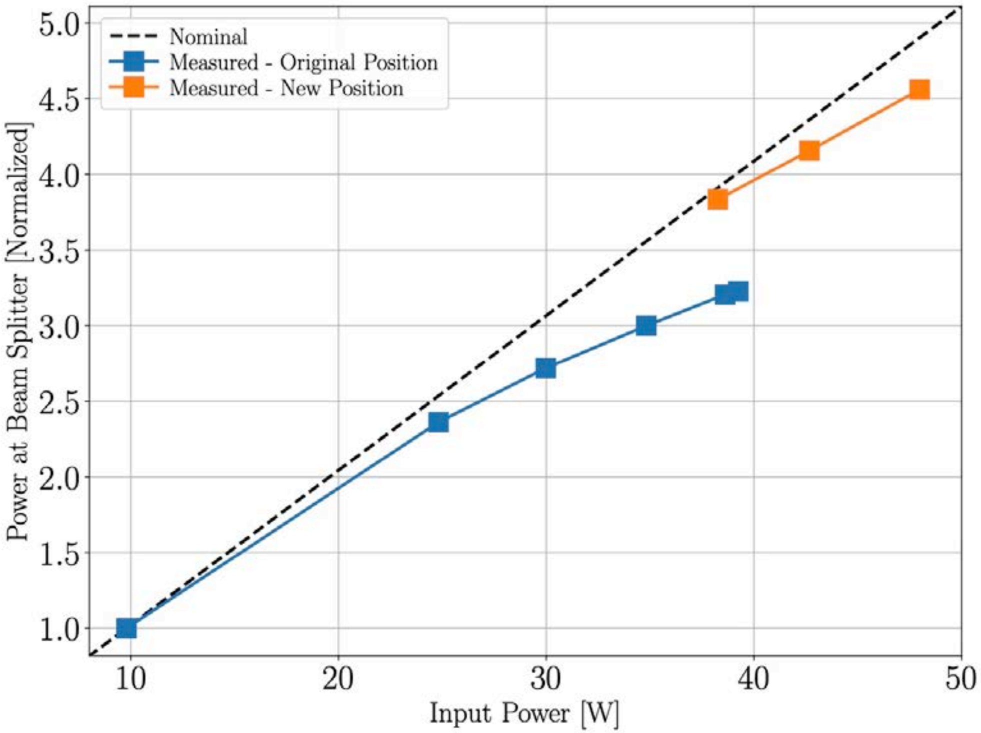
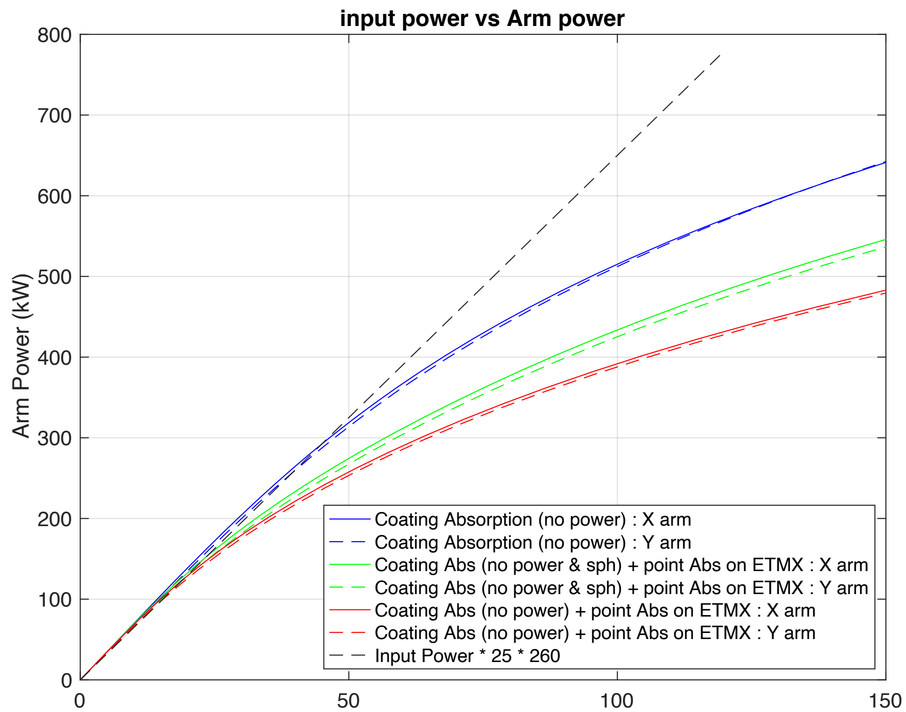
ETM Profiling to mitigate cavity loss due to point absorbers

G2001160, G2001530



LLO data
LIGO-P2000122 PRD accepted 2020



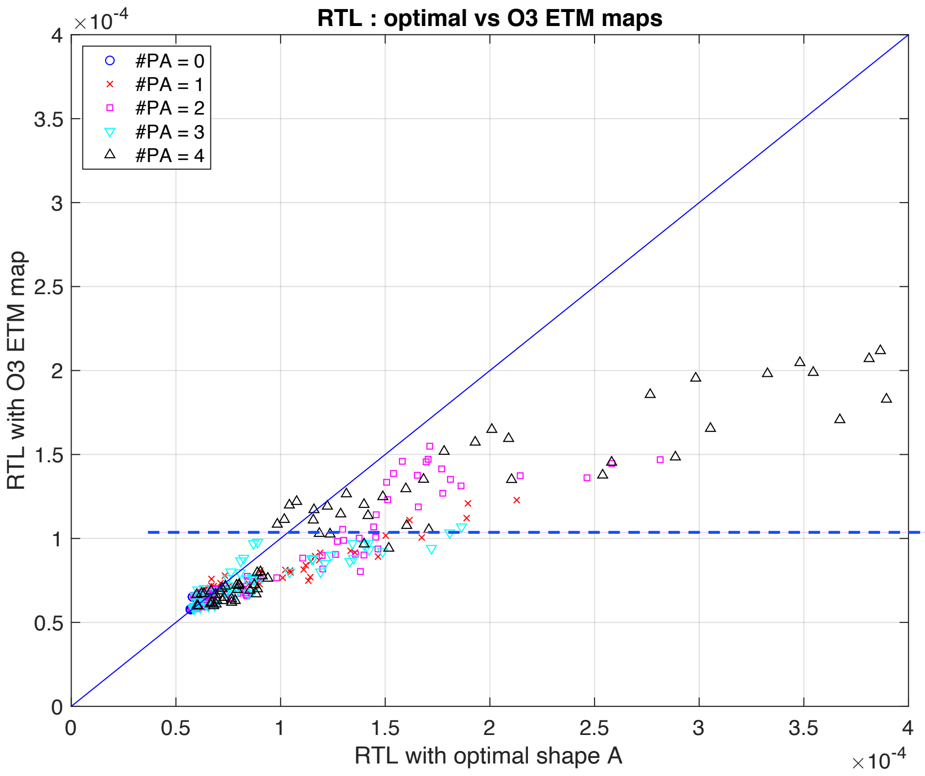
Model prediction of arm power loss due to point absorber and coating absorption

LIGO Addition on November 14, 2020

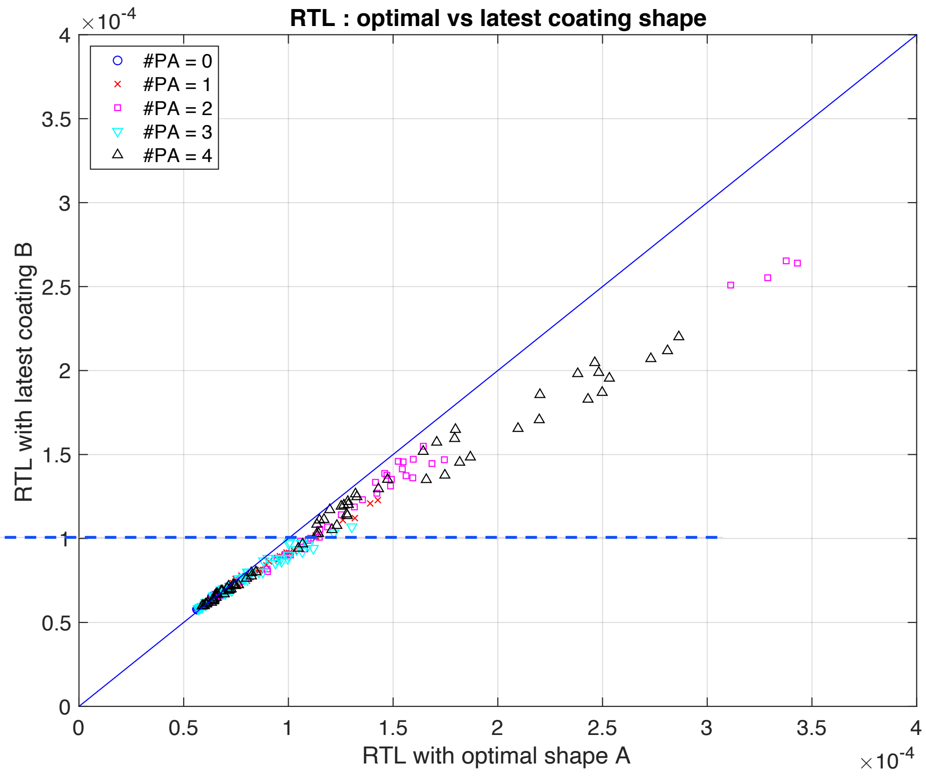
optimized polishing may not be necessary

RTL using optimized surface shape vs using coating thickness nonuniformity

O3 ETM map



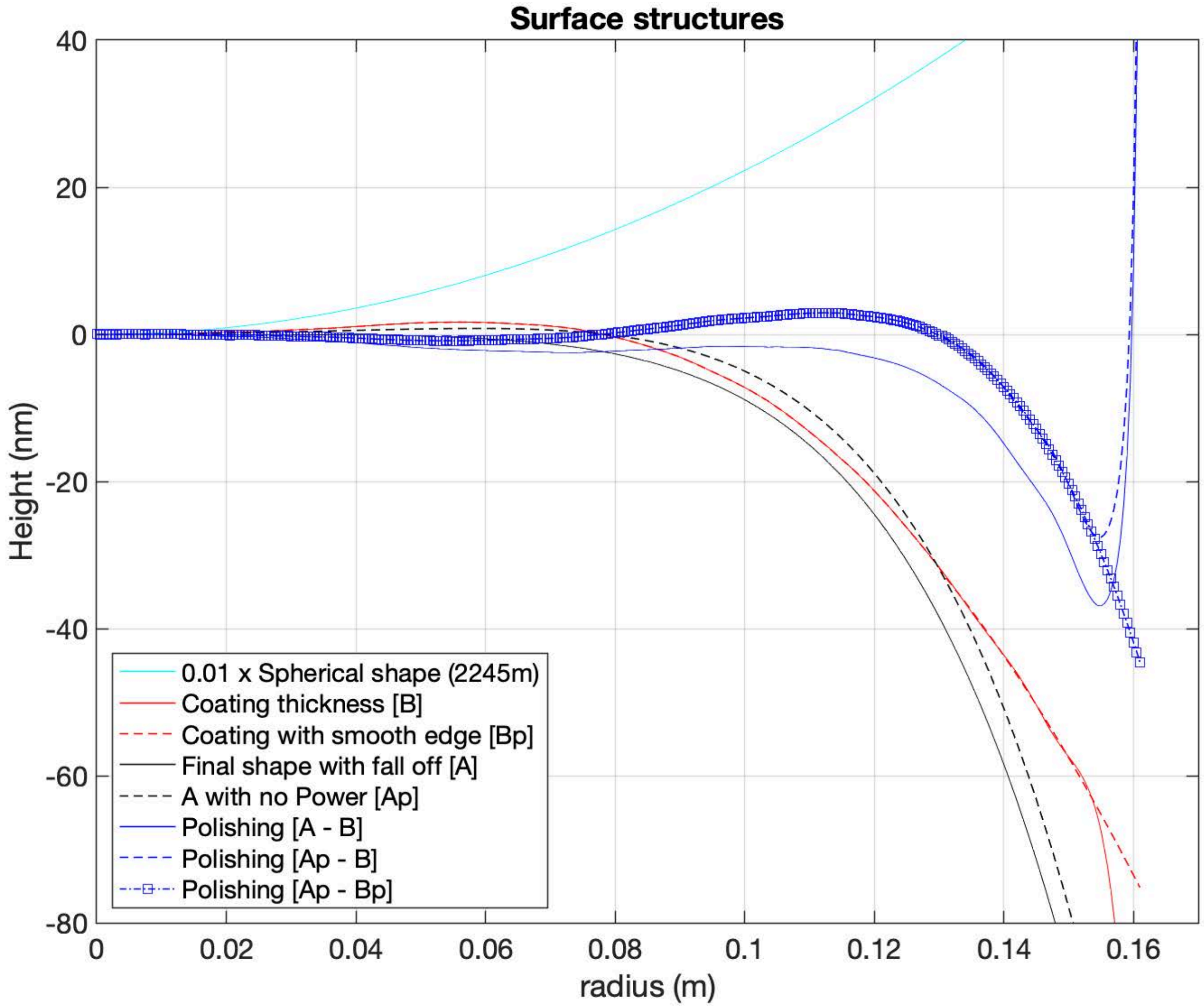
Latest coating nonuniformity



100 cases with #PA = 0~4, random location, random power

polishing design to realize idealistic mirror surface

- A is idealistic mirror surface
- Ap is A – power term to simplify the RoC specification
- B is the latest coating shape
- Bp is to make the polishing easier
- Polishing [A-B],[Ap-B],[Ap-Bp] are various options of mirror surface polishing



Effect of new coating is close to that of optimal shape

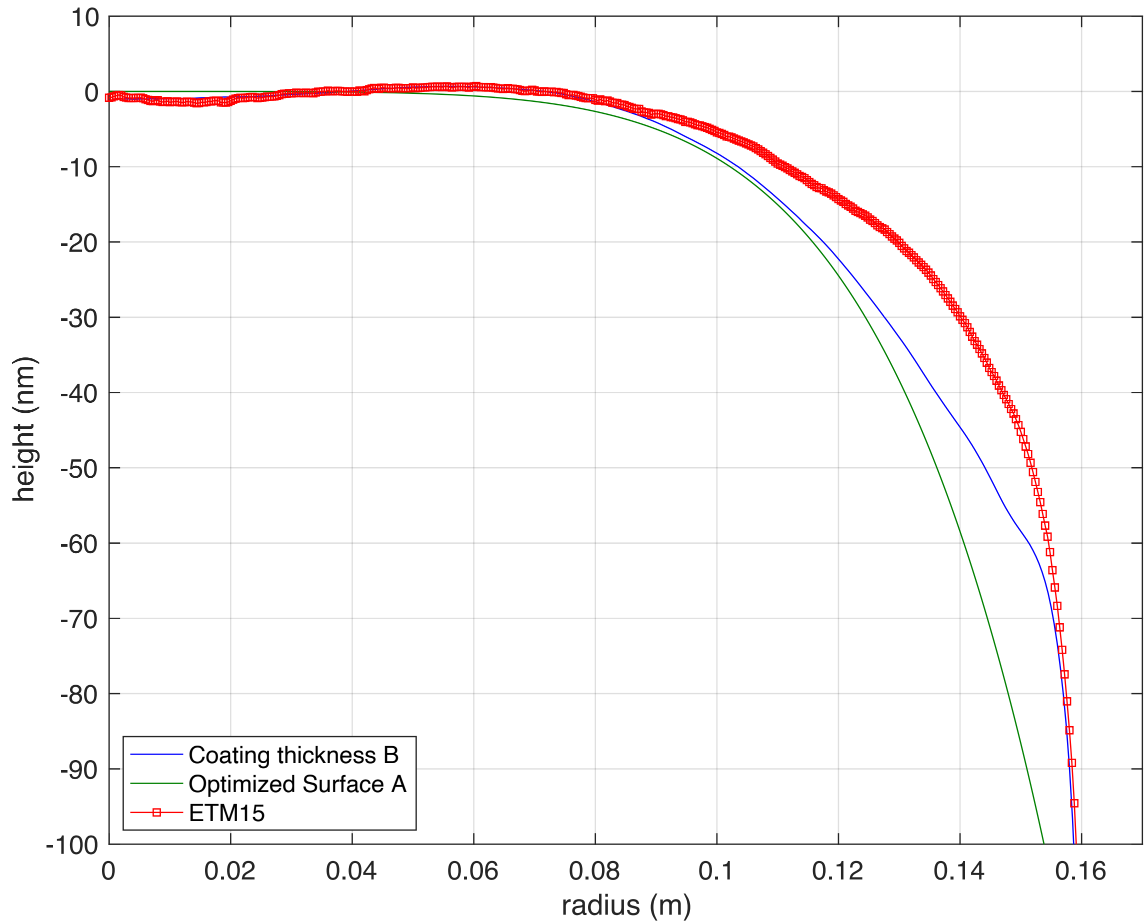
Power and RTL(ppm) with different ETM surface

sph+B : no special polishing, A-B : optimal polishing

		H1X		H1Y		L1X		L1Y	
		power	RTL	power	RTL	power	RTL.	power	RTL
No point absorber	sphere	262,	62.1	277,	65.4	266,	53.9	266,	55.5
	sph+B	262,	63.6	277,	63.8	266,	56.5	266,	57.2
	A-B	262,	65.2	277.	65.4	266,	57.8	266,	58.4
	A-Bp	262,	70.7	277,	71.0	266,	60.8	266,	61.1
	Ap-B	262,	65.6	277,	65.6	266,	57.7	266,	58.4
	Ap-Bp	262,	70.5	277,	70.6	266,	60.3	266,	60.7
One point absorber at 2cm with 30mW	sphere	257,	211	272,	183	261,	185	261,	195
	sph+B	261,	113	275	107	265	99.5	265,	94.9
	A-B	261,	98.9	276,	97.2	265,	89.3	265,	86.8
	A-Bp	261,	108	275,	107	265,	95.5	265,	92.5
	Ap-B	261,	102	276,	98.9	265,	90.5	265,	87.7
	Ap-Bp	261,	109	275	107	265,	95.5	265,	92.4

new coating shape is closer to optimal shape than O3 ETM

O3 map vs new LMA and optimal



Power (W)
RTL(ppm)
w_{ITM}, w_{ETM}(cm)

