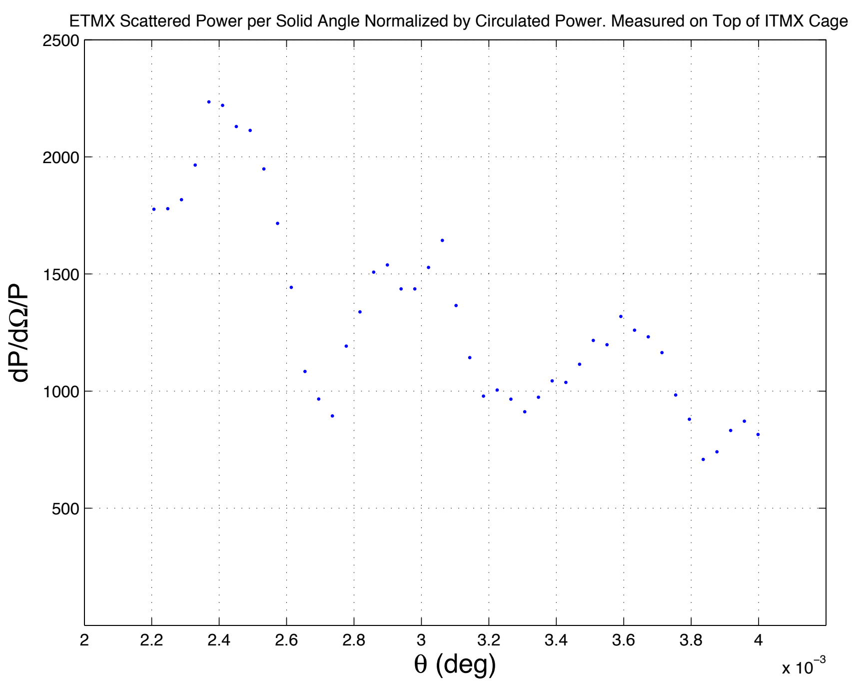
PSD to dF : $$|dF[x,y,z]|^2 = \frac{32\pi^2}{w^2\lambda^4 L^2}\left|\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Delta[f_u,f_v]\,\delta\left[f_u - \frac{x}{\lambda L},\varepsilon\right]\delta\left[f_v - \frac{y}{\lambda L},\varepsilon\right]\mathrm{d}f_u\mathrm{d}f_v\right|^2$$

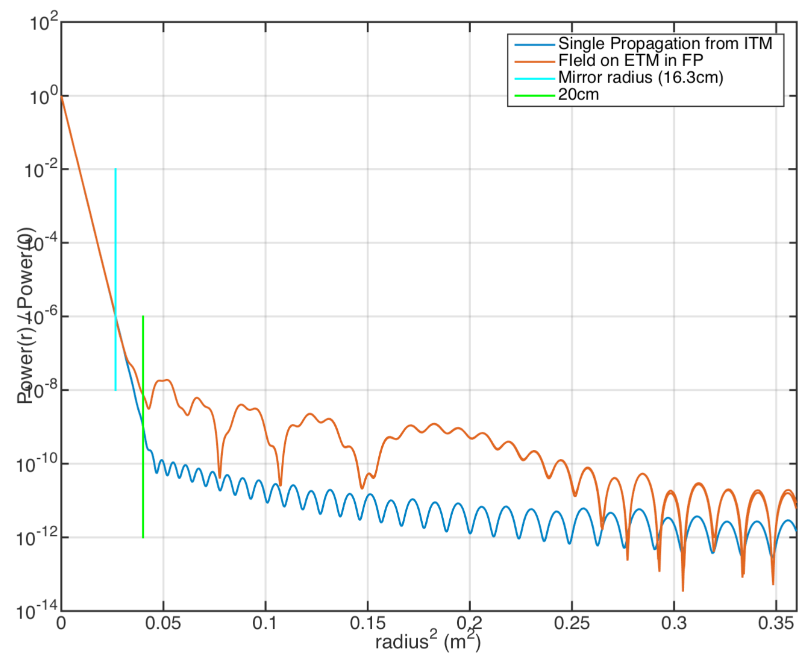
Δ : 2D amplitude spectral density, ε~1/a few cm

