Calibrating point absorber thermal lens measurements

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Order of Magntiude - OPD for effective steady state

$$\delta s \approx \beta\, w_m\, \delta T/2 \approx \frac{\beta}{4\pi\kappa} P_a\,.$$

For a very quick calibration, use the above formula from Winkler for sagitta (optical path distortion) [1]. This is for single pass optical path distortion.

β = 8.6E-6 K^{-1} , κ = 1.38 W/m.K

ds = β.P/(4$\pi\kappa$) ~ 0.5nm/mW single-pass

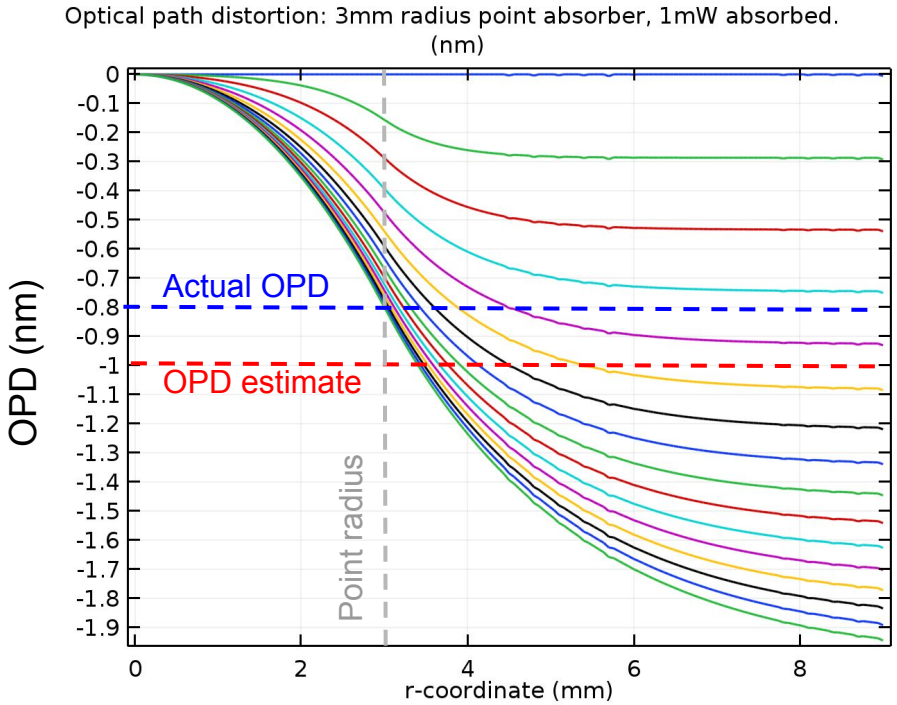
ds_{HWS} ~ 1nm/mW (for HWS measurements which are double-passed).

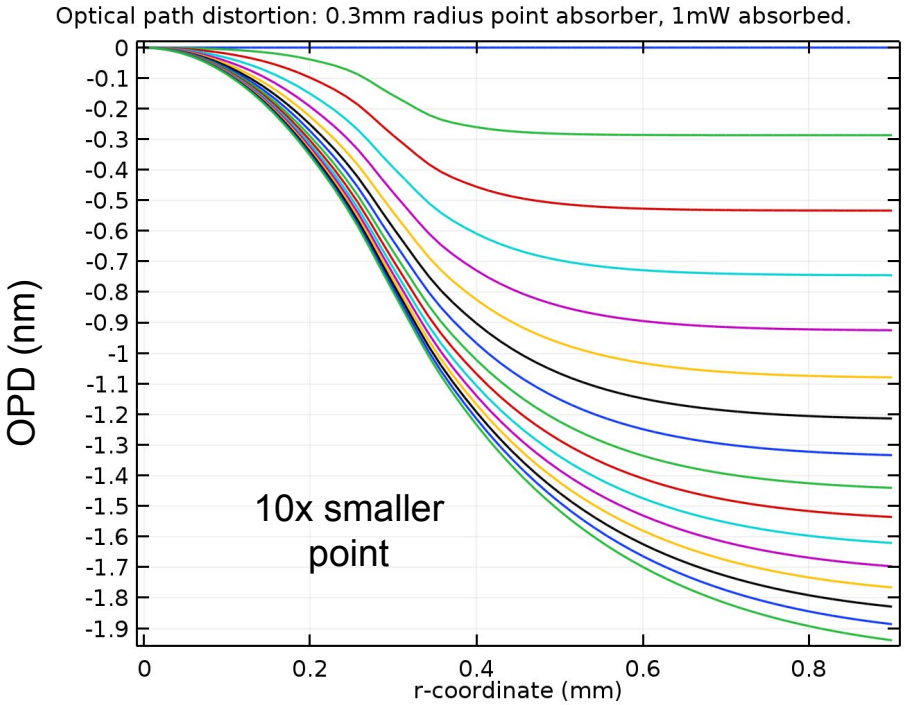
$$\tau \approx \frac{x^2}{3}\,\frac{\rho\, c}{\kappa} = \frac{x^2}{3\,D}$$