Performance with multiple PAs

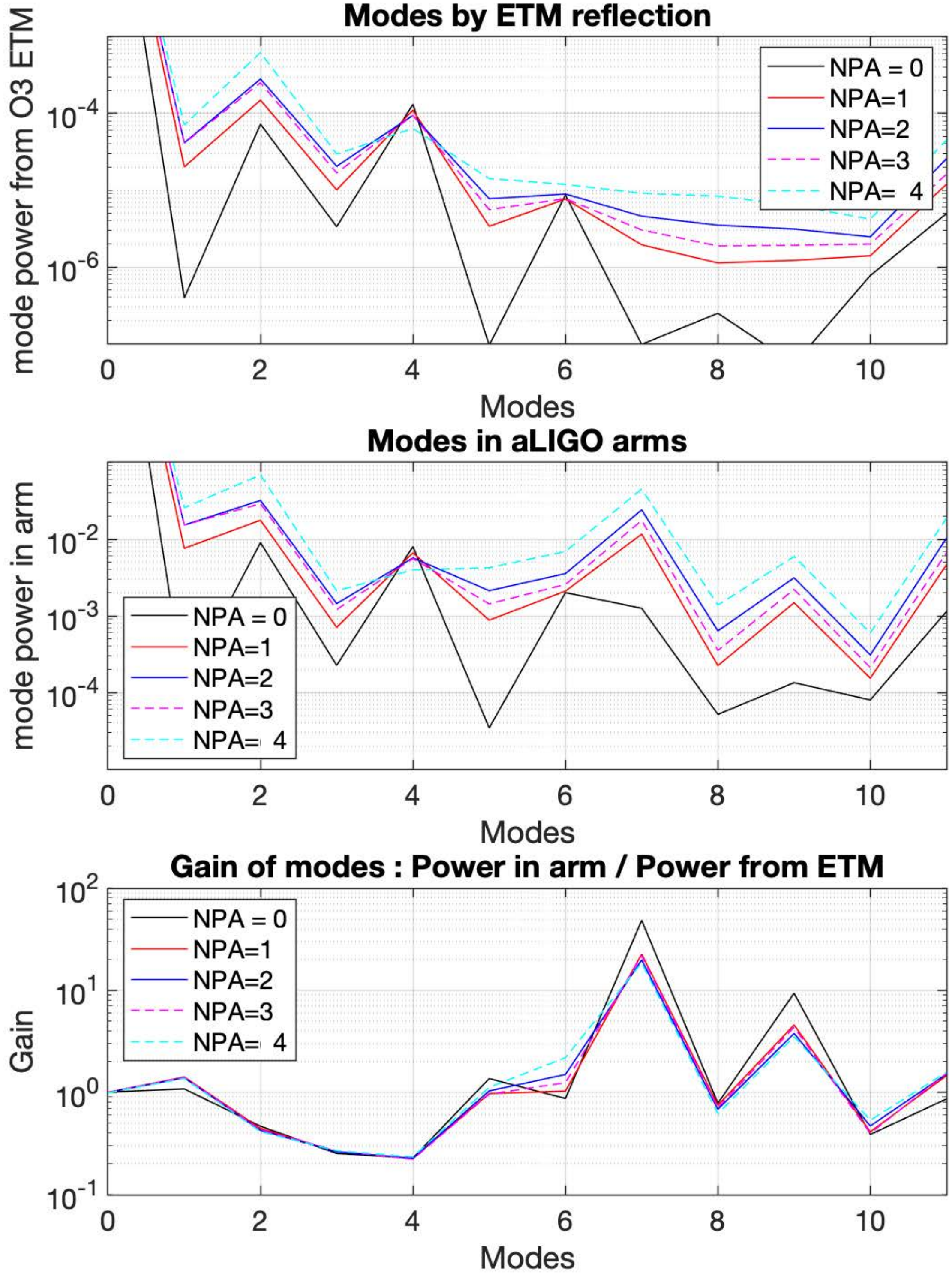
# point absorbers	0	1	2	3	4	all
Sph - Sph	264 55.9 5.26, 6.14	263 99.3 5.26, 6.13	262 121 5.25, 6.12	262 110 5.25, 6.12	257 271 5.22, 6.10	262 126 5.25, 6.12
ITM - Sph	264 58.4 5.26, 6.14	262 109 5.25, 6.12	262 131 5.25, 6.12	262 121 5.24, 6.12	257 282 5.22, 6.09	262 136 5.25, 6.12
As built O3 ETM maps	264 57.7 5.23, 6.12	263 88.0 5.22, 6.11	263 100 5.21, 6.10	263 94.0 5.21, 6.10	260 179 5.19, 6.08	263 102 5.21, 6.10
Latest coating map (B)	264 60.2 5.25, 6.12	264 77.6 5.24, 6.11	263 87.8 5.23, 6.11	263 82.3 5.23, 6.11	261 142 5.21, 6.08	263 88.5 5.23, 6.11
Optimal mirror shape (A)	264 61.7 5.23, 6.09	264 74.6 5.23, 6.08	263 83.1 5.22, 60.8	263 78.0 5.22, 6.07	262 124 5.20, 6.05	263 83.2 5.22, 6.08

Performance with multiple PAs

- 200 cases with #PA = 0~4, random location, random power, generated in 4 aLIGO arms
- RTL(#PA=3) > RTL(#PA=2) is because the production rate of relevant HOM is less with #PA=3 than #PA=2 in the analyzed case
- Sph-sph : ITM is spherical, all other cases use as measured phasemap
- Beam size variation is 2%
- Polished surface maps are used when real ITM or ETM maps are NOT used

Mode analysis

- Random PA sources in aLIGO arms
- The optical gains (3rd column), cavity power (2nd column) / production of modes by ETM (1st column), are independent on the number of point absorbers.
- The ordering of HOM powers in the arm (colored lines in 2nd col) is the same as the ordering of production rates.
- RTL is determined by the 7th HOM population, so smaller 7th mode in the arm means smaller RTL.
- Less production of 7th mode with #PA=3 than #PA=2 is the cause of RTL(#PA=3) < RTL(#PA=2).



Addition on October 6th

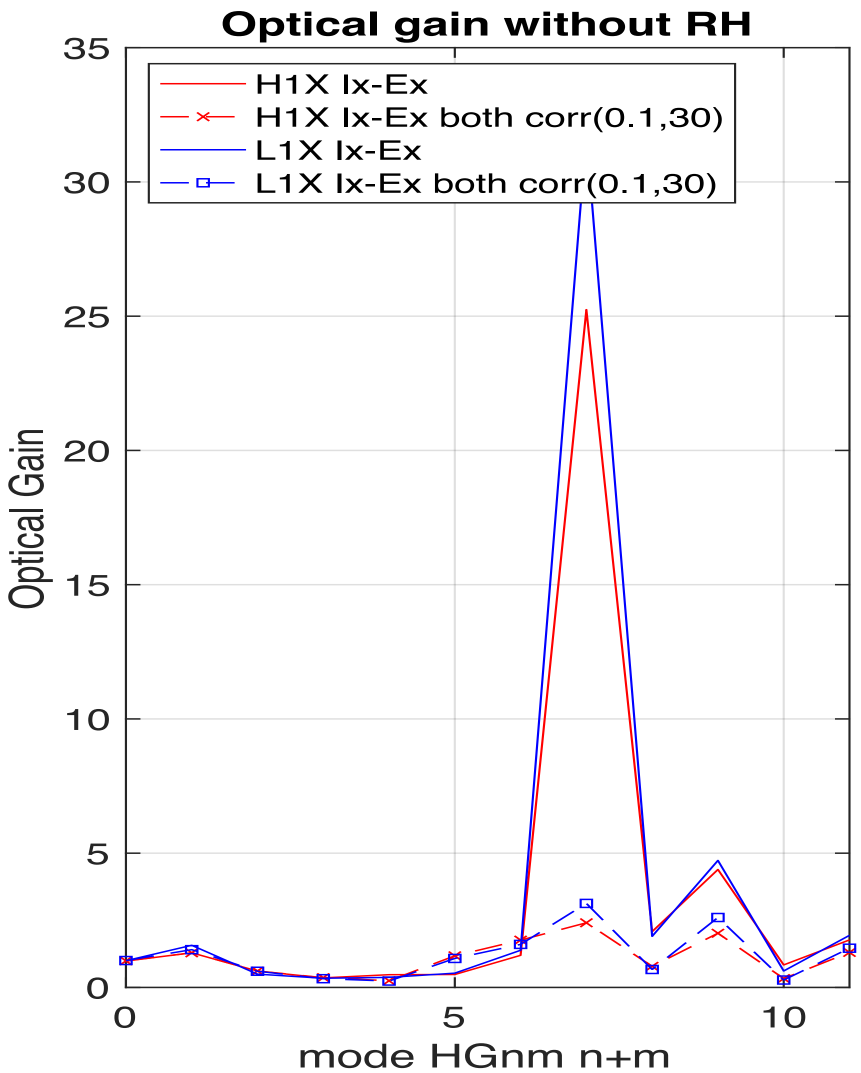
- 100 cases of point absorbers are analyzed
- 11 FP cases, different map combinations, studied
- RoC variations among 4 arms are small
- ITM coatings with and without LMA coating masks do make difference
- Optical gain vs map combinations
  - » No surprise
- RTL vs map combinations
  - » No surprise

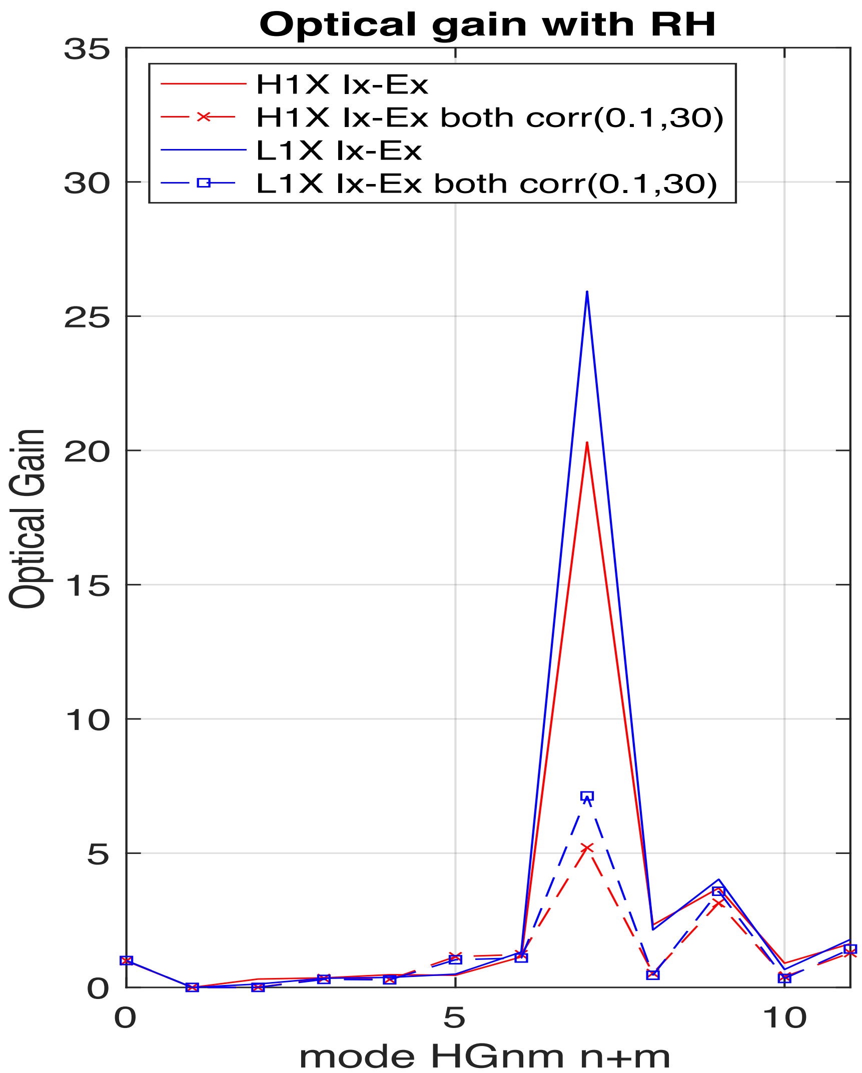
11 FP map combinations for 4 arms

- I, E means coated maps of ITM and ETM
- Ix, Ex means the maps of uncoated maps (very uniform out to the edge) are used with RoC of the coated surface. This is used to make a surface with specified fall off shape.
- Corr(a,b) is the fall off correction
- Differences among four arms for case 1 and 11 are RoC's of coated surfaces
- 100 sets of point absorbers are generated, and RTL and cavity powers are calculated for 4 arms with these mirror maps.
- Following are average of events.
- Plots with and without RH give uncertainty due to RoC correction

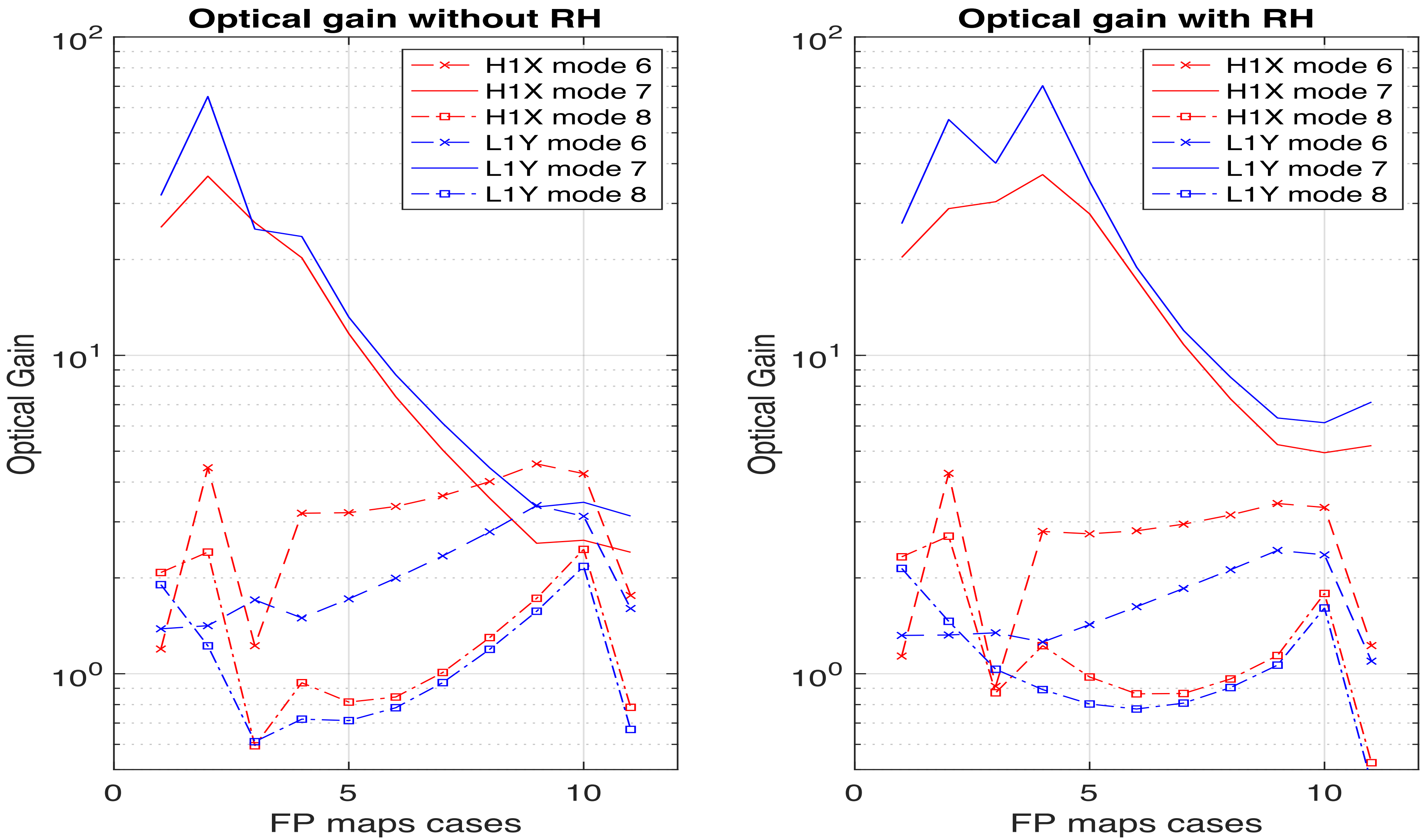
1. Ix - Ex
2. I - Ex
3. I - E
4. I - Ex*corr(0.1,15)
5. I - Ex*corr(0.1,20)
6. I - Ex*corr(0.1,25)
7. I - Ex*corr(0.1,30)
8. I - Ex*corr(0.1,35)
9. I - Ex*corr(0.1,40)
10. I - Ex*corr(0.1,30,2e4)
11. Ix *corr(0.1,15) - Ex*corr(0.1,15)