Single propagation vs cavity field
Airy ring outside of mirror

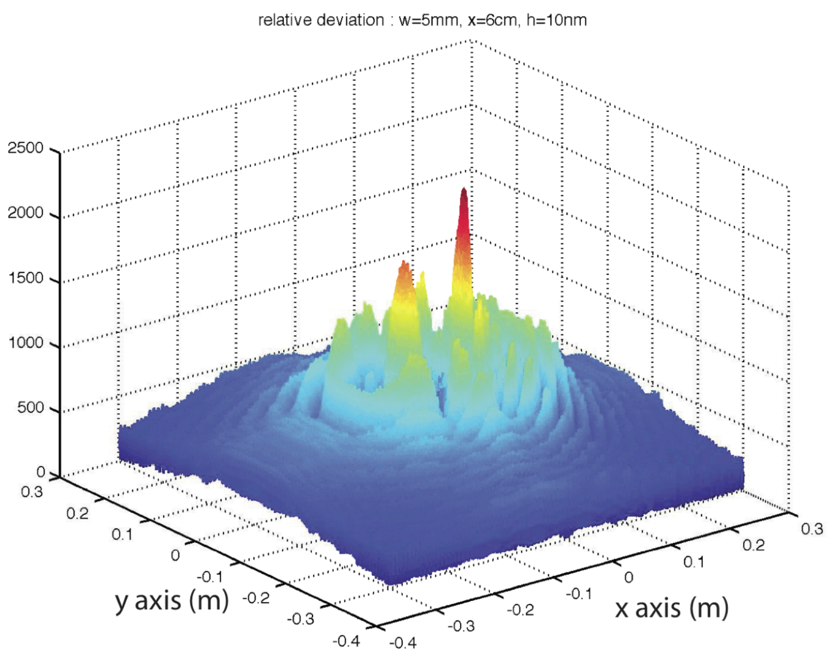
iLIGO data by Valera

aLIGO simulation :
single propagation vs
resonating field around cavity





Small anomaly induces widespread tiny disturbance



$$dW(loss) = \sum_{anomalies} \left(\frac{4\pi\sigma_a}{\lambda} \right)^2 S_a \cdot P_a$$

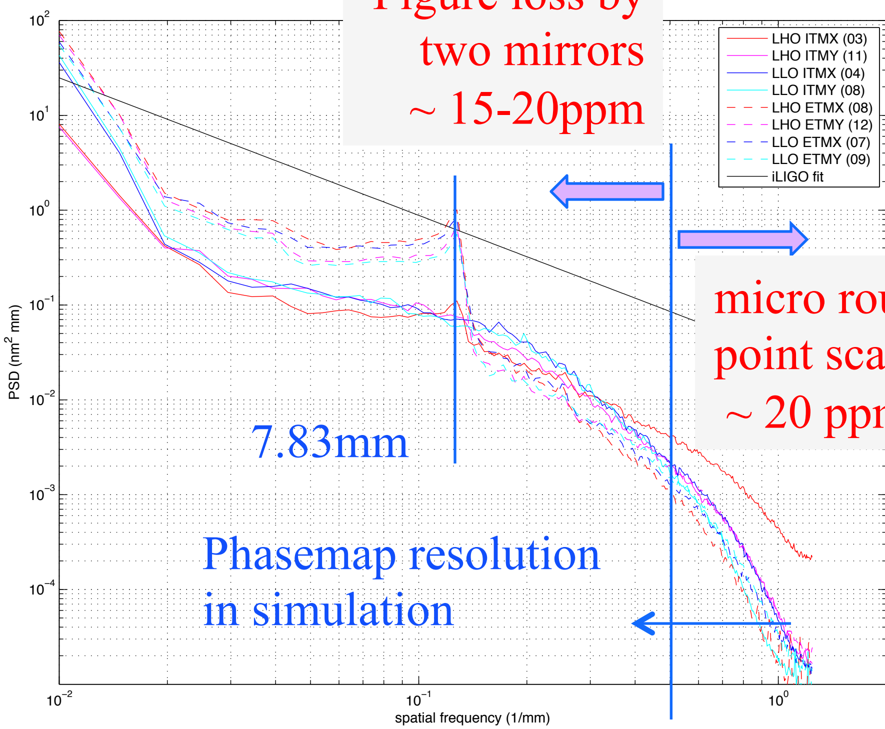
- Disturbance of fields by a point anomaly propagates out spherically
- Intracavity field is affected entirely, not partially
- Disturbance induced by a point anomaly is widespread weakly
- Difficult to measure the effect, except for using the total loss measurement

LMA coating on ETMs

- This is about the installed ETMs at L1 and H1
- State of the art coating is presented in the talk by Laurent Pinard of LMA

Periodical structure on a mirror induces reflected field into a cone with a fixed angle