- Transverse scale isn't specified by assume spatial resolution of HWS (if point is smaller than HWS scale). Steady state isn't specified (assume t > **thermal time constant, tau**). Tau is a function of size and thermal diffusivity (product of density, heat capacity and 1/thermal conductivity)
- This gives Order of Magnitude - but over the diameter of the point. We *actually* fit to region outside the point

[1] Eq 10, Winkler et al, Phys. Rev A, **44** (11), 1 Dec 1991, p7022

COMSOL models - double passed, t = 3*tau, dt = tau/5





These COMSOL models show the Winkler OPD estimate is close to actual OPD predicted by a finite-element model. Also show scale invariance when heating time is scaled by time constant

Estimating equivalent point absorber size (or minimum absorber diameter)

- Always assume absorption coefficient equals 100%
- Determine local intensity of heating beam W/m^2
- Divide absorbed power by intensity to determine equivalent area
- Convert area to **diameter** of equivalent circular region

IFO response to point absorbers is **dependent** on:

- Absorber location relative to IFO beam
- Absolute power absorbed (see arXiv:2101.05828 Figure 9)

IFO response is **independent** of

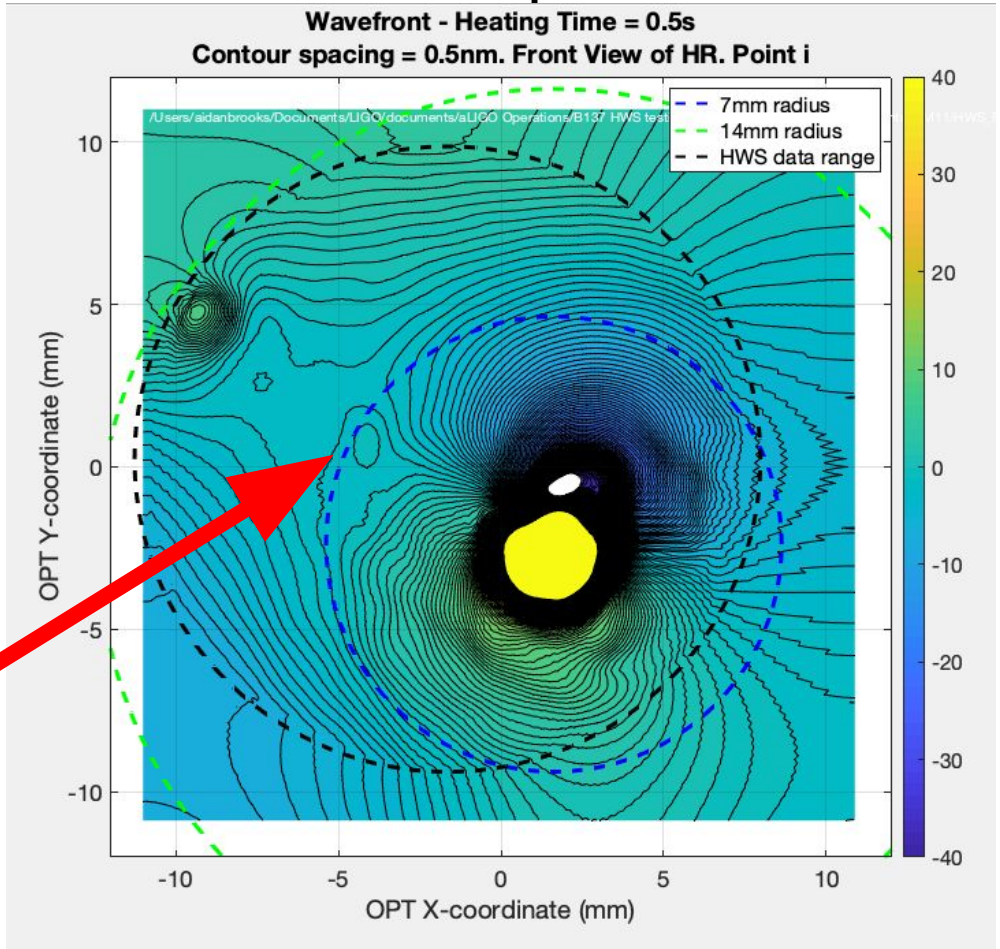
- absorber size*, shape and absorption coefficient (for fixed absorbed power)