Optical gain
1:no fall off vs 11:both fall off

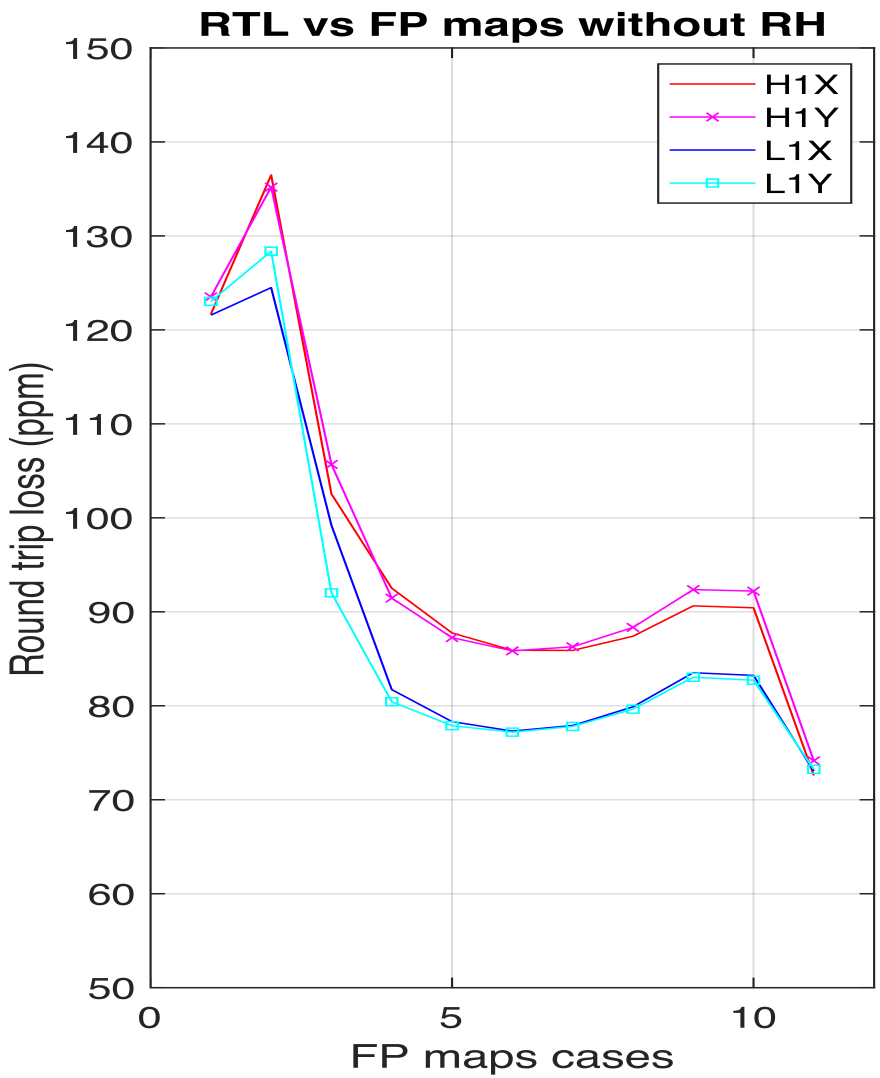


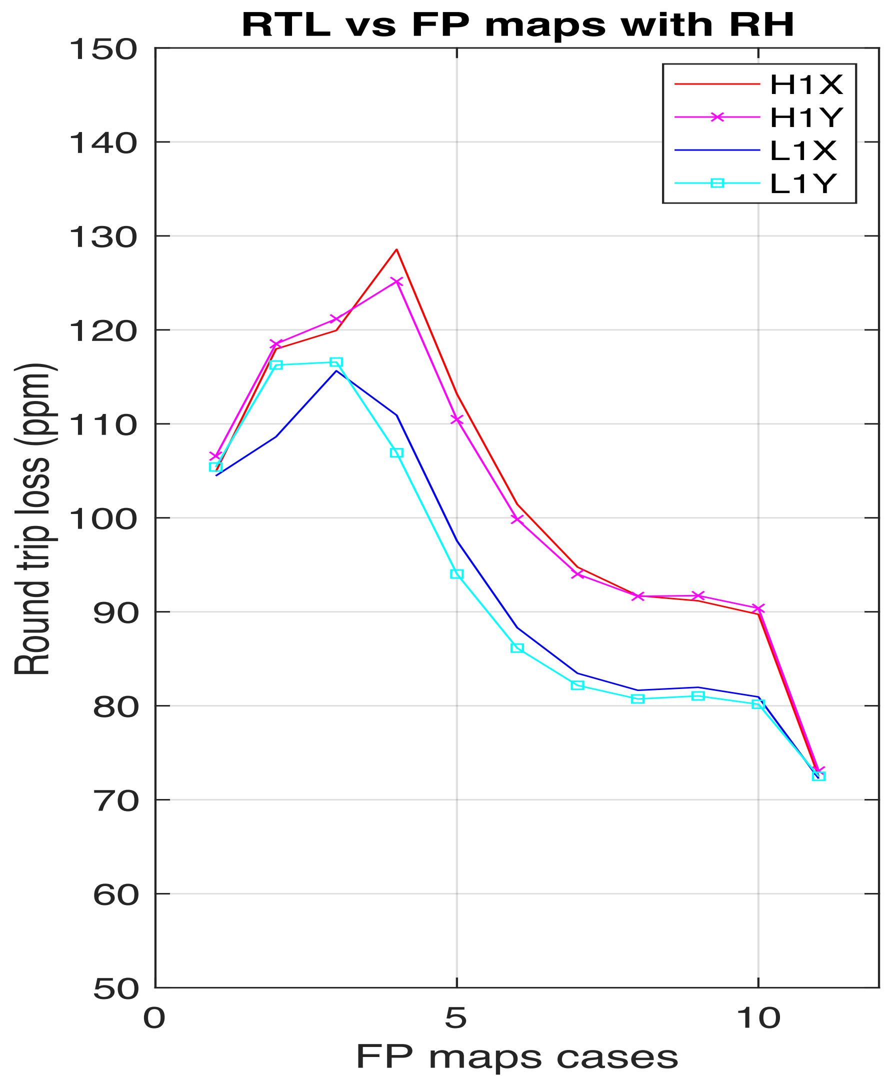


Optical gains of 6,7,8th modes shapes of different #PAs are close



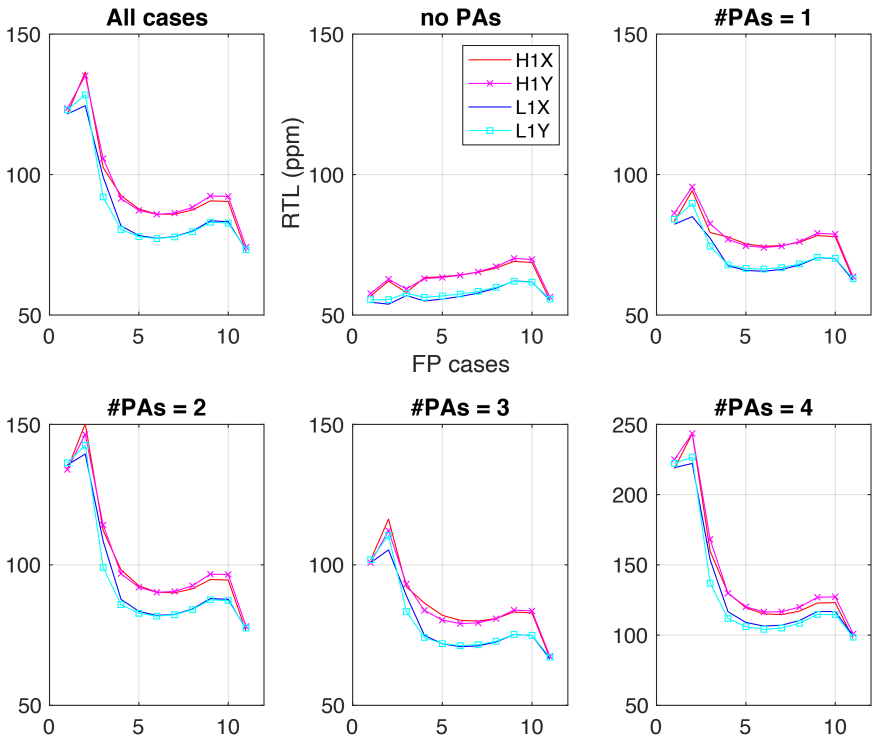
RTL vs FP maps
average of all events



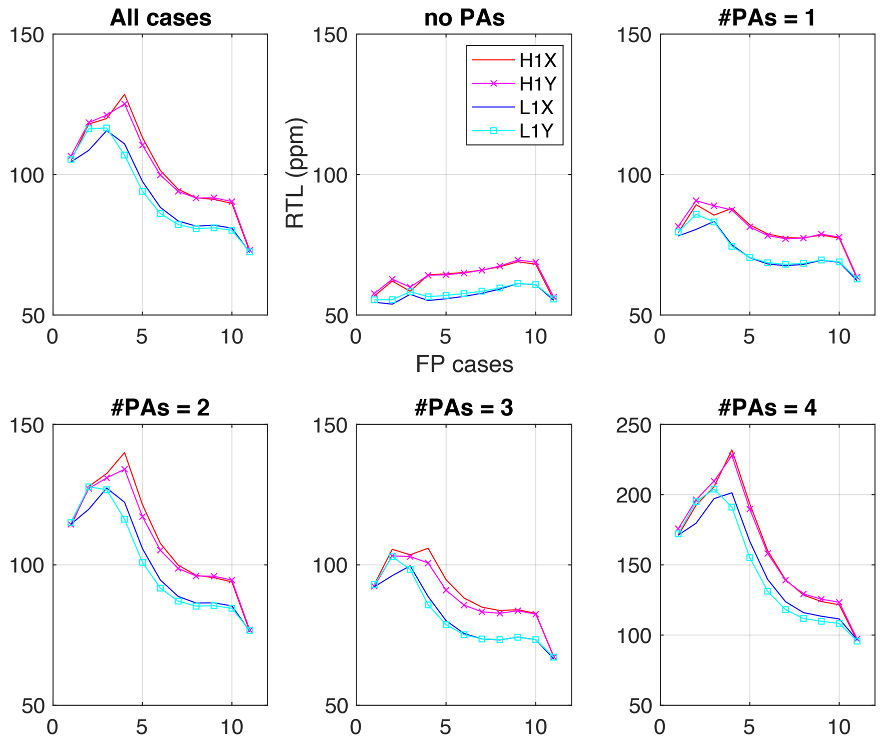


RTL for difference #PAs

Without RH



With RH

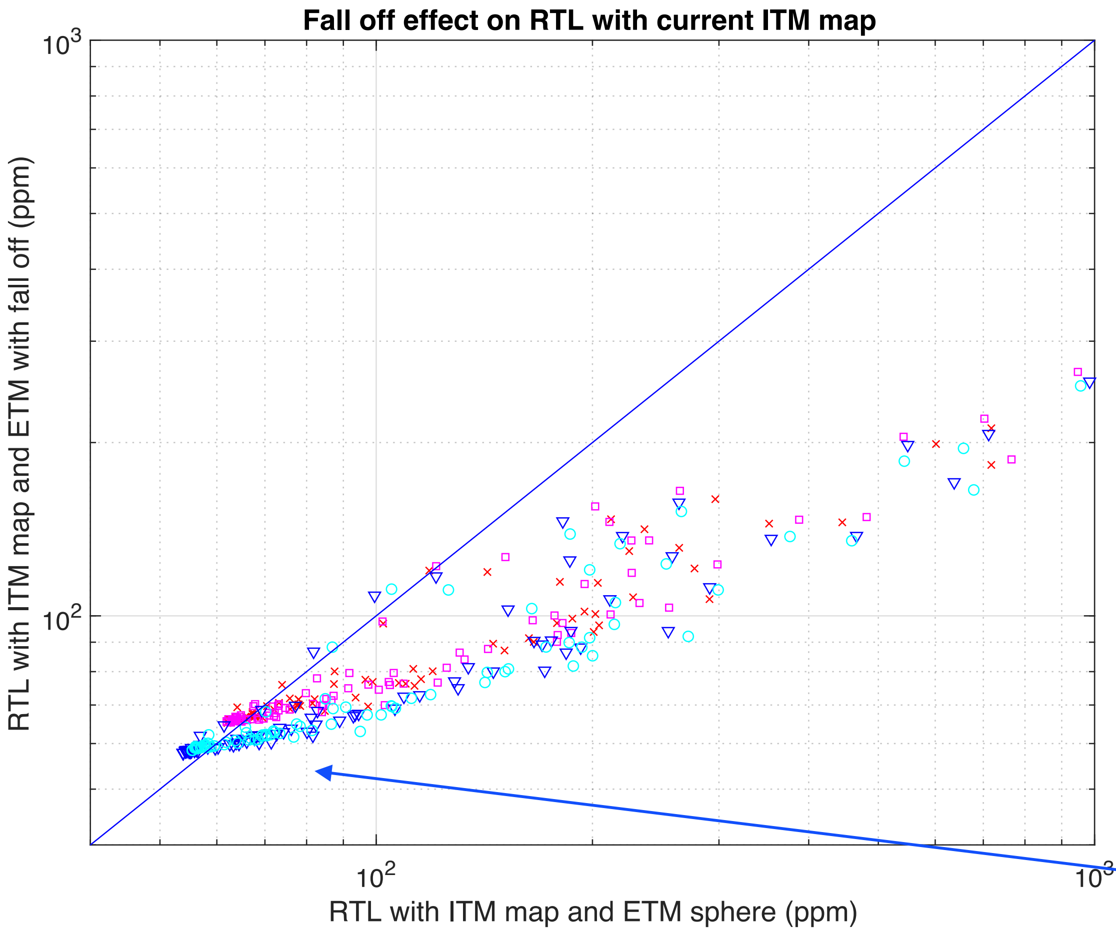


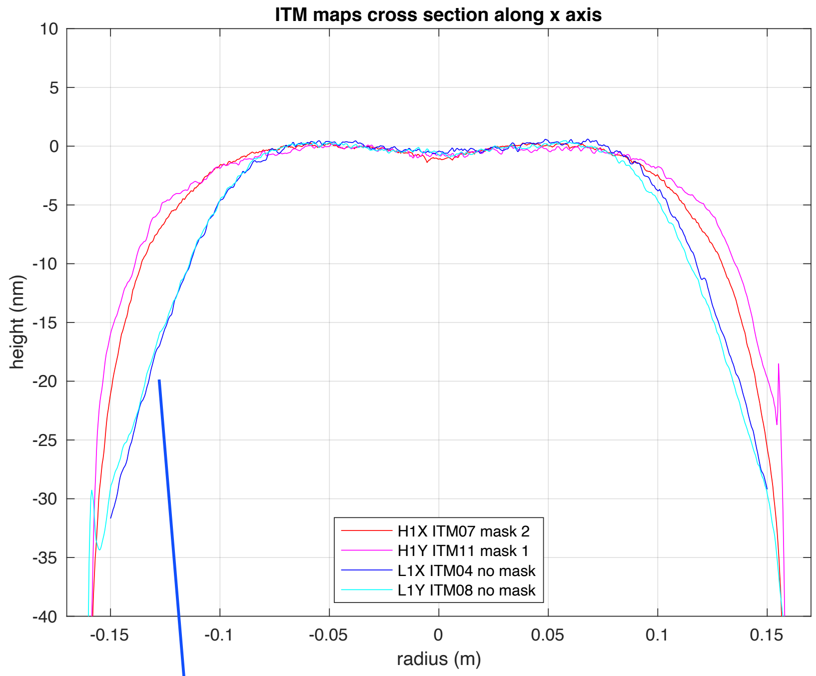
Addition on October 4tn

- "Spherical surface" is based on polished surface map with spherical shape using the RoC of coated surface
- Comparison of H1 and L1 with the current ITM masks
  - ITM coating mask affects some
- Optical gain of 7th mode
  - Fall off improve for all cases
- Small difference affects small
  - Fall off affects in a similar way for all arms
  - Ring heater correction does not change the main effects
  - Different point absorbers cause different effects
- More analysis coming with more case studies
  - Different correction shapes

RTL : for A+

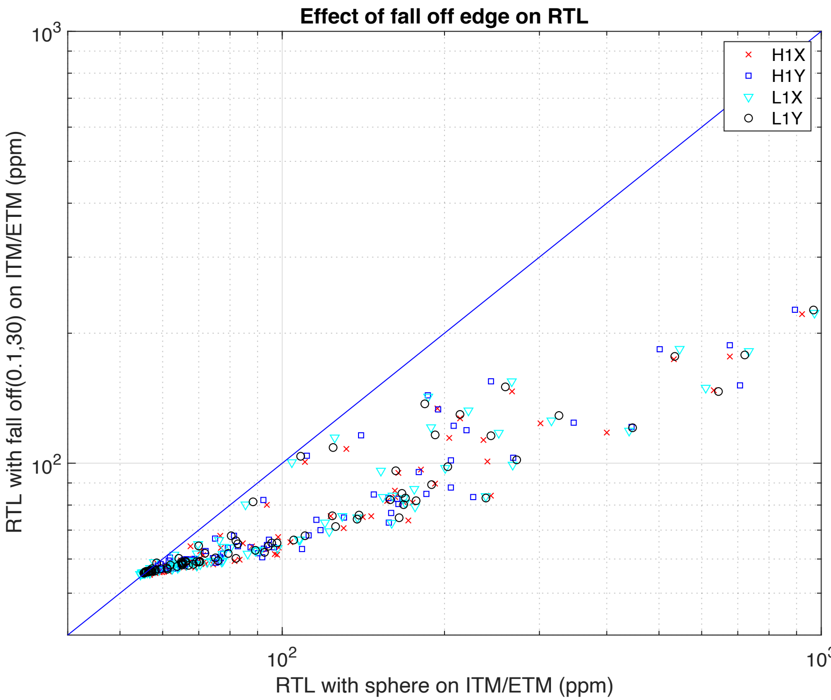
ITM with existing mask
ETM : sphere vs fall off

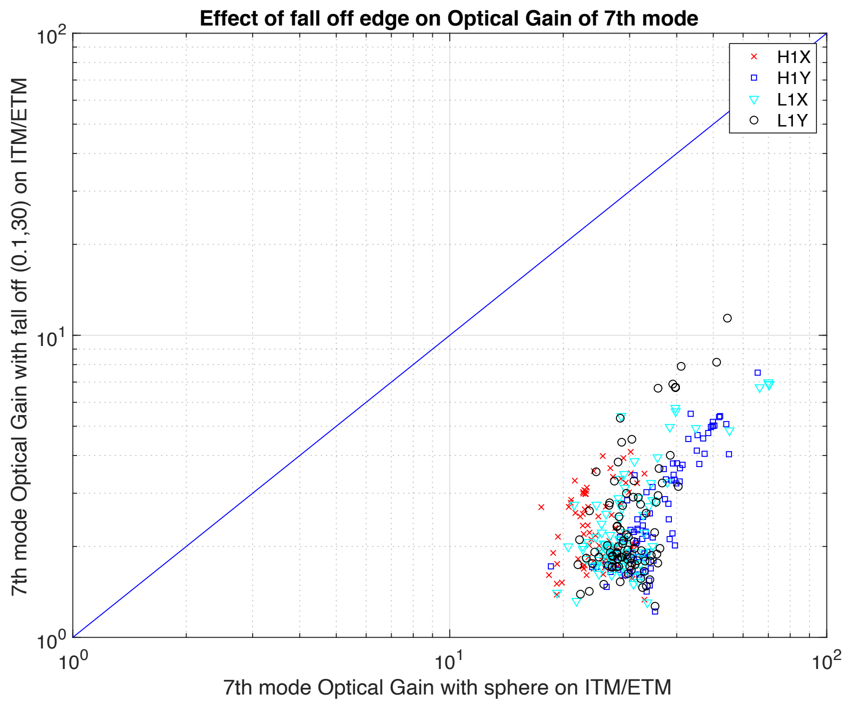




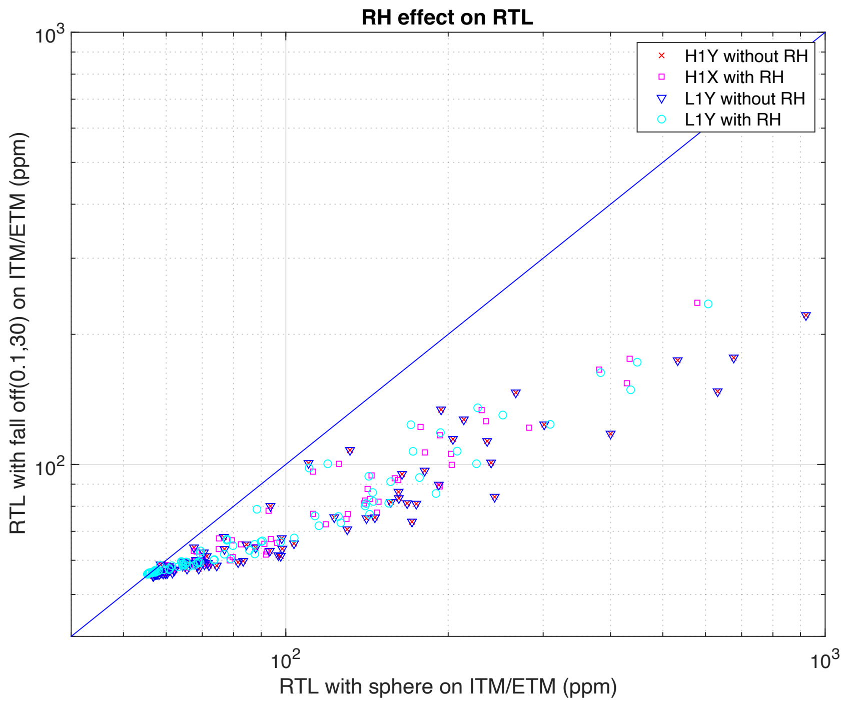
This fall off helps to reduce RTL

In the future,
When both ITM and ETM are polished both are spherical vs with fall off



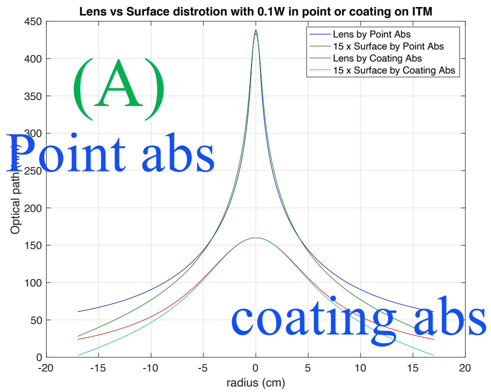


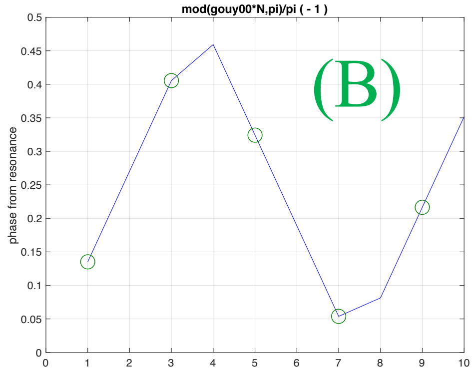
- The difference among 4 cases are caused by RoCs of mirrors
- Effects of fall off on optical gain and RTL are the same
- Gains and loss can be different from case by case, depending on PA populations