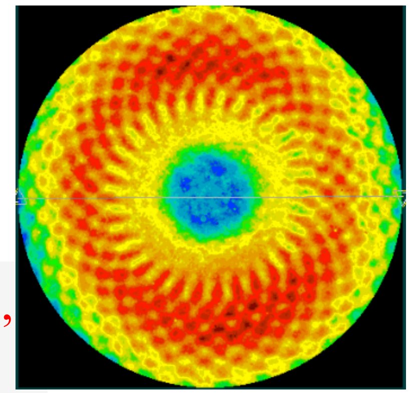
Figure loss by two mirrors ~ 15-20ppm



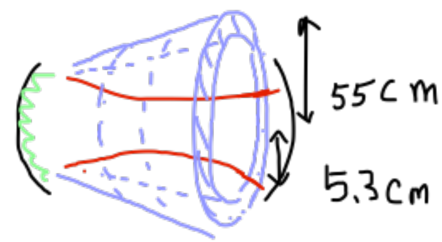
micro roughness, point scattering ~ 20 ppm

7.83mm

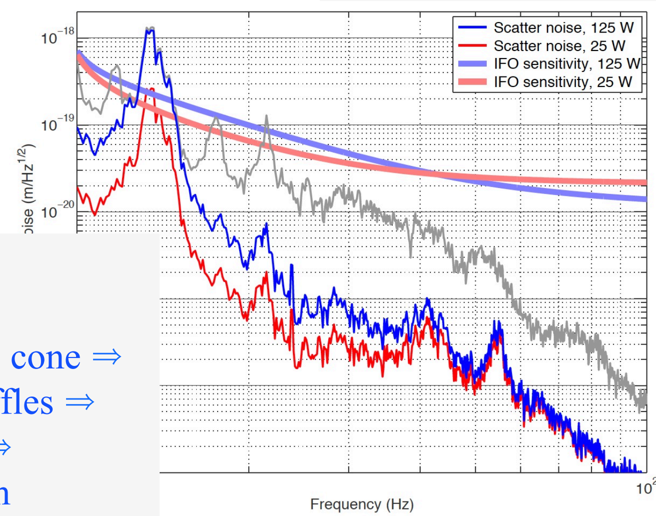
Phasemap resolution in simulation



ETM07 map



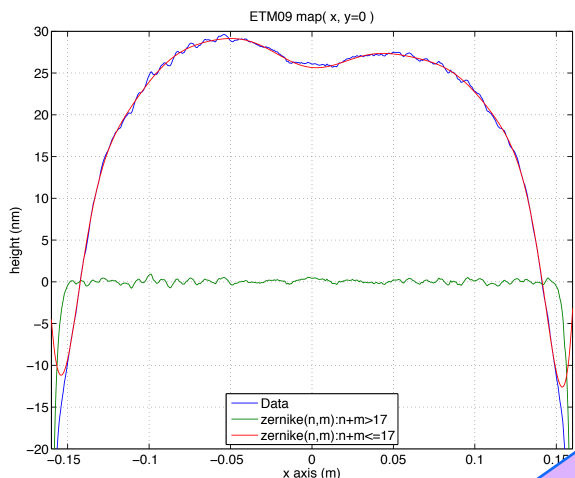
T1300354 by PF,HY

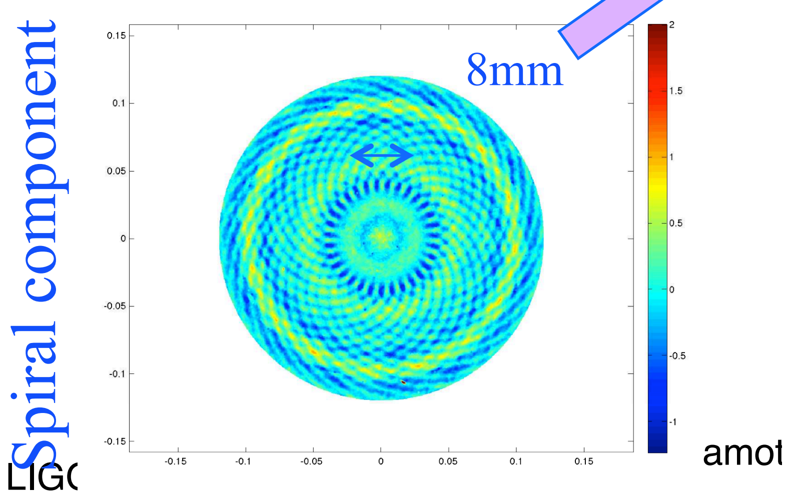


main beam ⇒
ETM reflection ⇒
larger angle scattering into cone ⇒
reflected by beam tube baffles ⇒
back scattered into ETM ⇒
merged into the main beam