* There may be some very high spatial scattering that is a function of point absorber size but we don't consider those effects right now

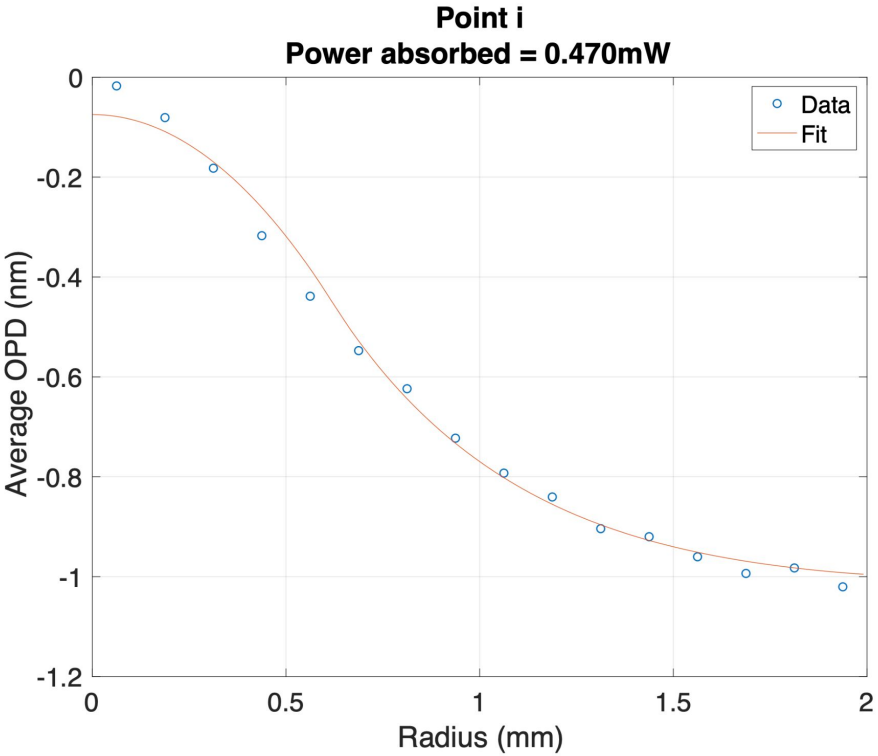
HPAD measurements of ITM11

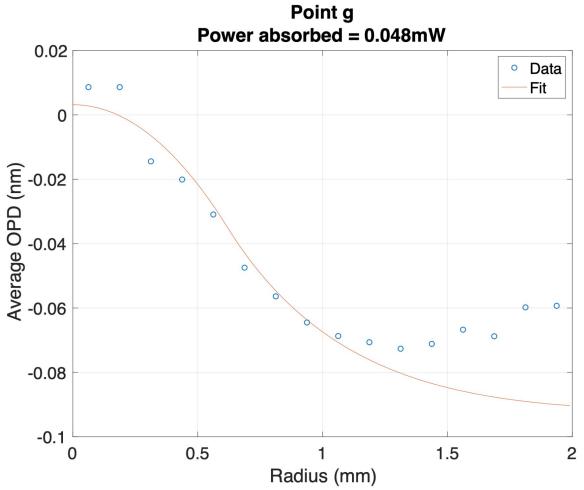
HWS wavefront measurement example - Point i

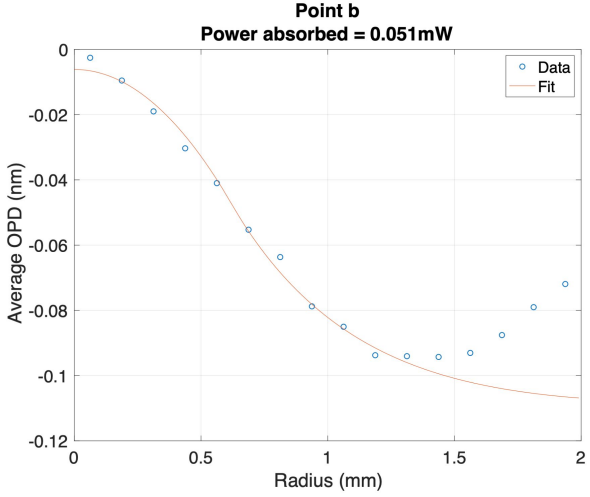
Location of point “i”