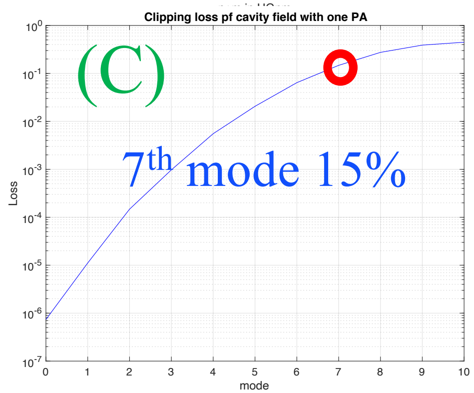


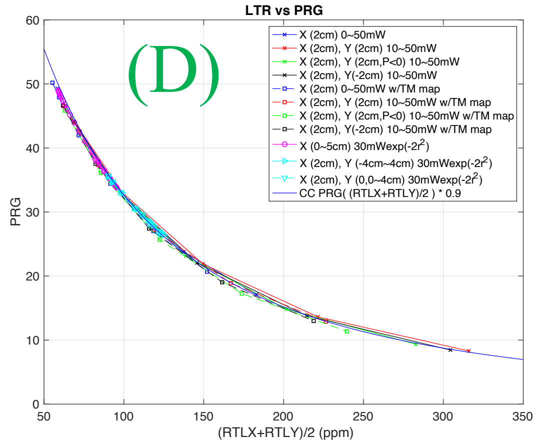
Cause and effect of point absorbers on test masses

- Mirror
  - (A) Point absorption on mirror surface causes thermal distortion of the surface and substrate
  - Many HOMs are induced on reflection
- FP cavity
  - (B) aLIGO arm is close to resonance of TEMnm, n+m=7, and this mode is amplified in the cavity,
  - (C) HOM has long power tail and induces large RTL
- aLIGO IFO, DRFPM
  - (D) Large RTL reduces PRG
  - Curvature mismatch of fields from two arms reduces PRG
    - RTL of FP
    - PRG of full DRFPM







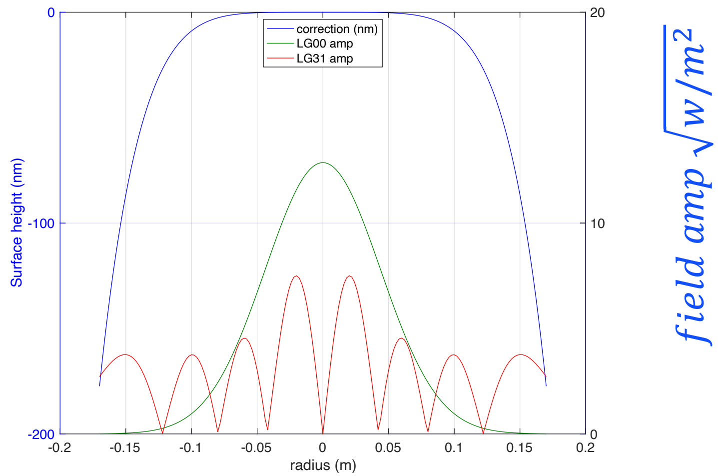


Test Mass surface profiling to suppress higher order modes

A. PRG is compromised by point absorbers on test masses
- Higher order mode excitation by point absorber on a mirror
- Large roundtrip loss due to long tails of resonating higher order modes

B. Two ways to reduce point absorber effects
- Suppress the excitation of higher order mode by point absorbers
- Suppress the resonance condition of the 7th order mode

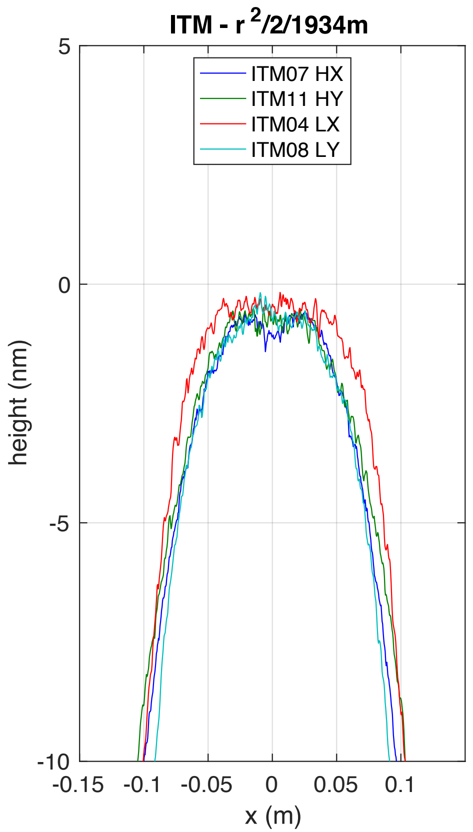
C. A mirror surface profile suppressing the 7th mode resonance (motivated by LMA coating, next page)
- $surface(r) = \frac{r^2}{2\,R_m}\,\mathrm{cor}(\,r\,), \mathrm{cor}(\,r\,) = \exp(-\mathrm{a}\,r^2 - \mathrm{b}\,r^4),\ \ a = 0.1, b = 30$
- at central region : RoC=Rm,
  at peripheral region : RoC > Rm
- Low order mode (00) :
  spherical surface with RoC=Rm
- High order mode (7th) :
  RoC change from central to edge,
  affects resonance condition

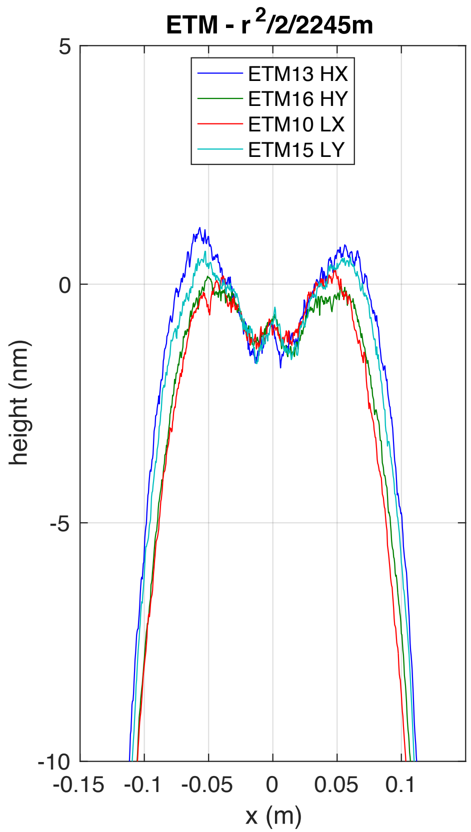


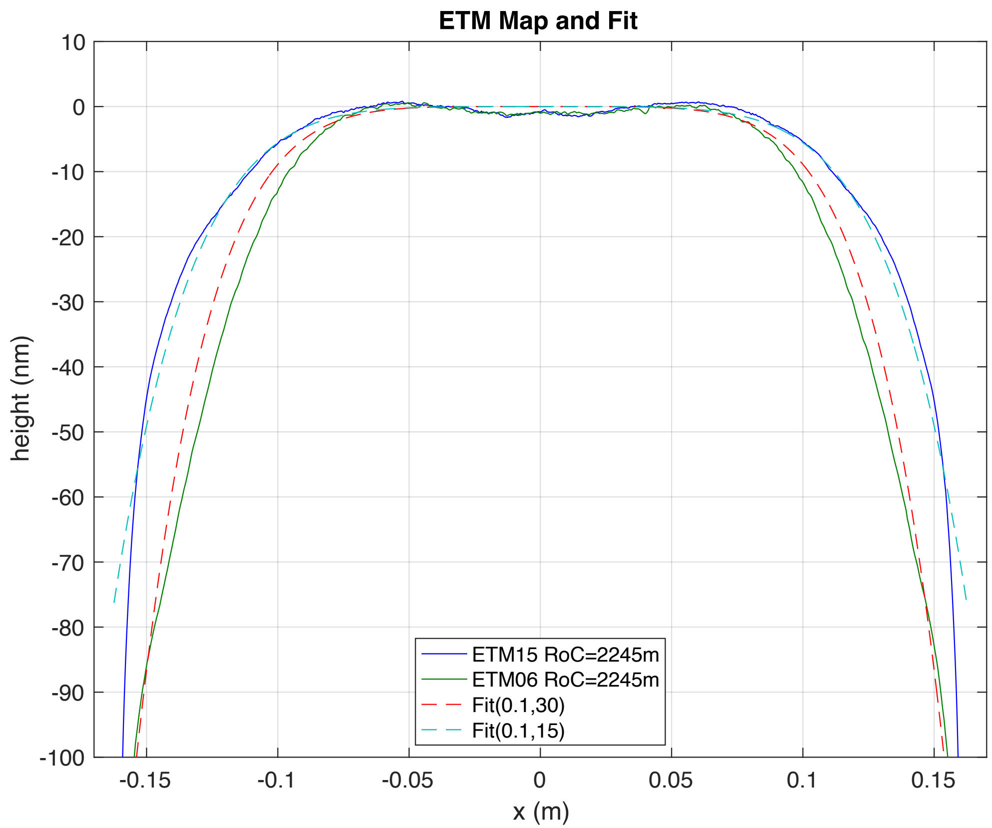
Map specifications and performance

$$\frac{r^2}{2\,R_m} e^{ar^2+br^4}$$

Functional form motivated by
"Diffraction losses of a Fabry-Perot cavity with nonidentical non-spherical mirrors"
by Poplavskiy, Matsko, Yamamoto, Vyatchanin
Article reference: JOPT-107582.R1







What are studied

1) Does this shape suppress 7th mode efficiently
2) Performance when there is no point absorber
3) Performance when there is coating absorption
4) Performance when beam is tilted to reduce the point absorber effect
5) Requirement on polishing and coating