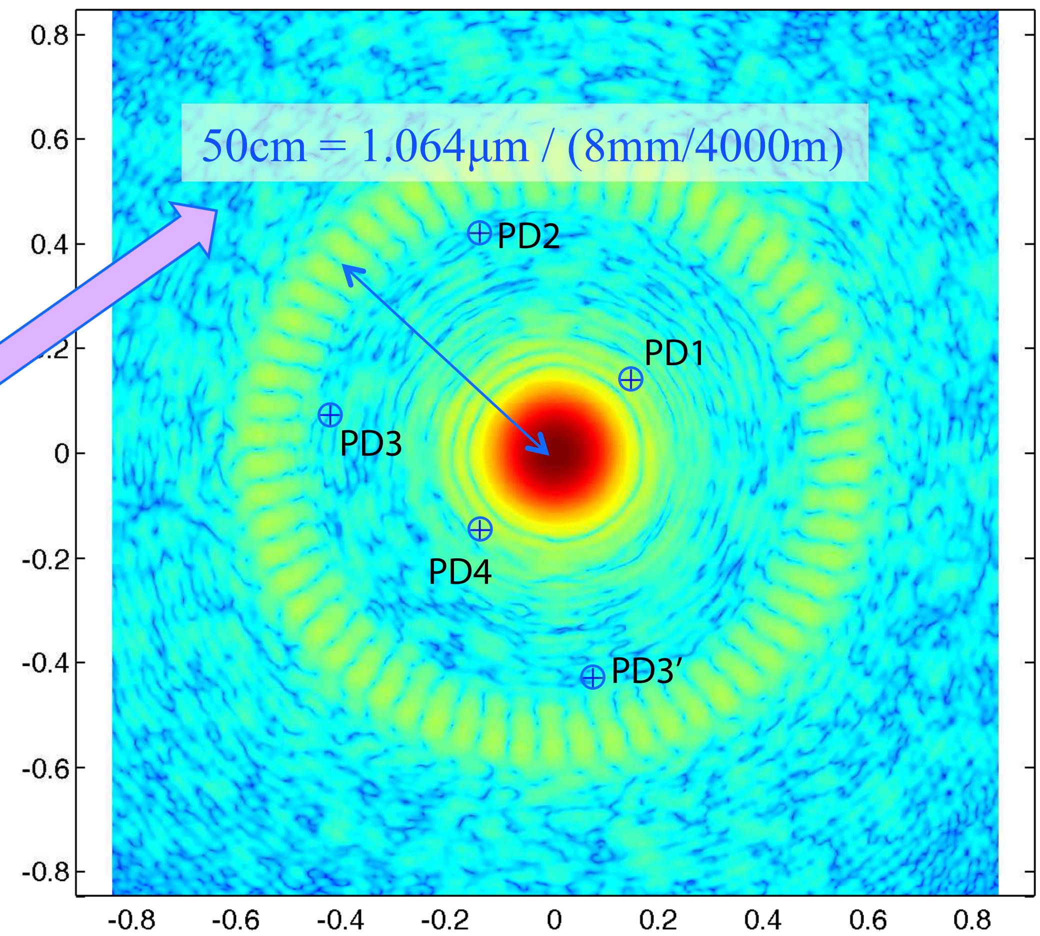
Detection of the scattering to cone using test mass baffle PDs

ETM09 map



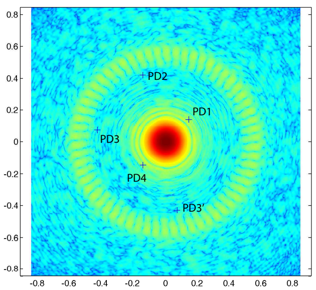


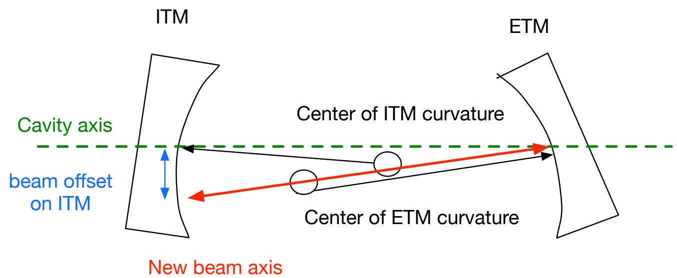
Field going to ITM

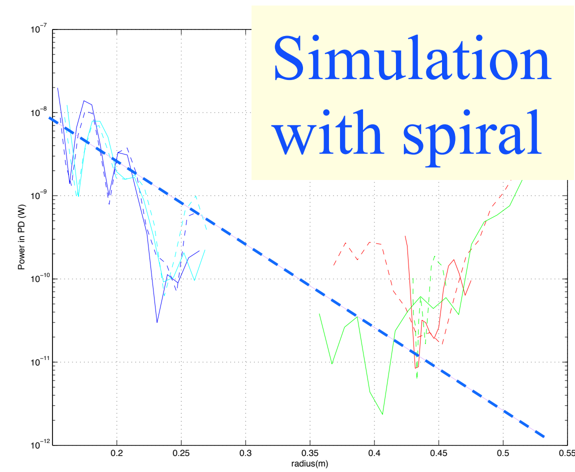


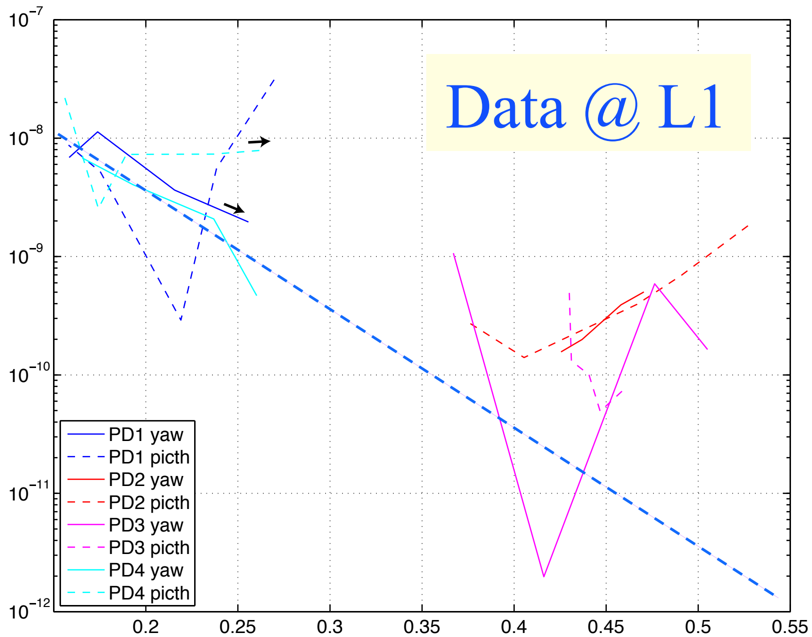
Real PD diameter is ¼ of ○

Signature at L1 ITM baffle PDs

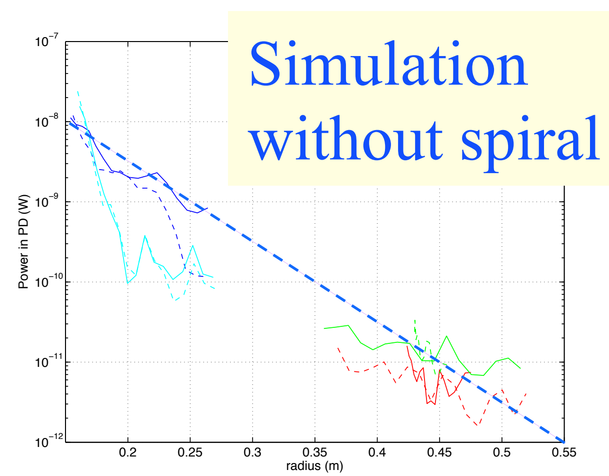








Distance of PD from center

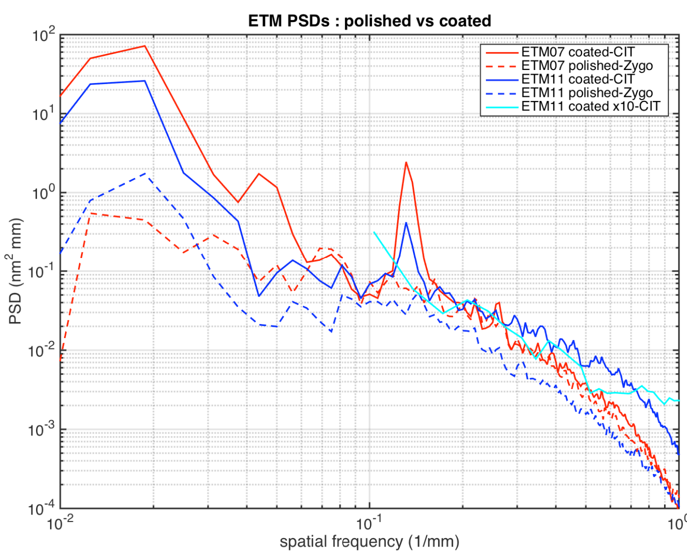


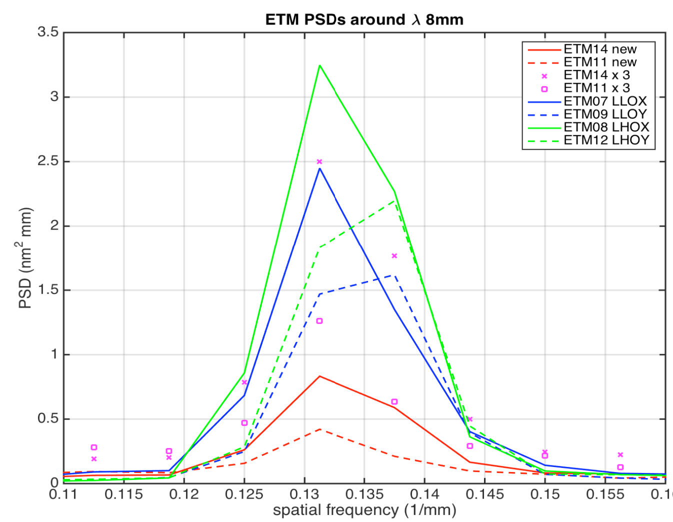
Different backscattering noise?