* Stationary field by FFT
* Field is mode-expanded using standard HG or LG

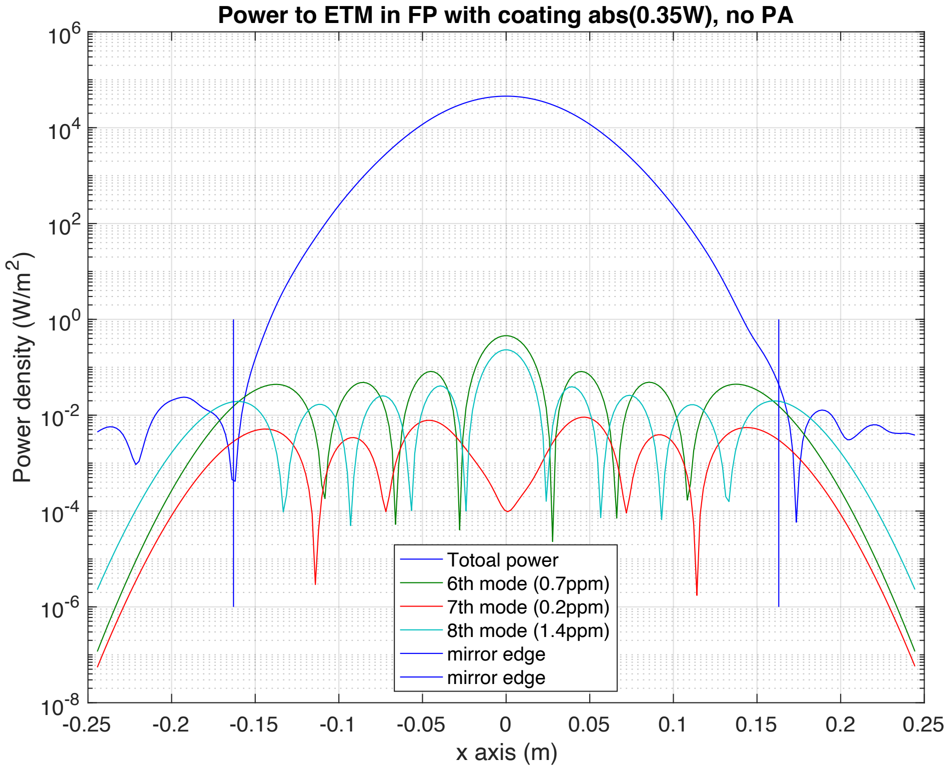
FFT simulation

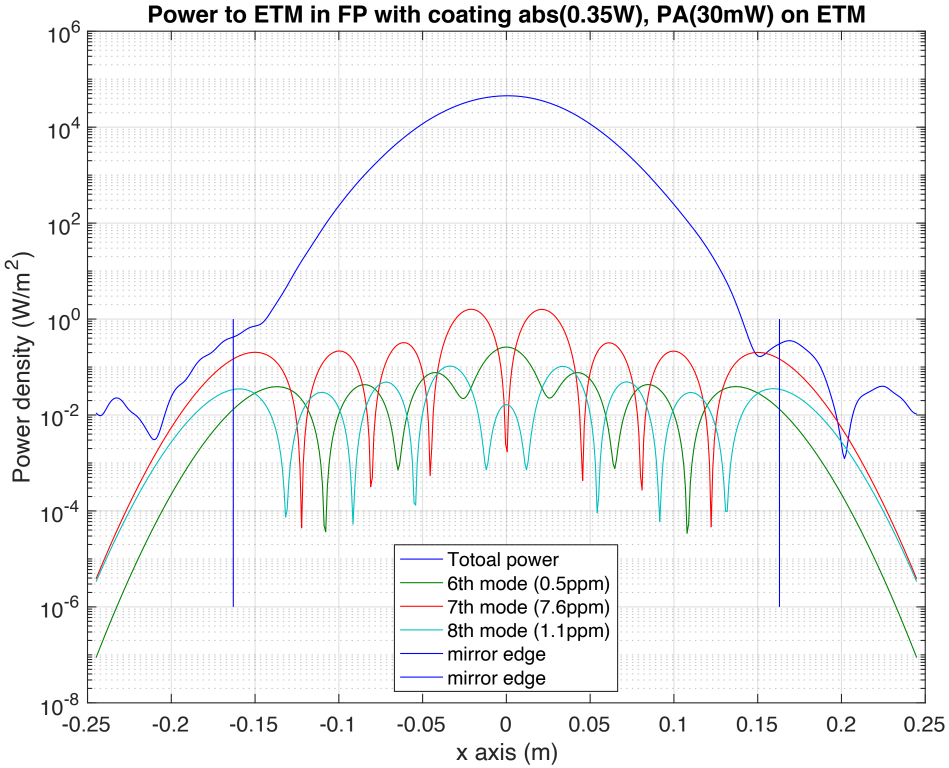
standard HG or LG

$$E = \sum_{n,m} C_{nm} \cdot HG_{nm}$$

$$E_{mode} = \sum_{n+m=mode} C_{nm} \cdot HG_{nm}$$

$$loss = \iint_{r>R_{mirror}} {E_{mode}}^2$$

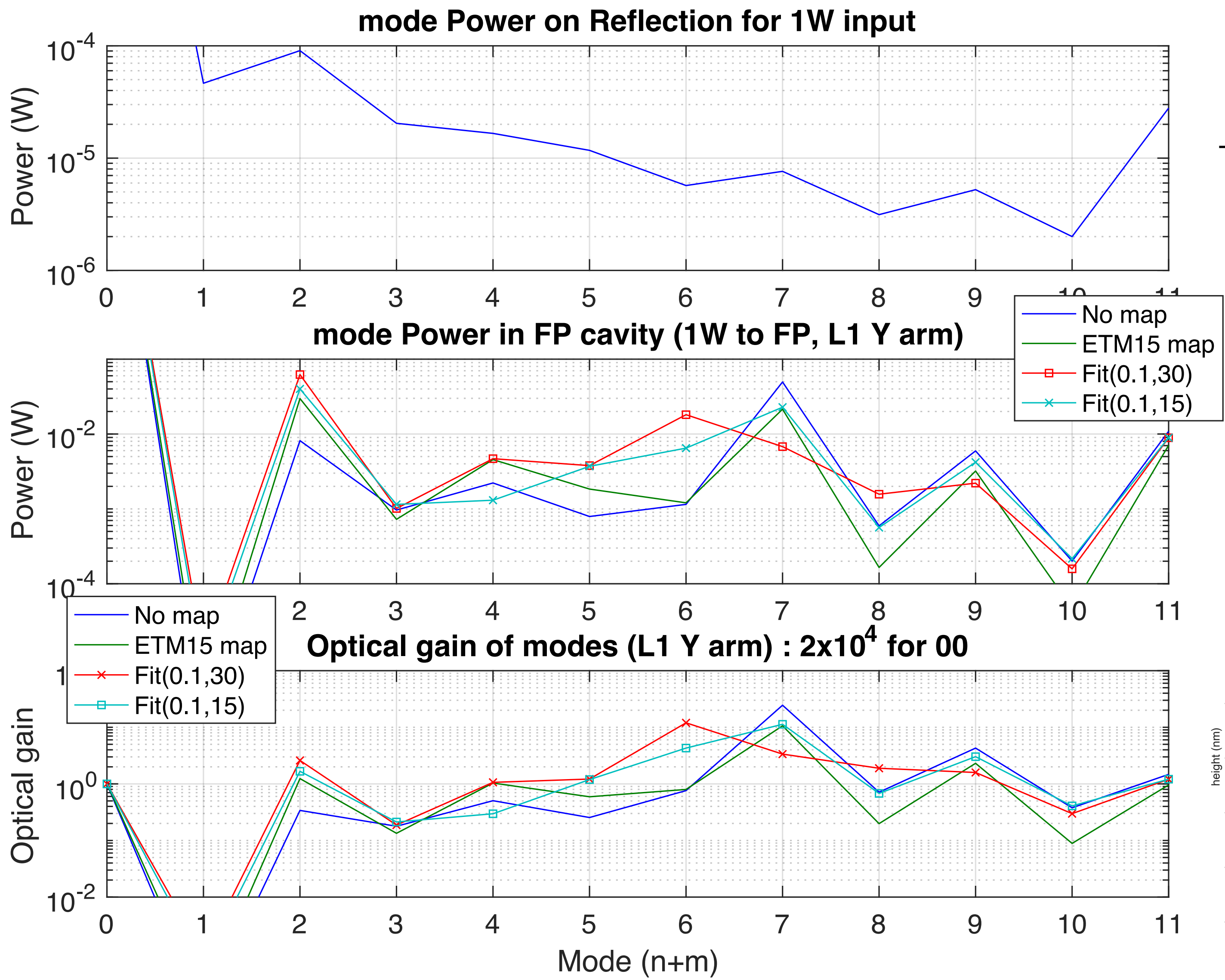


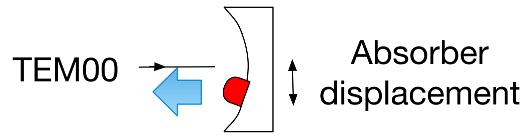


Does this shape suppress 7th mode efficiently

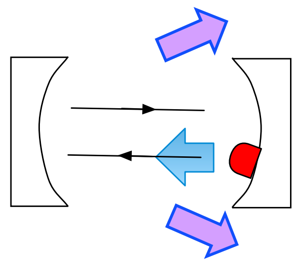
Optical gain

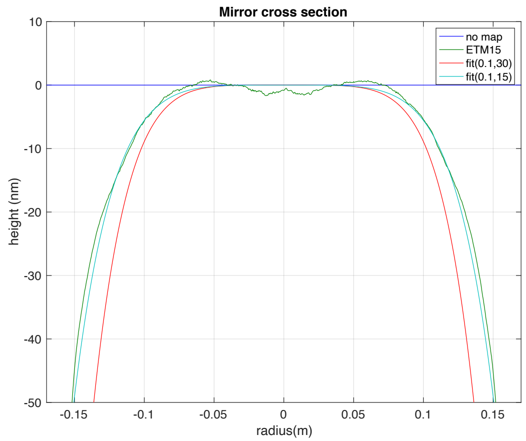
7^{th} mode gain is suppressed but …



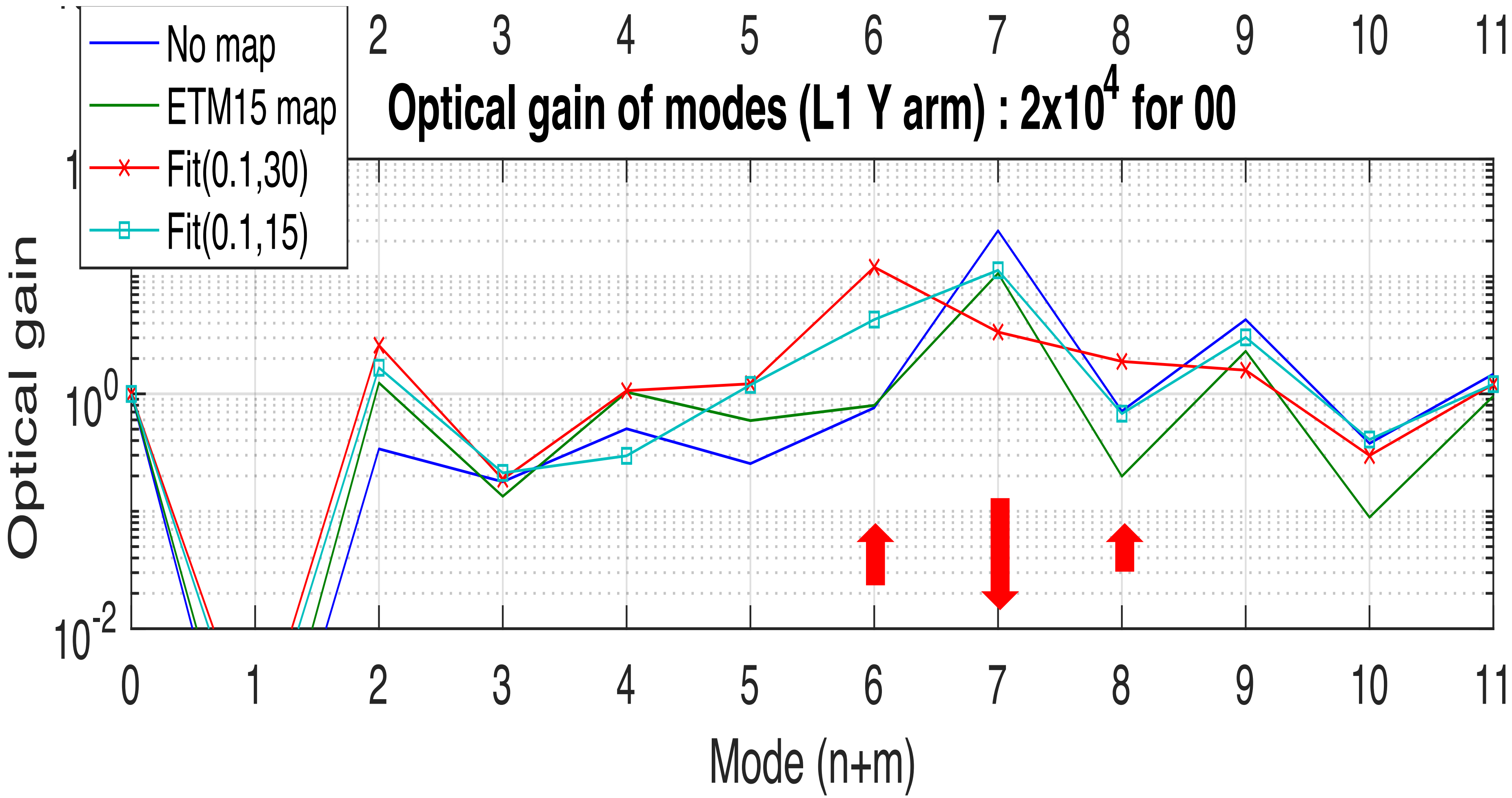


Clipping loss

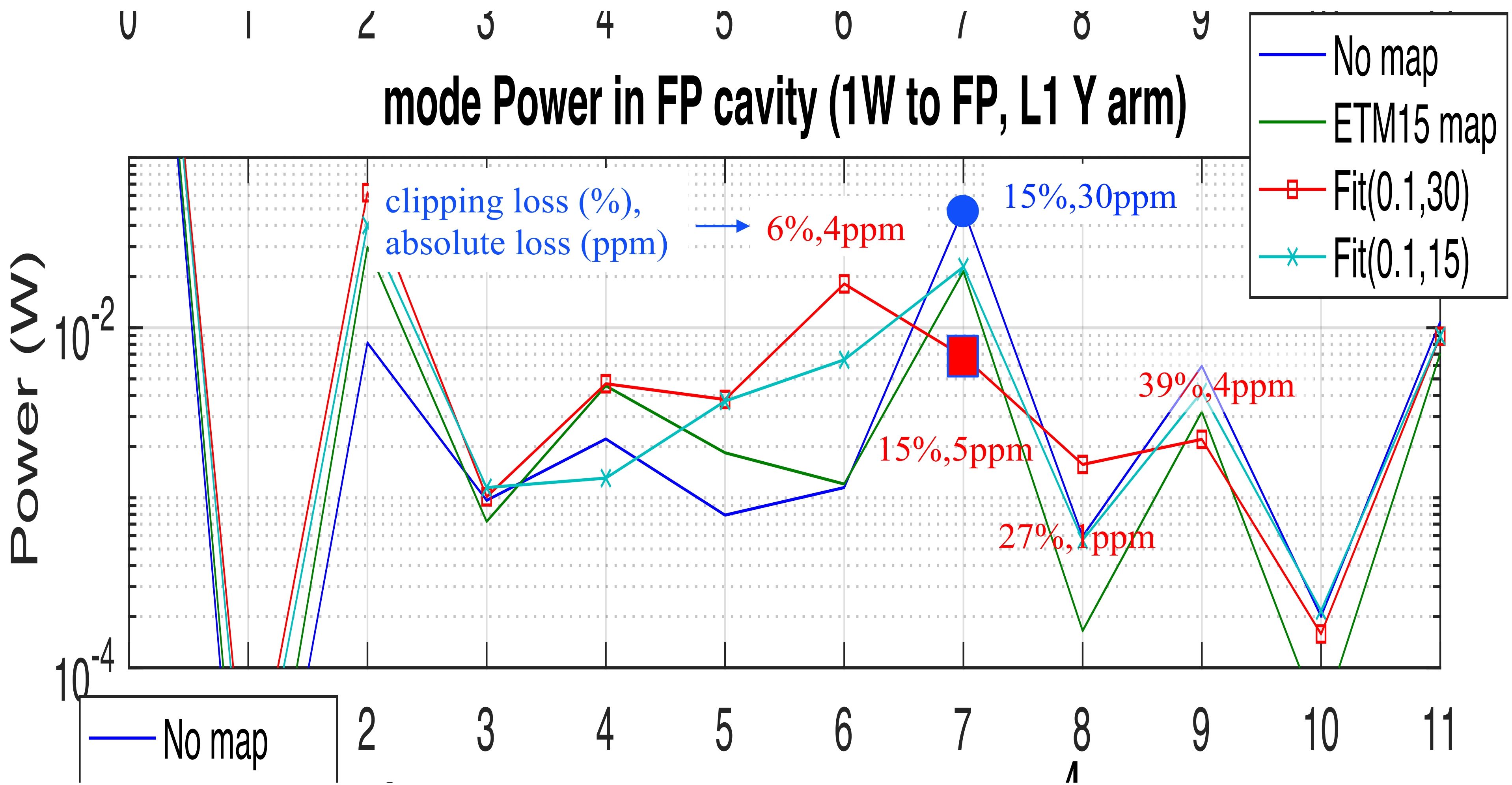




Optical gain with various ETM surface profile



RTL = gain x clipping loss



Does this shape suppress 7^{th} mode efficiently

Dependence on mirror maps

RTL with one PA on ETM (2cm, 30mW)

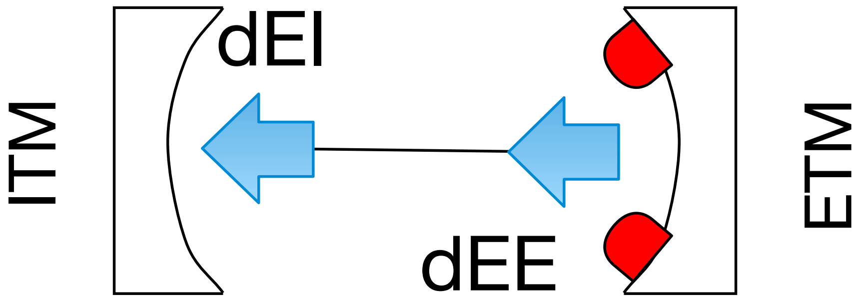
Fit : a=0.1, b=30

00 loss = 1 - 00 power on ETM with PA / without PA

	ITM and ETM maps	ITM map ETM no map	ITM map ETM cor (0.1,30)	ITM no map ETM cor(0.1,30)	TEM00 gain loss
	Current performance (PA / no PA)	Larger loss w/o ETM map	Performance with new ETM maps (O4)	Smooth ITM (O5) with new ETM maps (O4)	Loss of the signal (fit / as is)pp
H1 X arm ITM07-ETM13	148 / 58	195	95	91	0.5% / 1.3%
H1 Y arm ITM11-ETM16	140 / 59	190	96	90	0.5% / 1.2%
L1 X arm ITM04-ETM10	137 / 57	180	88	91	0.5% / 1.1%
L1 Y arm ITM08-ETM15	120 / 58	193	87	90	0.5% / 0.9%

one vs two PAs

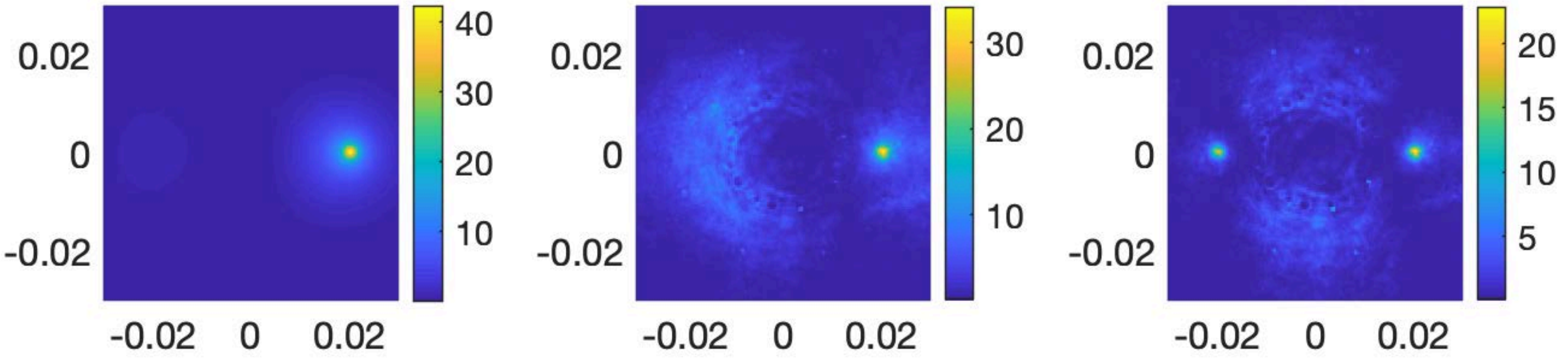
dE = E-TEM00



dRTL = RTL – RTL0, RTL0 = RTL(without map and absorber) = 48ppm

dEE

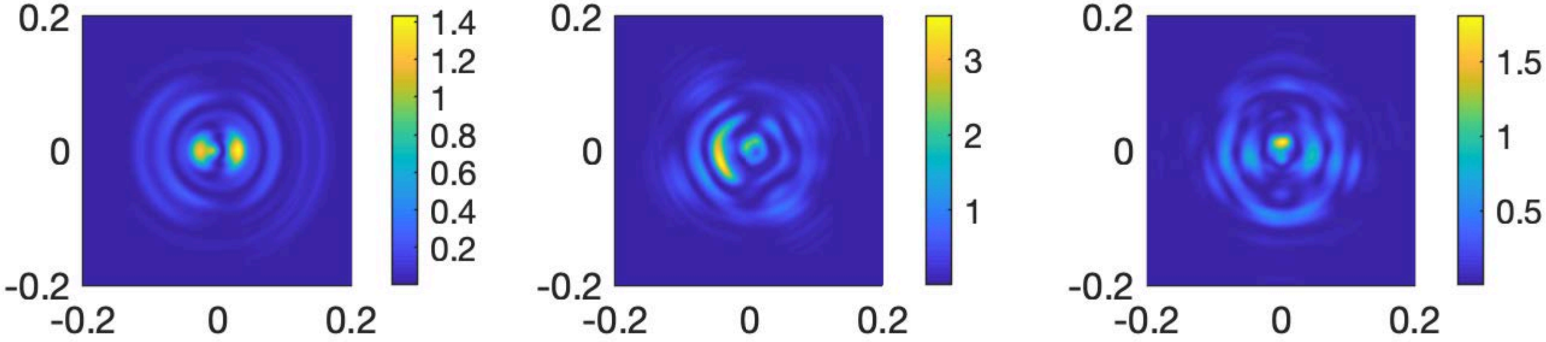
±3cm



one absorber 10mW at x=2cm, y=0	one absorber 10mW at x=2cm, y=0	two absorbers 10mW at 2cm & -2cm
No mirror maps dRTL=10ppm	L1 x arm maps dRTL= 17ppm	L1 x arm maps dRTL= 11ppm

dEI

±20cm



Does this shape suppress 7th mode efficiently

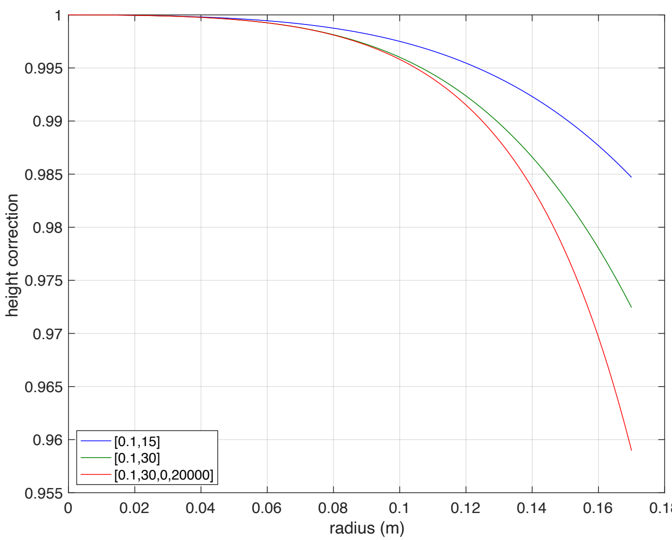
Multiple point absorbers

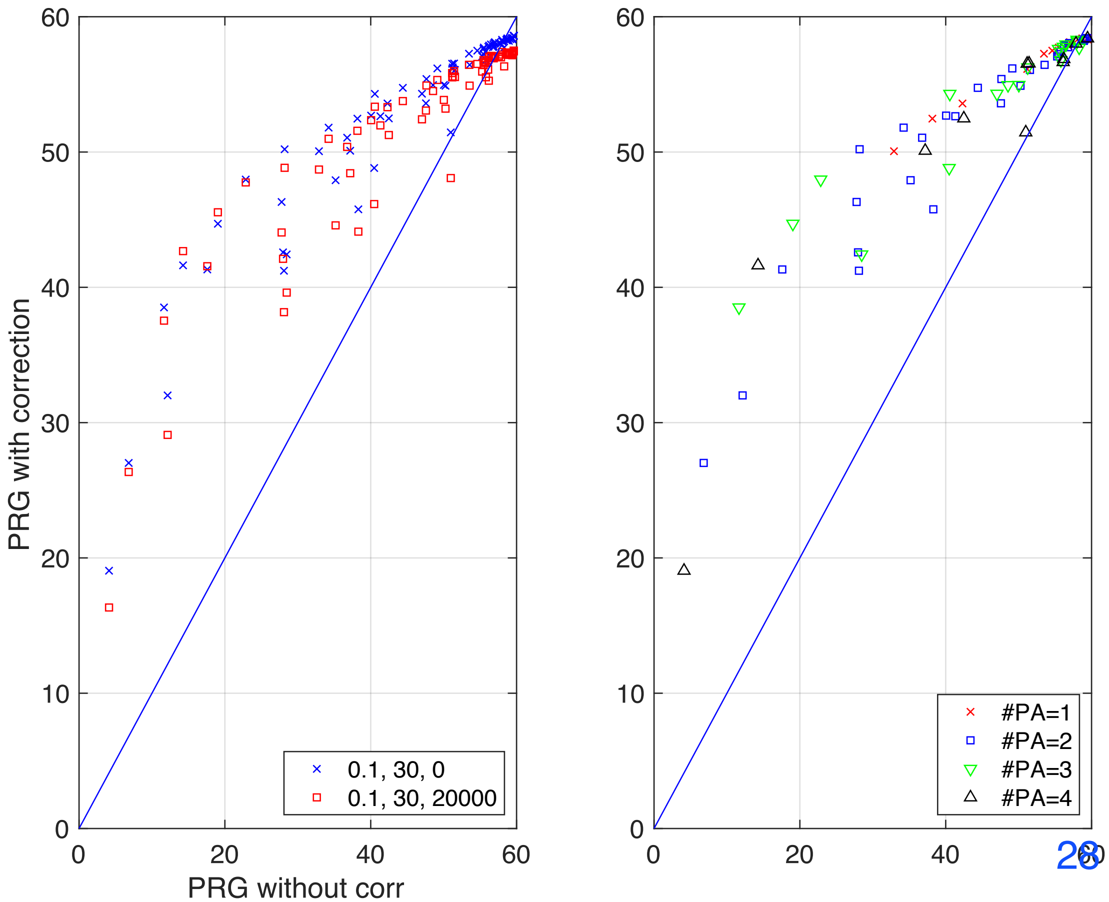
Random locations and powers

$$corr(a,b,c) = \frac{r^2}{2\,R_m}\exp(-a\,r^2 - b\,r^4 - c\,r^8)$$

#PAs : 0~4 poisson (ave=2)
Locations(x,y) : normal (sig=3cm)
Power(r) = normal(30mW)*exp(-2r^2/w^2)

LLO Y arm
ITM:phase map
ETM:uncoated map
+correction





Performance when there is no point absorber

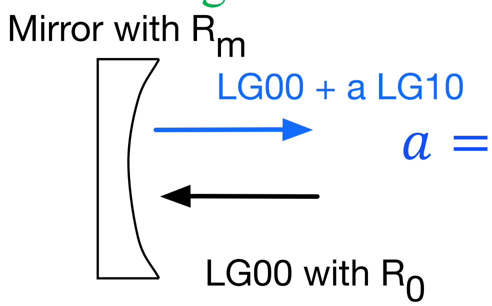
Effect of edge fall off shape
when there is no PA
but with coating absorption

ITM : phasemap as is

ETM : uncoated map + fall off shape exp(-a r^2 –b r^4)

	LHO X	LHO Y	LLO X	LLOY
No thermal (power/RTL)	262 / 62 262 / 65	277 / 63 277 / 65	266 / 54 266 / 57	266 / 55 266 / 58, 266 / 58
Coating abs No RH	261 / 57 260 / 64	276 / 57 275 / 66	265 / 54 264 / 60	265 / 55 264 / 60, 264 / 59
Coating abs RH corr	262 / 61 262 / 69	277 / 62 277 / 71	266 / 55 266 / 58	266 / 56 266 / 59, 266 / 60

Poorman's ring heater



$$a = i\frac{k\,w^2}{4}\left(\frac{1}{R_m} - \frac{1}{R_0}\right)$$

Arm power (W) / RTL (ppm) without fall off

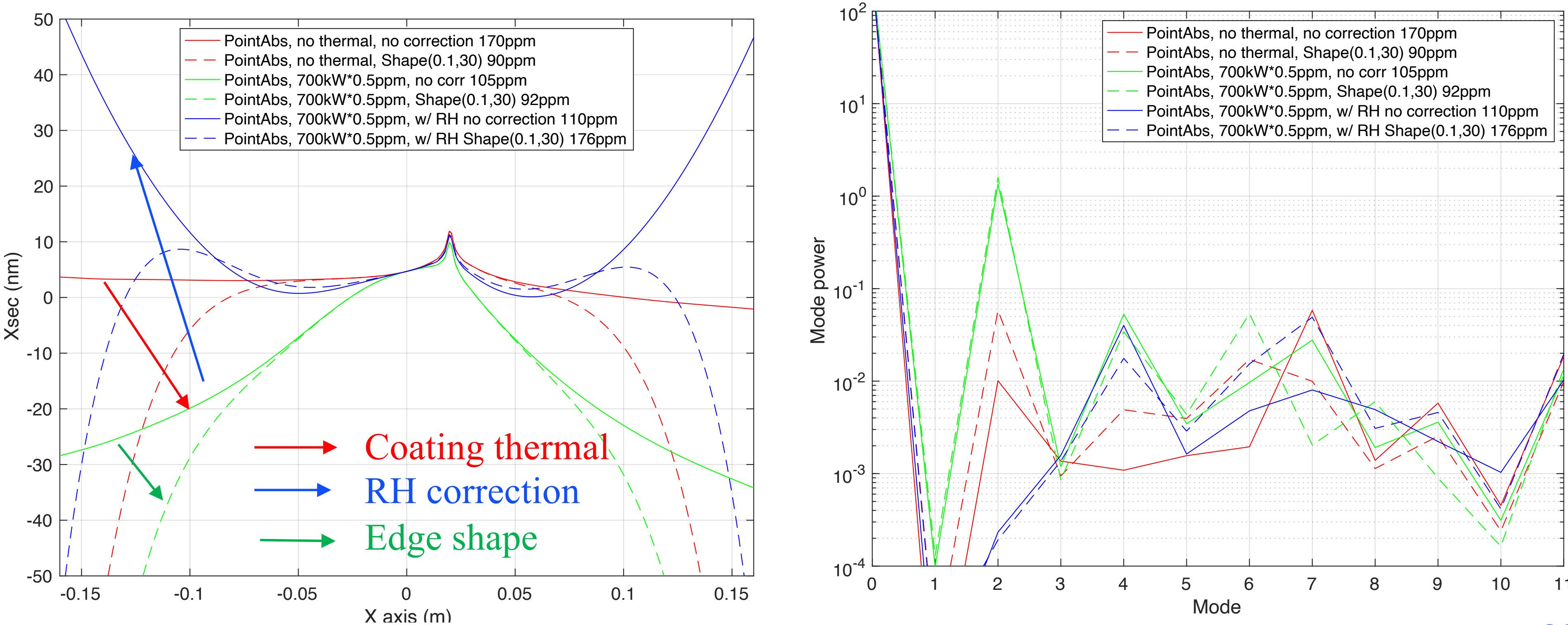
Arm power (W) / RTL (ppm) with fall off

Arm power (W) / RTL (ppm) with ETM15 map

Point absorber (2cm,30mW) on ETM, Coating absorption(700kW,0.5ppm), Ring heater (HR RoC)

Thermal aberration by coating absorption by Hello-Vinet
Ring heater nullifies LG(1,0) excitation by HR RoC change

LLO PRG : without RH 30.3, with RH 28.5



Thermal effect in DRFPM

When or how to use RH

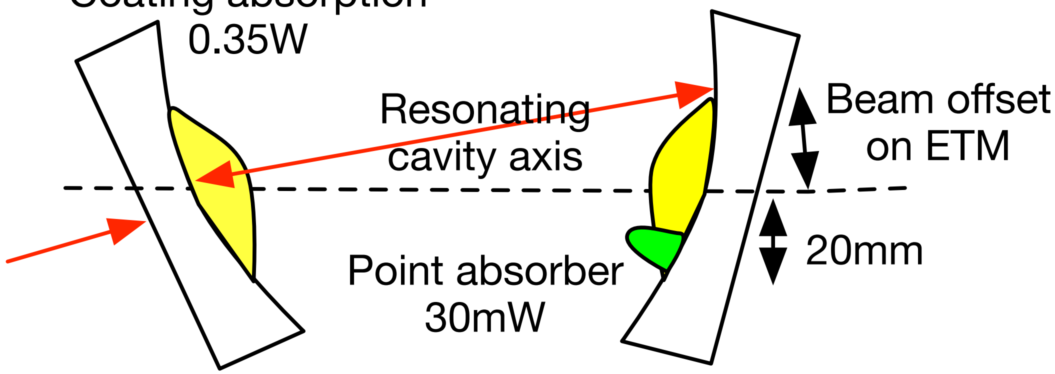
LLO : ITM coated map, ETM uncoated map + corr(0.1,30)

case	Coating abs	PA on EY	Correction ETM	RH (ITM,ETMX)	RH (ETMY)	PRG
1	0	0	no	no	no	53
2 vs 4	0	30mW	no	no	no	27
3 vs 5~7	0.35W	30mW	no	no	no	33
4	0	30mW	0.1,30	no	no	44
5	0.35W	30mW	0.1,30	no	no	33
6	0.35W	30mW	0.1,30	yes	no	27
7	0.35W	30mW	0.1,30	yes	yes	23

Beam offset on ETM

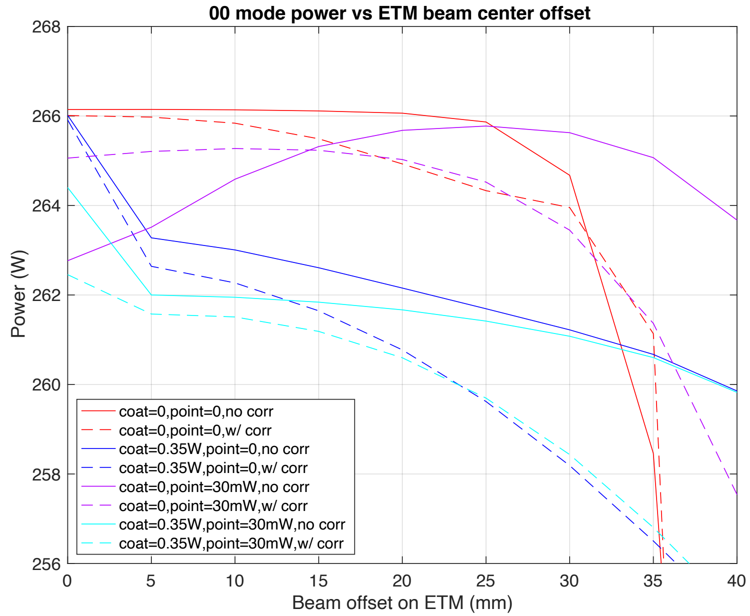
- ITM : ITM08 coated phase map
- ETM : ETM15 uncoated phase map with correction (0.1,30)
- Coating absorption on ITM and ETM, 0.35W each
- Point absorber on ETM at -20mm from center (power=30mW exp(-2 r^2 / 6.2cm^2))
- Tilt ETM to make the resonating beam position on ETM to have offset, 0~40mm (opposite to point absorber), keeping the beam on ITM to be centered
- RH correction calculated with beam at the center of ETM

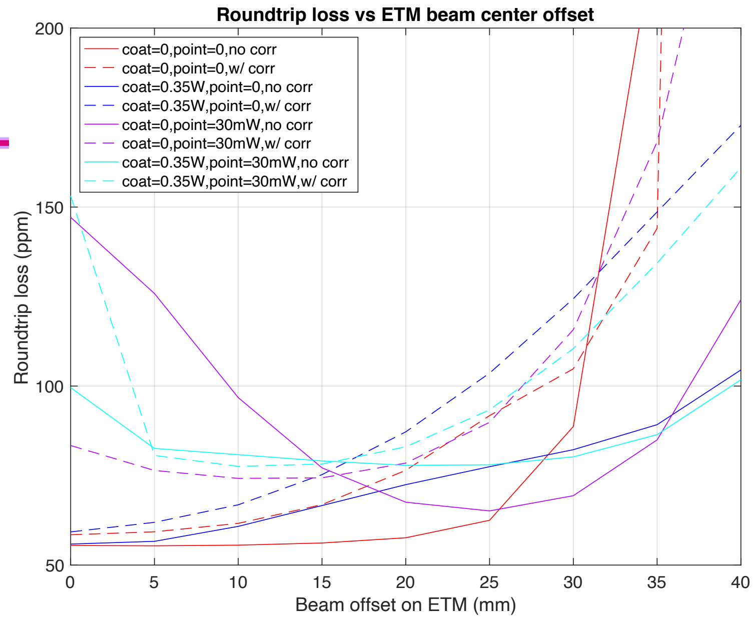
- Input beam is tilted to make proper mode matching between the input and the resonating cavity mode
- Mode expansion using the cavity axis
- 8 cases compared
  - » Coating absorption off / on
  - » Point absorber off / on
  - » shape correction off / on

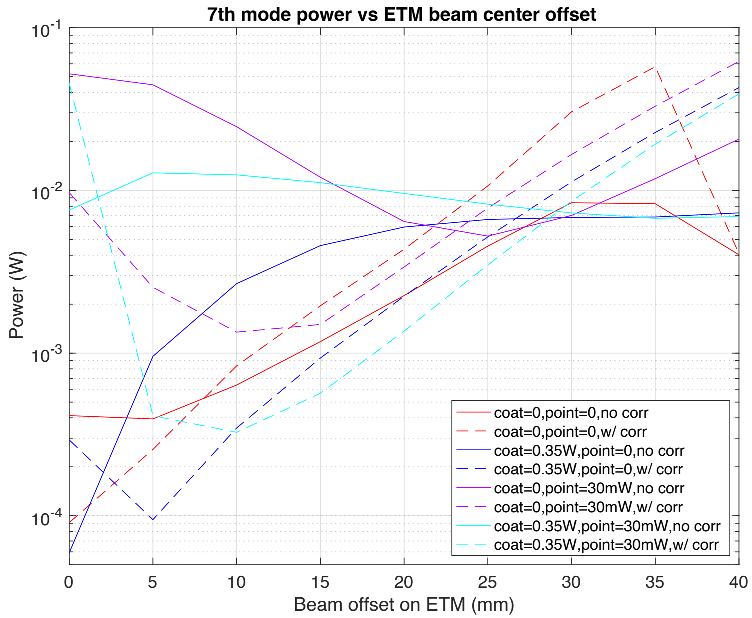


Performance when beam is tilted to reduce the point absorber effect

Power and RTL vs offset







- solid : flat map,
  dashed : fall off
- red and purple : no coating abs
  blue and cyan : with coating abs
- red and blue : no point abs
  purple and cyan : with point abs

Extra factors

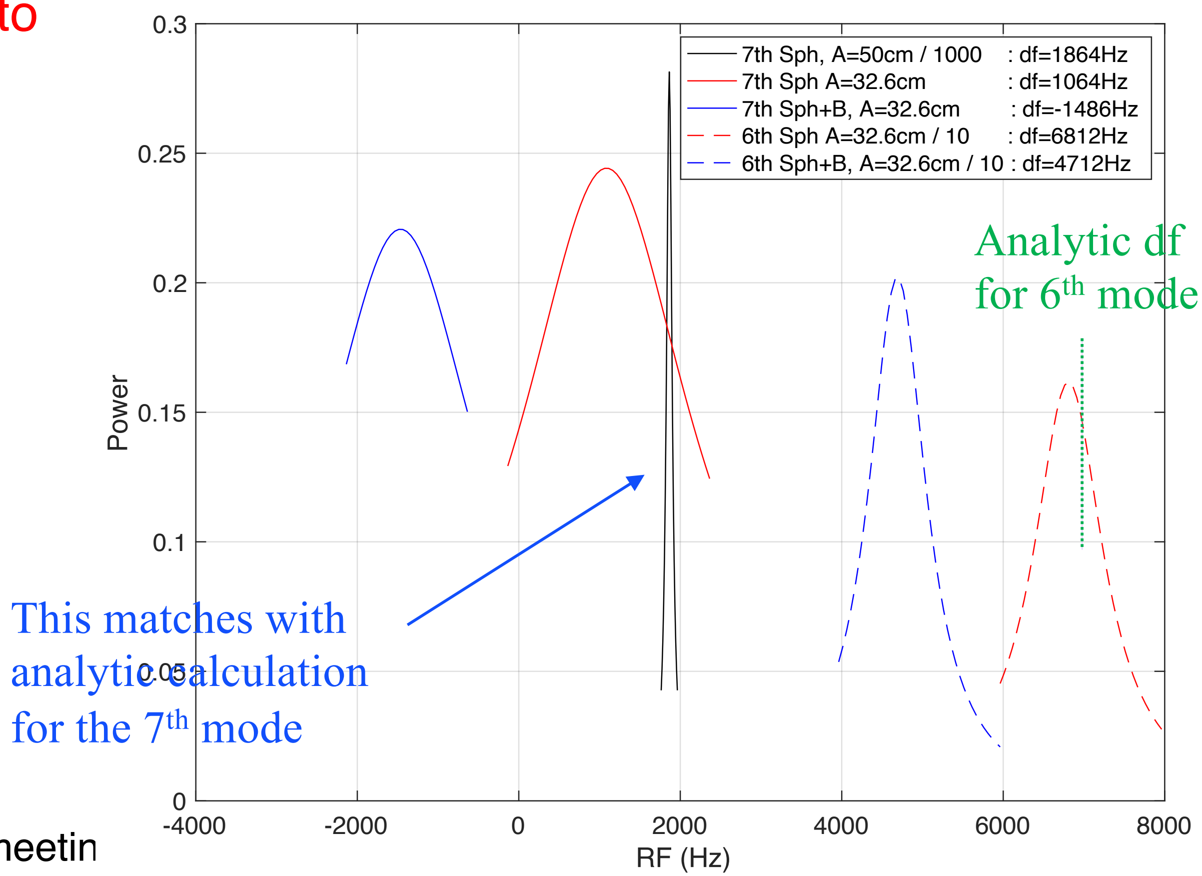
- Polishing spec = idealistic surface – all possible deformations
- Coating stress effect on RoC (T970176, T050057)
  - Waiting for LMA report
- Intrinsic coating non uniformity (T2000398)
  - Waiting for LMA report
- Deformation by gravity (T050184)
  - Negligible
- Polishing requirement
  - In radius > 8cm, height variation less 10%
- Anything else?

Summary

- The surface shape correction of test mass to reduce the thickness at the edge by O(1%) works OK
- The effect by a single absorber seems to be improved by a factor
- When the thermal deformations by coating absorption and point absorber mix badly, a careful ring heater correction will be necessary and this shape does not help, nor does it harm.
- Nominal ring heater to restore the central region curvature adds to much curvature at the edge. Another ring heater to handle the edge may be necessary.

Answer to recommendations

- For this case, what is the eigenfrequency for the 6th & 7th order modes (delta_f from the TEM00 mode)?
  - » df is not all to determine the mode gain
  - » loss or width or coupling to other modes matter

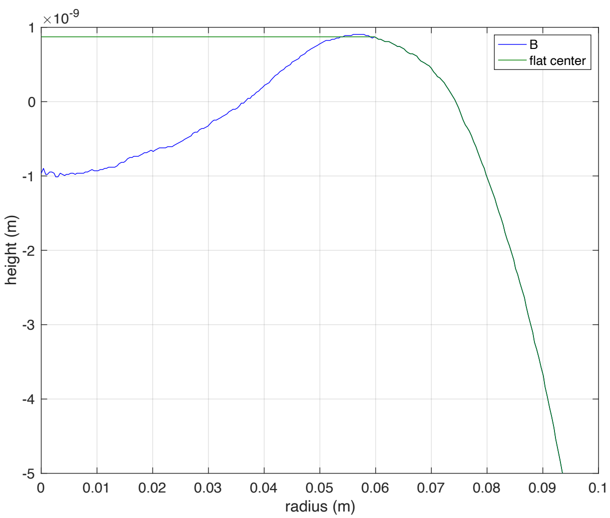


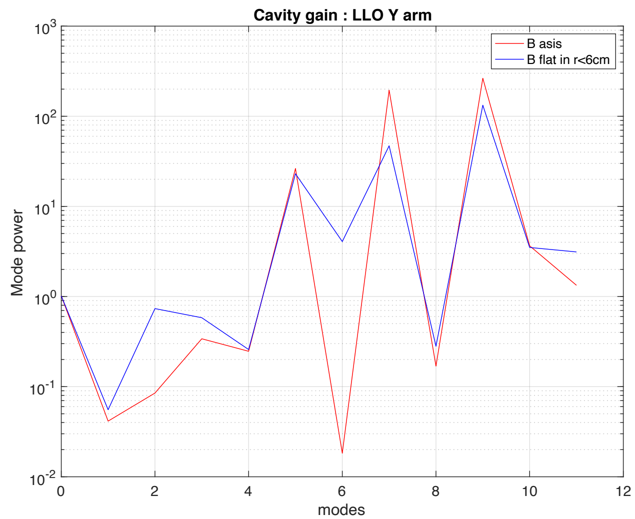
Answer to recommendations

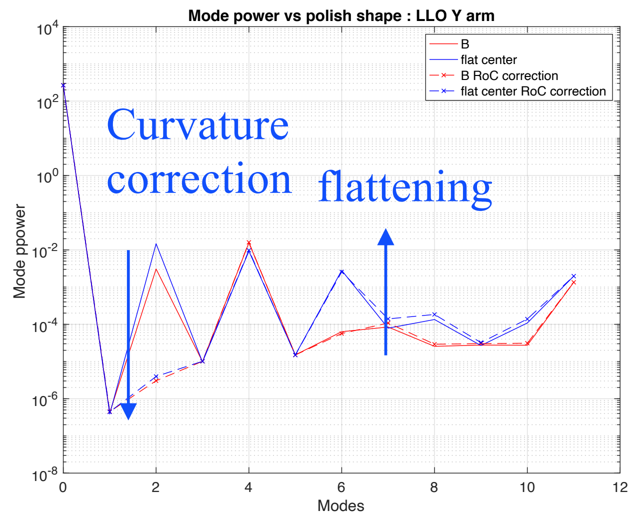
- G2001747-v3, slide 32, upper right plot. Is there any understanding why the RTL for the solid purple curve is lower than for the solid red curve for offsets greater than 2.5 cm ?
  A : there was a bug to setup a FP cavity with offset. Needs to be redone.
- Also why is the RTL for the dashed cyan curve higher than for the solid cyan at zero offset?
  A : see the answer in the last page. The thermal bump by the coating absorption distorts the field and the edge fall off does not work as is naively expected.
- As the beam is moved, does the absorbed power stay the same, or decrease as it's moved away from the PA?
  A : Power changes as $\exp(-2\, d^2 / w^2)$ where d is the distance between the beam and the point absorber.