L1 H1

	ETM14	ETM11	ETM07	ETM09	ETM08	ETM12
power (45cm~70cm)	2.4	1.5	6.3	4.3	7.7	5.2
round trip loss	74	73	80	78	80	80
HOM	226	283	208	288	227	312

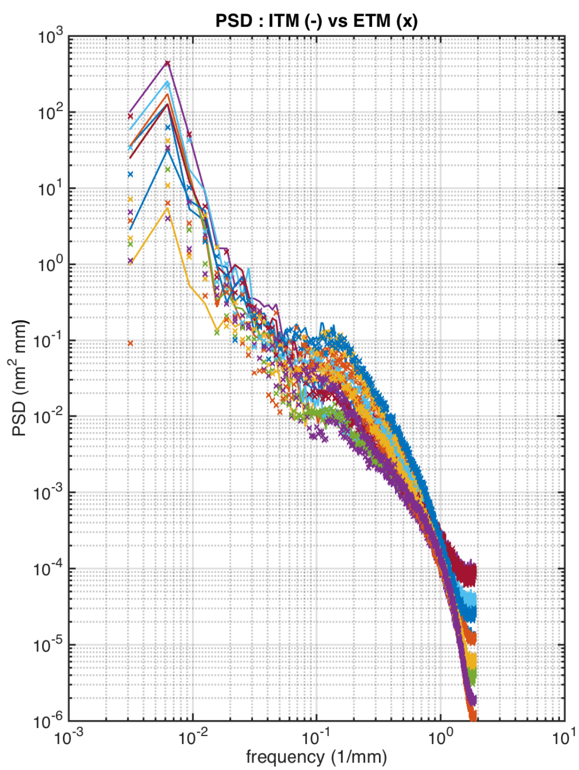
Small, but into a fixed direction



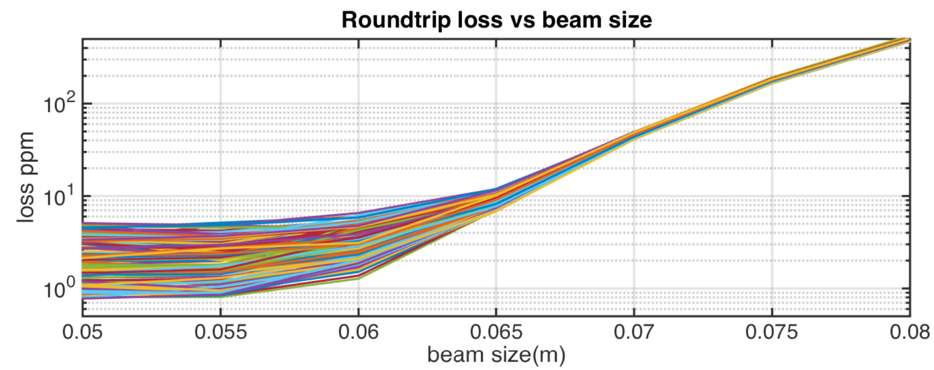


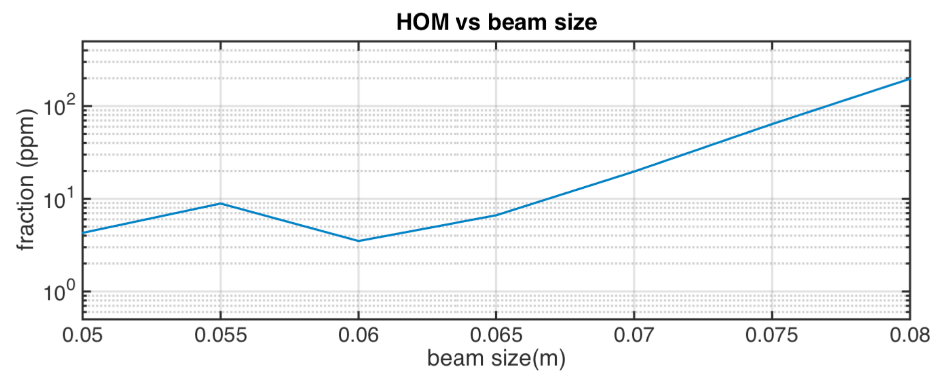
For the future …
Polishing, not bad

aLIGO ITM/ETM Polished map PSD

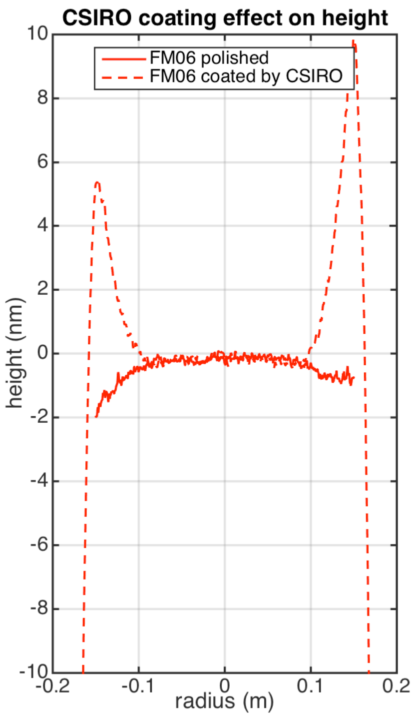


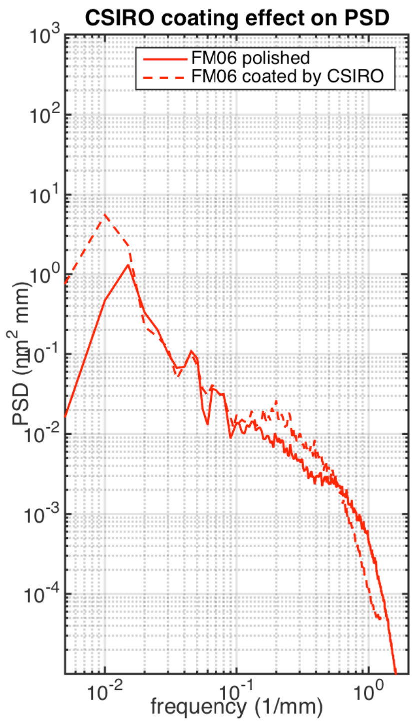
Round trip loss and HOM in a symmetric FP cavity