Answer to recommendations

- Can you comment on the benefit of retaining or removing the slight spherical aberration, induced by the coating, using a custom polish?
  - » Simply filling the central dip harms => larger 6^{th} mode gain
  - » RTL(flat) is 10% larger than RTL(B)





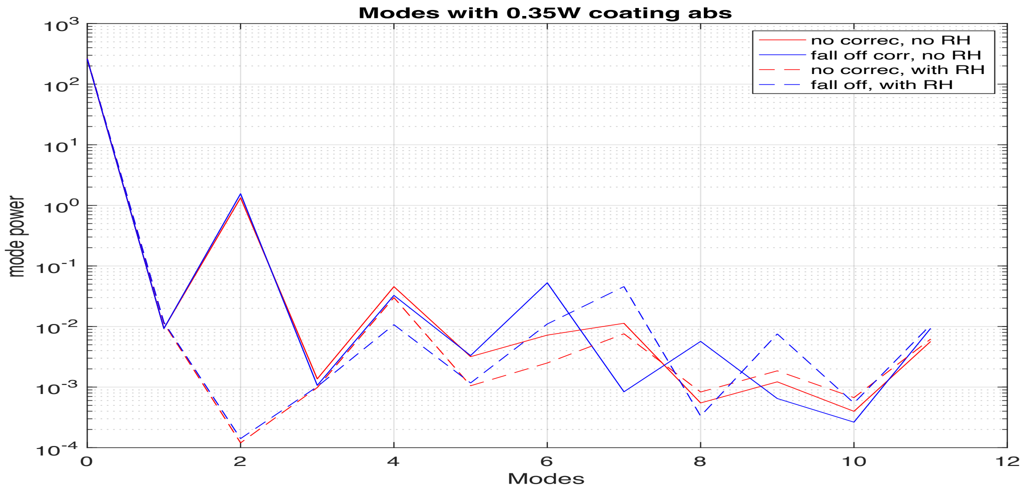


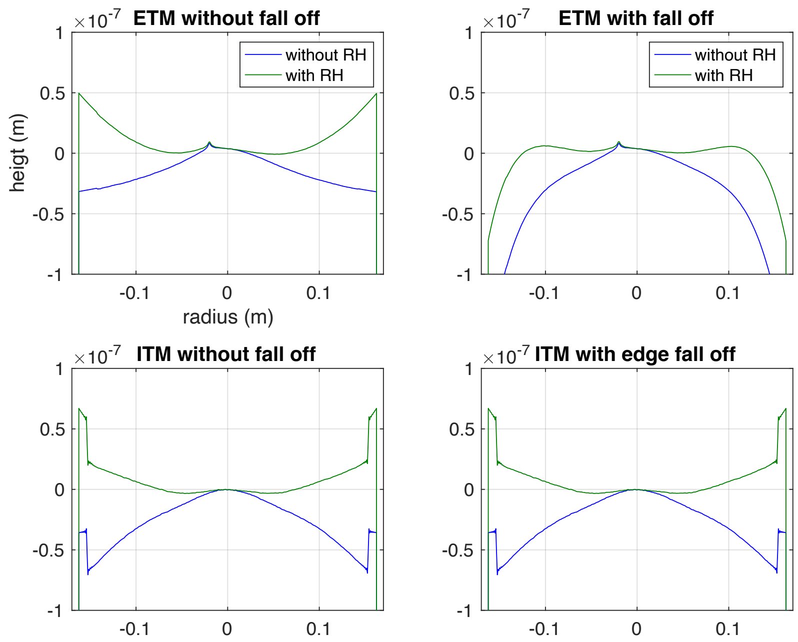
Answer to recommendations

- From G2001747-v3 page 32 - Are labels swapped? Cyan with corr is worse than without at center alignment.

  A: labels are not swapped.

  These are plots of ITM and ETM surfaces with 0.35W coating absorption. Bump at the center by the absorption affects the cavity mode a lot.





- Also plots on slide 2 - are the axes labels swapped?

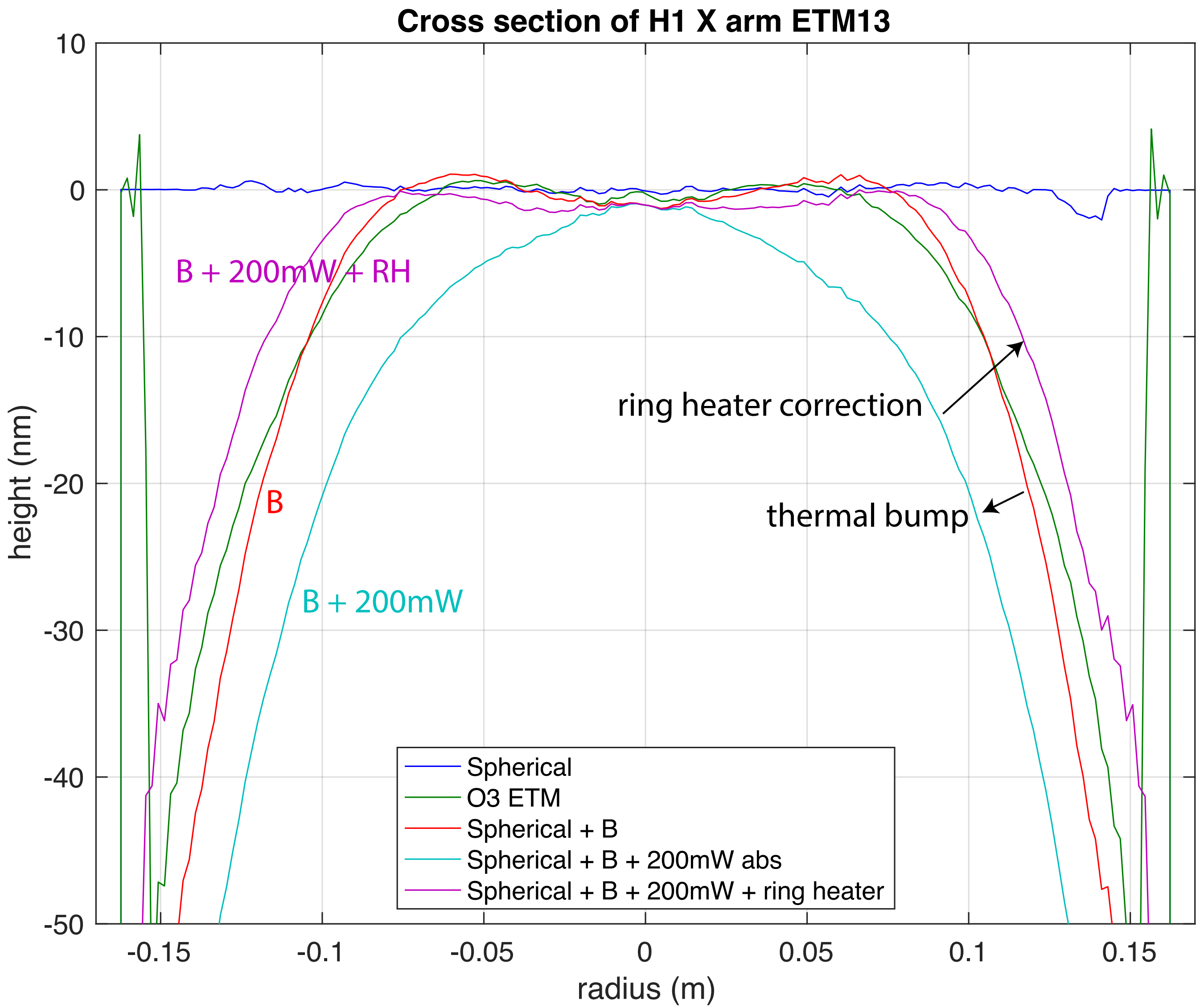
  A : Yes, axes are swapped

Cases studied

100 events generated, up to 4 point absorbers on ETM, at random locations with random power Prand, each PA absorbs Prand*exp(-$2r^2/w^2$) (r is distance between the beam at center and the individual PA).

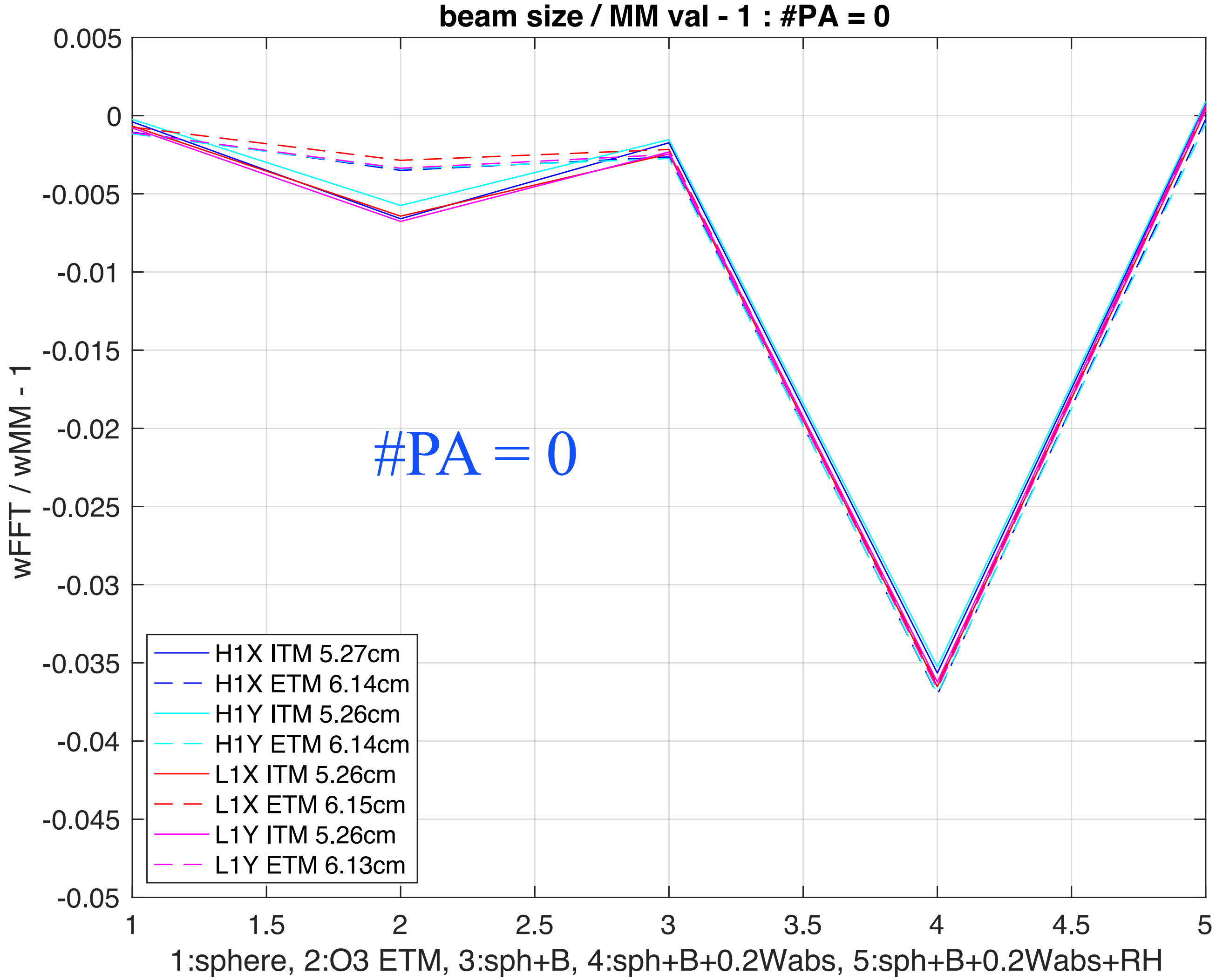
1. ITM (measured map and measured RoC) + ETM sphere (polished surface + measured RoC of the arm)
2. ITM + ETM as measured map and measured RoC
3. ITM + ETM sphere + coating thickness B
4. ITM + ETM sphere + B + 200mW coating absorption
5. ITM + ETM sphere + B + 200mW + ring heater RoC correction

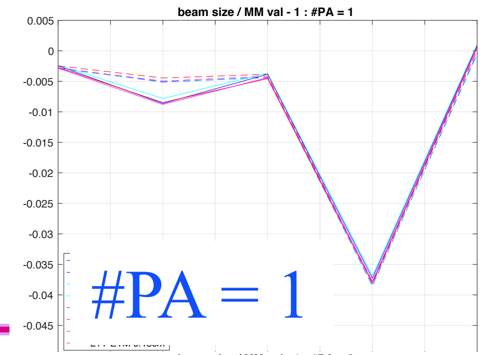
ETM surfaces

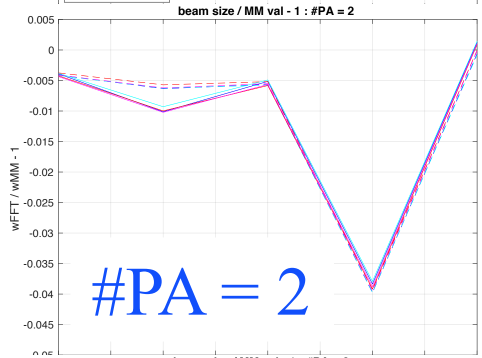


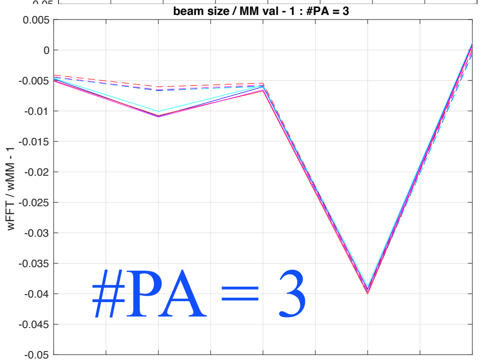
Beam size

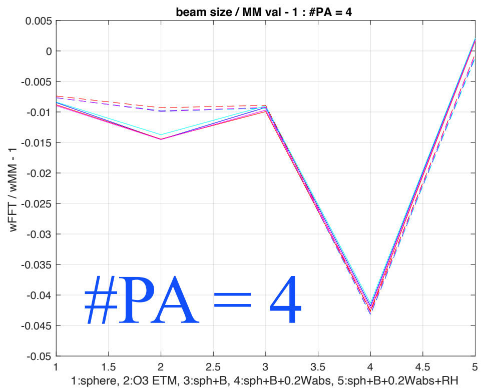
measured beam size / modal model value - 1



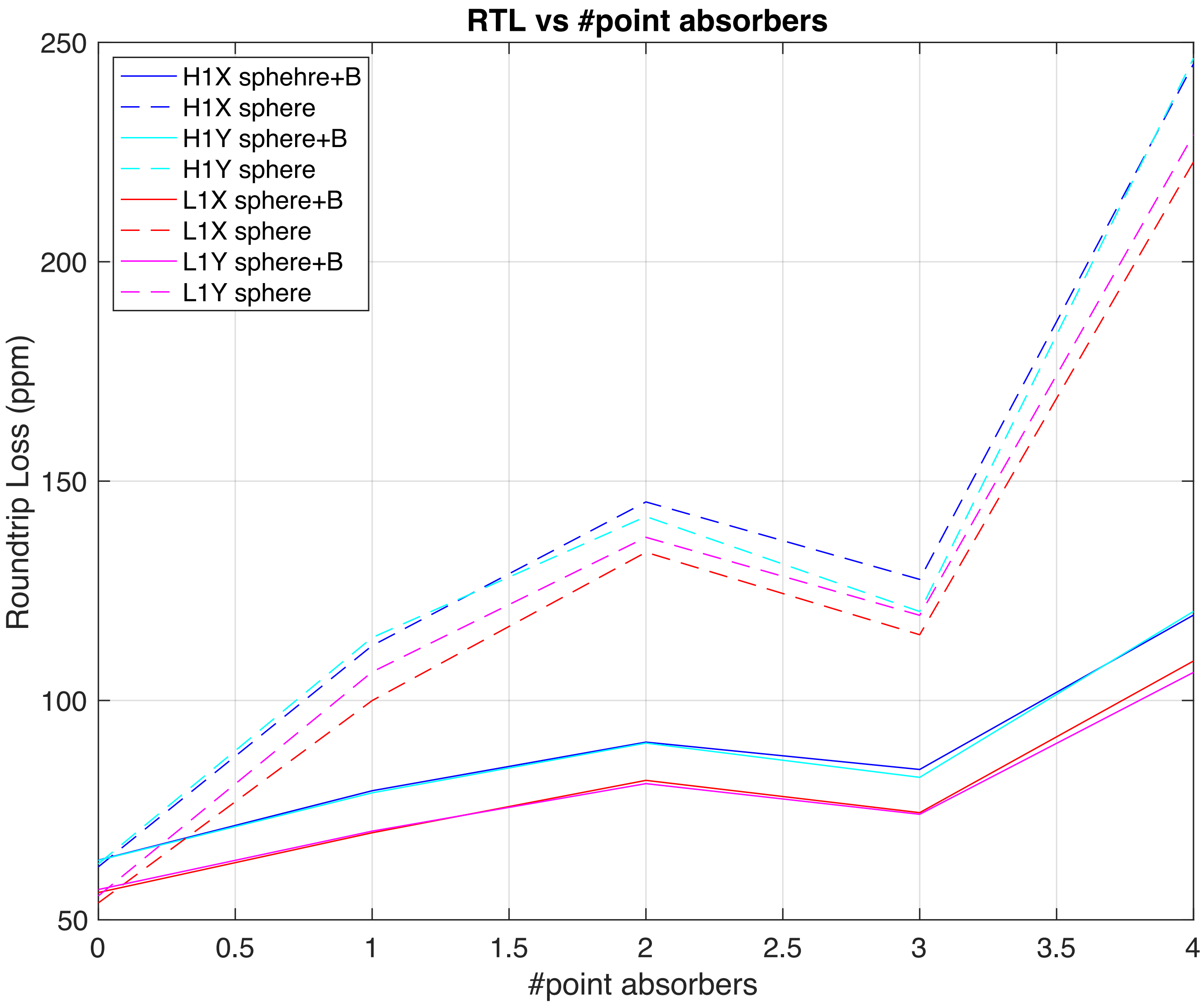




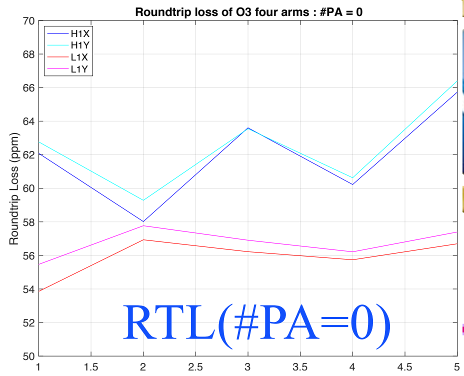


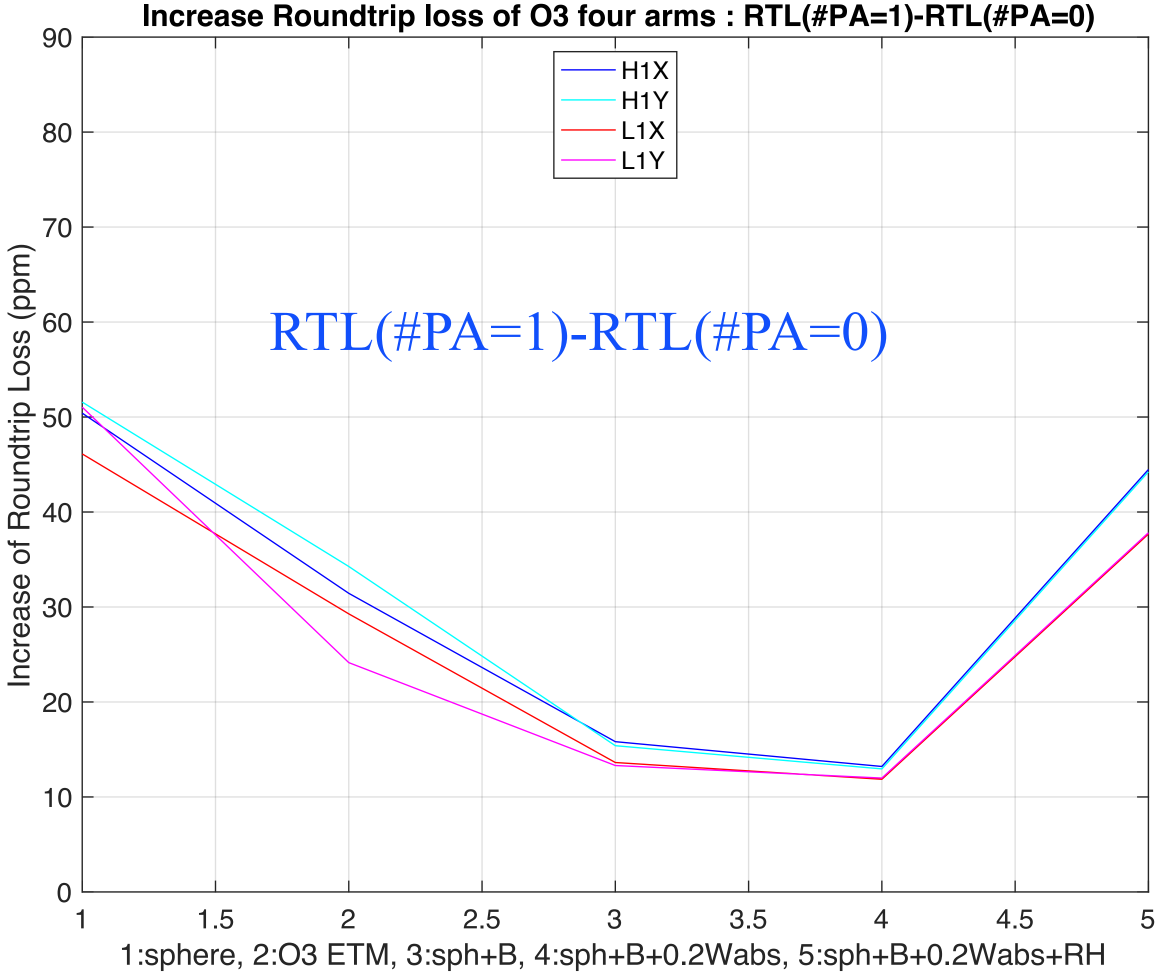


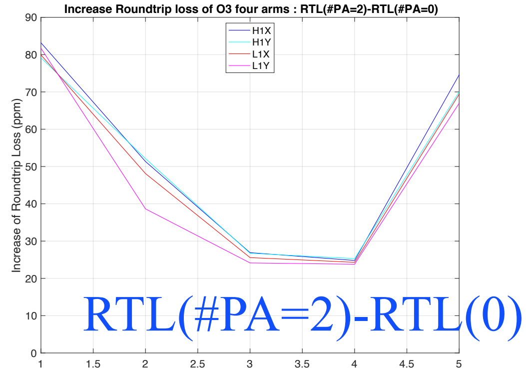
RTL, #PAs and effect of B

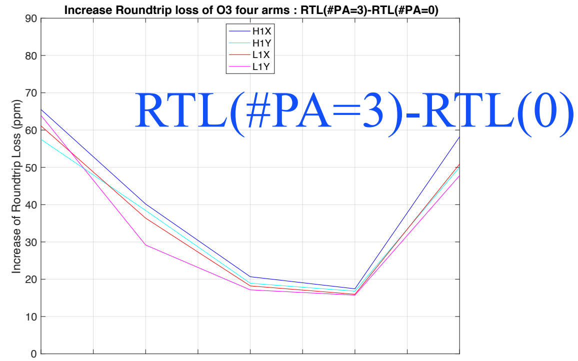


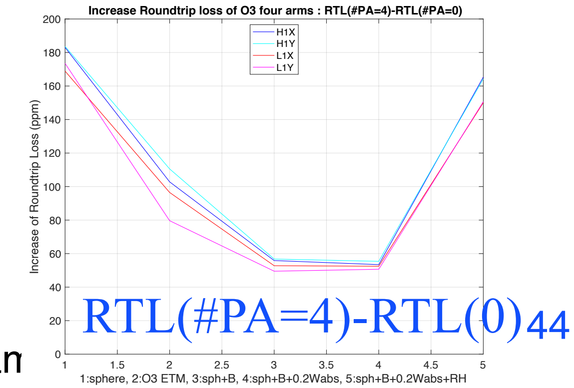
More on RTL vs shape





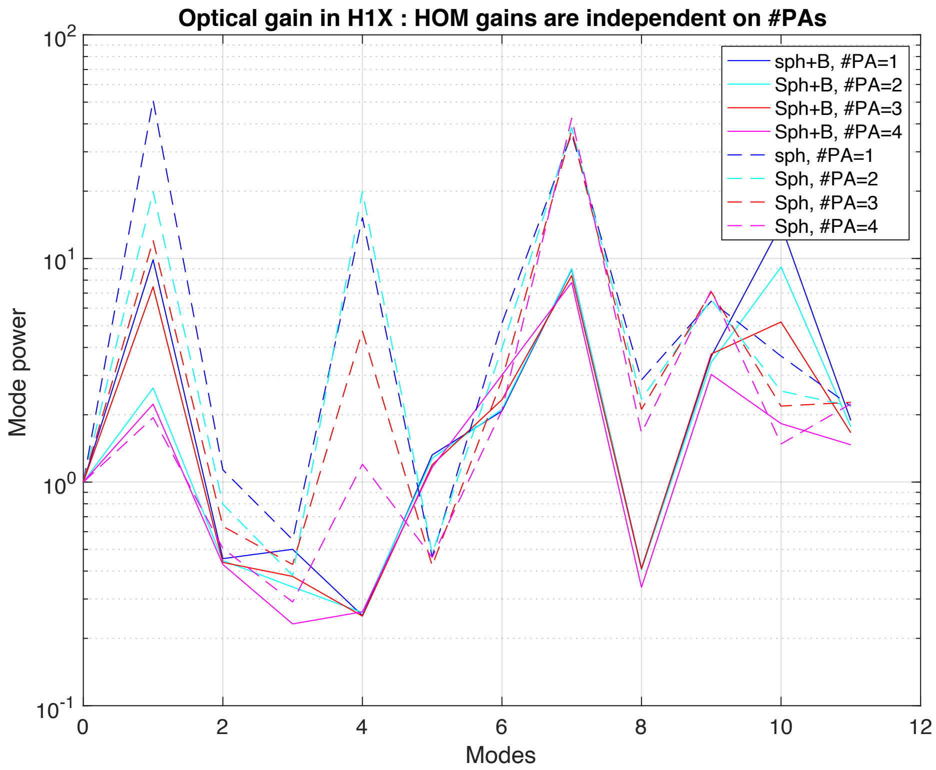


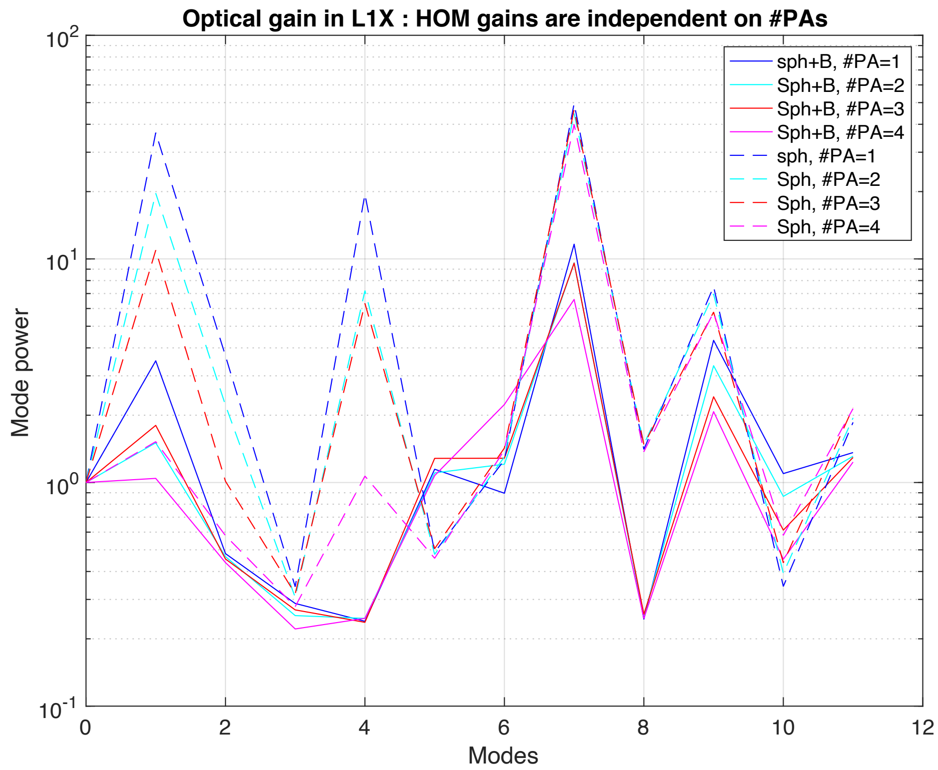




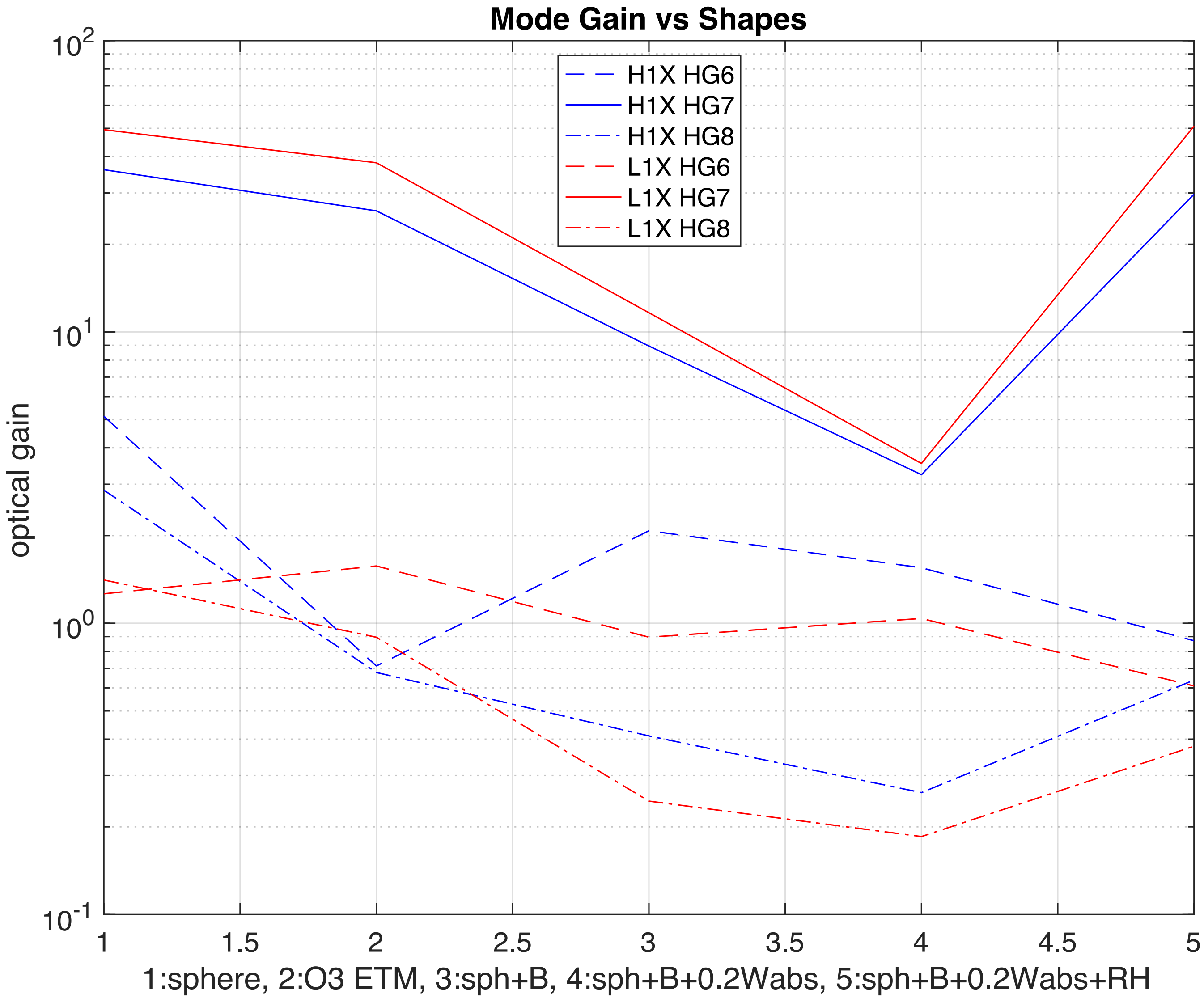
Optical Gains vs Modes

HOM gains are weakly depends on #PAs



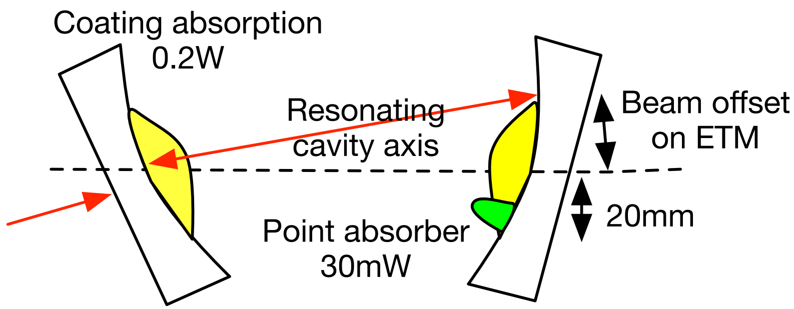


Mode gain vs shape (#PA=1)

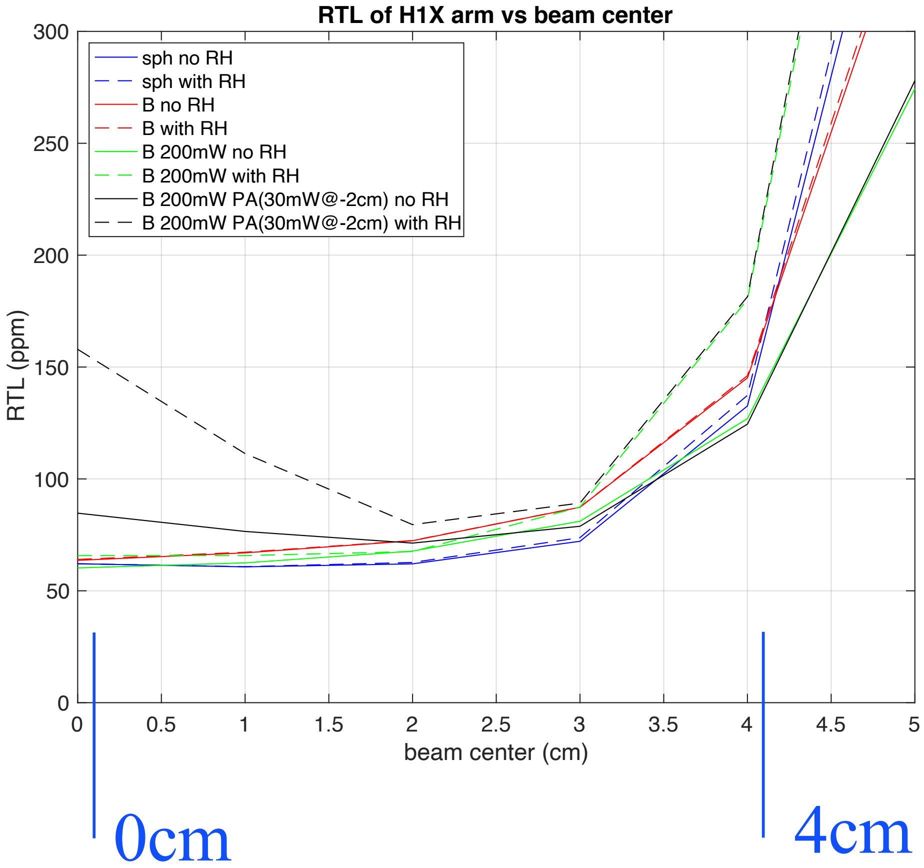


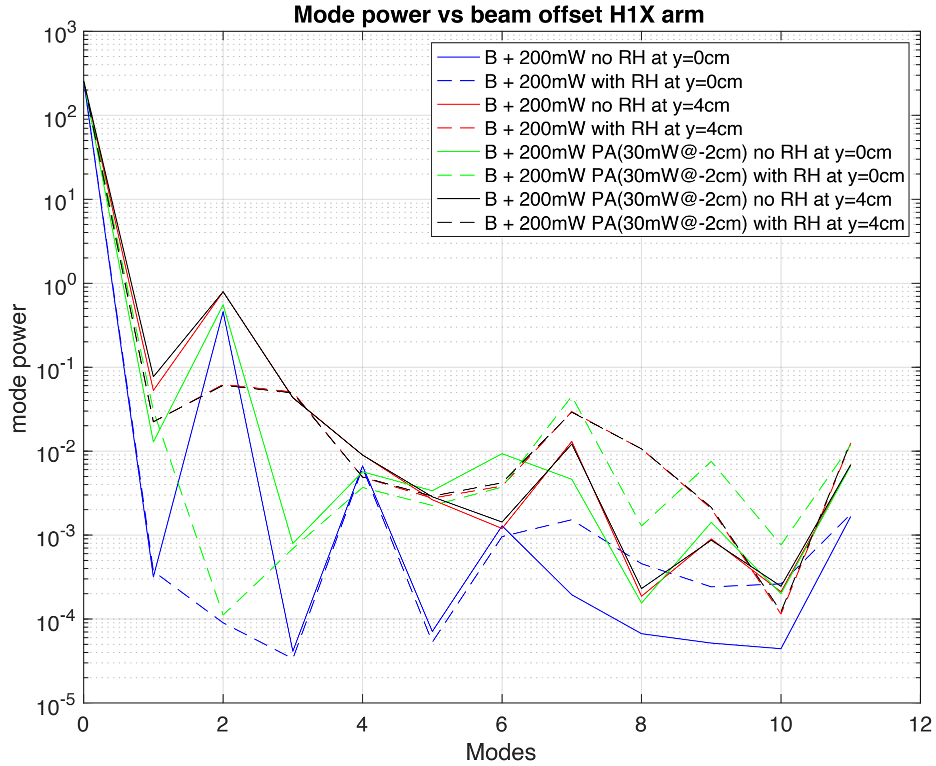
Offset dependence

- PA absorption of 30mW x $\exp(-2r^2/w^2)$ is placed at -2cm, where r is the distance between the PA and the beam center
- Beam center is moved away from the PA
- The center of the 200mW thermal bump by coating is the location of the beam on EM
- Mode is calculated using the cavity axis as z axis



RTL vs offset





0cm vs 4cm