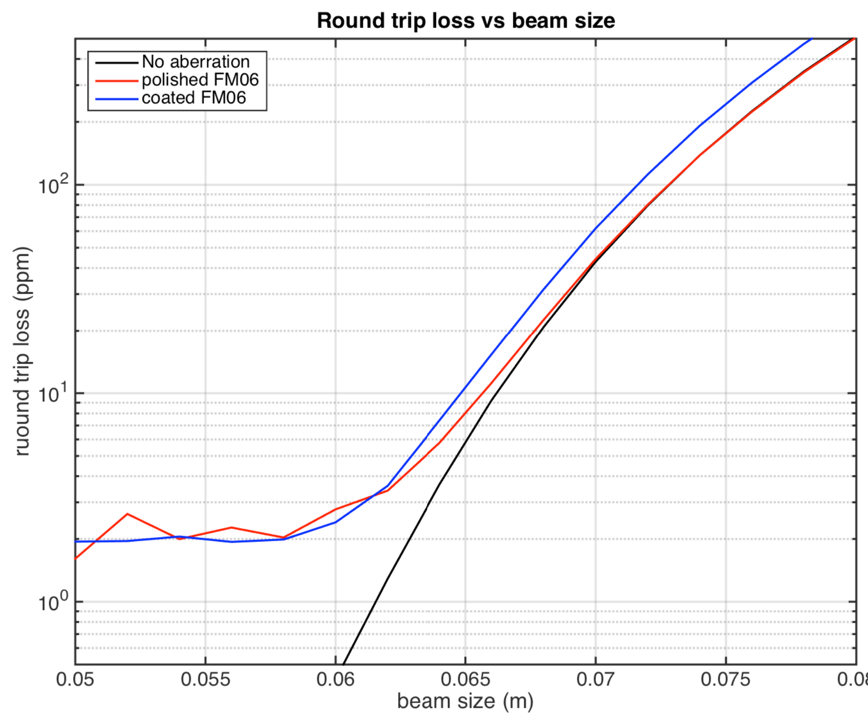




Coating uniformity
some improvement wanted

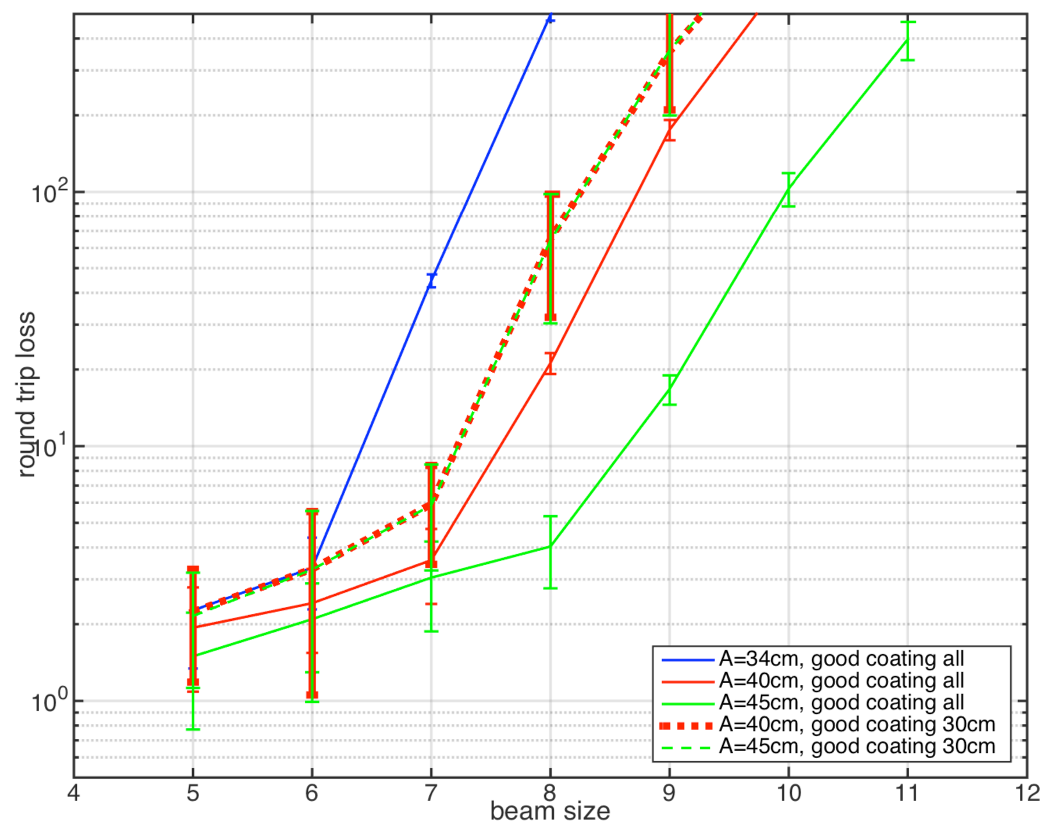






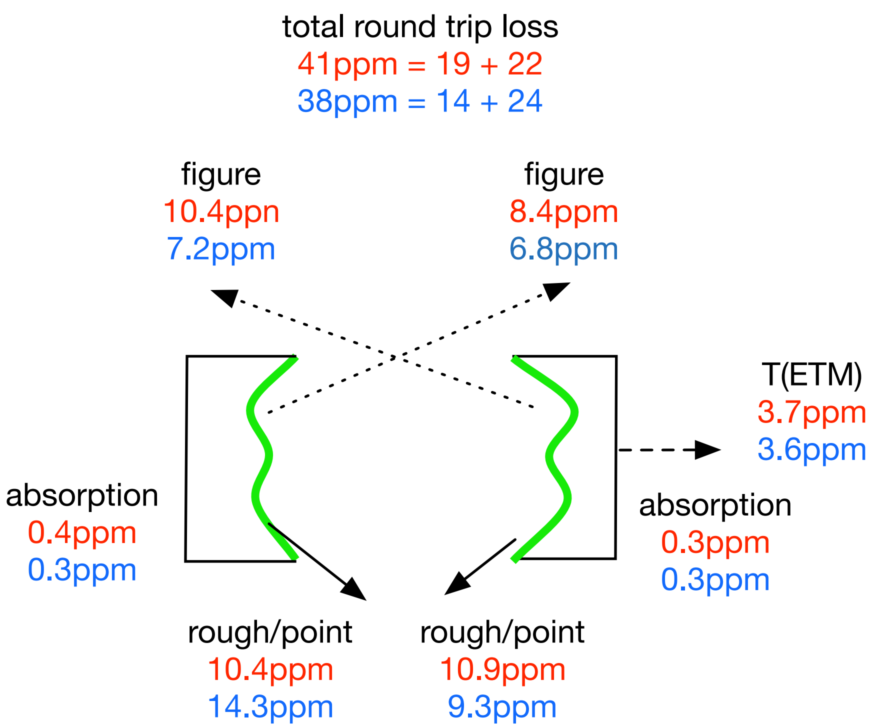
Coating limits
larger beam size configuration

- Larger optics can accommodate larger beam size
- Polishing is good enough for that (solid lines)
- Polishing uniformity can limit that (two dashed lines)



Missing loss of 40ppm needs to be well understood to discuss future IFO loss

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