COMSOL model fitted to data







Data = average radial OPD at point absorber location
Model = double-passed OPD from 1mW absorption for 0.5s, with a “point” that has radius of 620um
Fitted over radius of 1.2mm (tau = 0.6s)

OPD fitting

Fit curve to estimate absorbed power

Point	Fitted OPD (over 1mm)	Fitted absorption	Estimated intensity [50% - 100% peak]	Equivalent point diameter
`i`	900pm	0.47mW*	1.2 - 2.4W/mm^2	16 - 22µm
`b`	80pm	51µW	1.2 - 2.4W/mm^2	5 - 7µm
`g`	70pm†	48µW	1.2 - 2.4W/mm^2	5 - 7µm

* Original estimate underestimated absorbed power by just counting contours. This is based on fit to OPD model.
† About 1.5mm from the point centered between fiducials (closest “point” visible in wavefront)
The Gaussian beam radius is approximately 5mm (yielding the above intensity)

Points: fit modeled OPD to measured OPD

Uncertainties

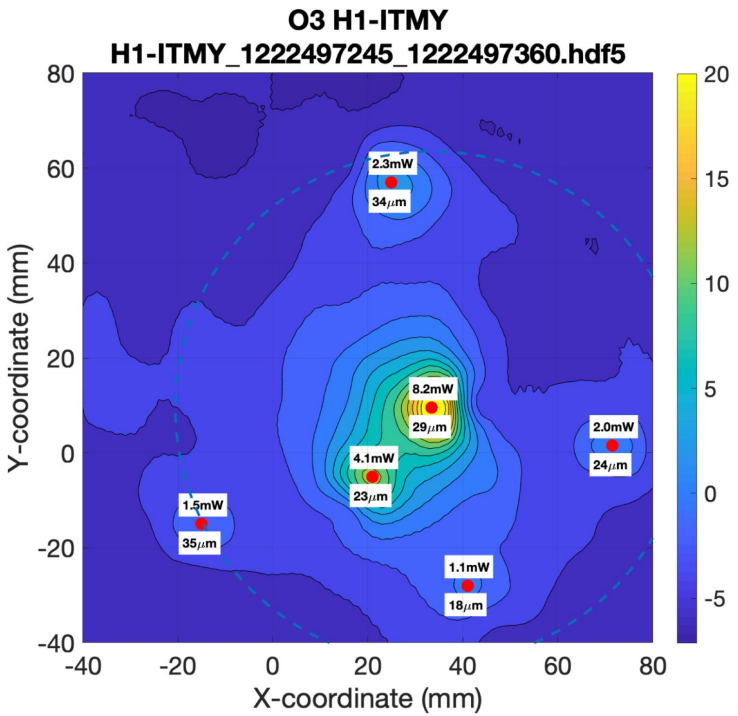
- Local intensity (uncertainty in center of heating beam)
- Exact heating power and duration (possibility of turn on transients)
  - Is heating slightly less than I think?
  - Power is measured by laser and reported back once a second: heating duration is only 0.5s
- Exact location of point in HWS measurements
  - fiducials measurements overlap with signal
  - Average radial OPD has attempted to remove tilt from fiducials

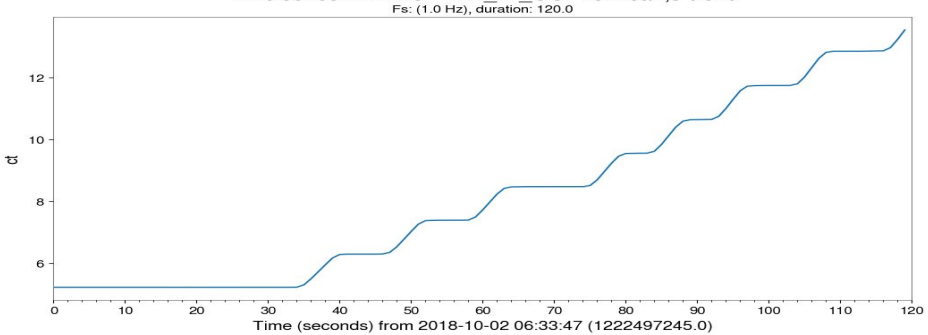
In-situ HWS measurements of ITM11 (Prior to O3)

H1ITMY - short duration fit

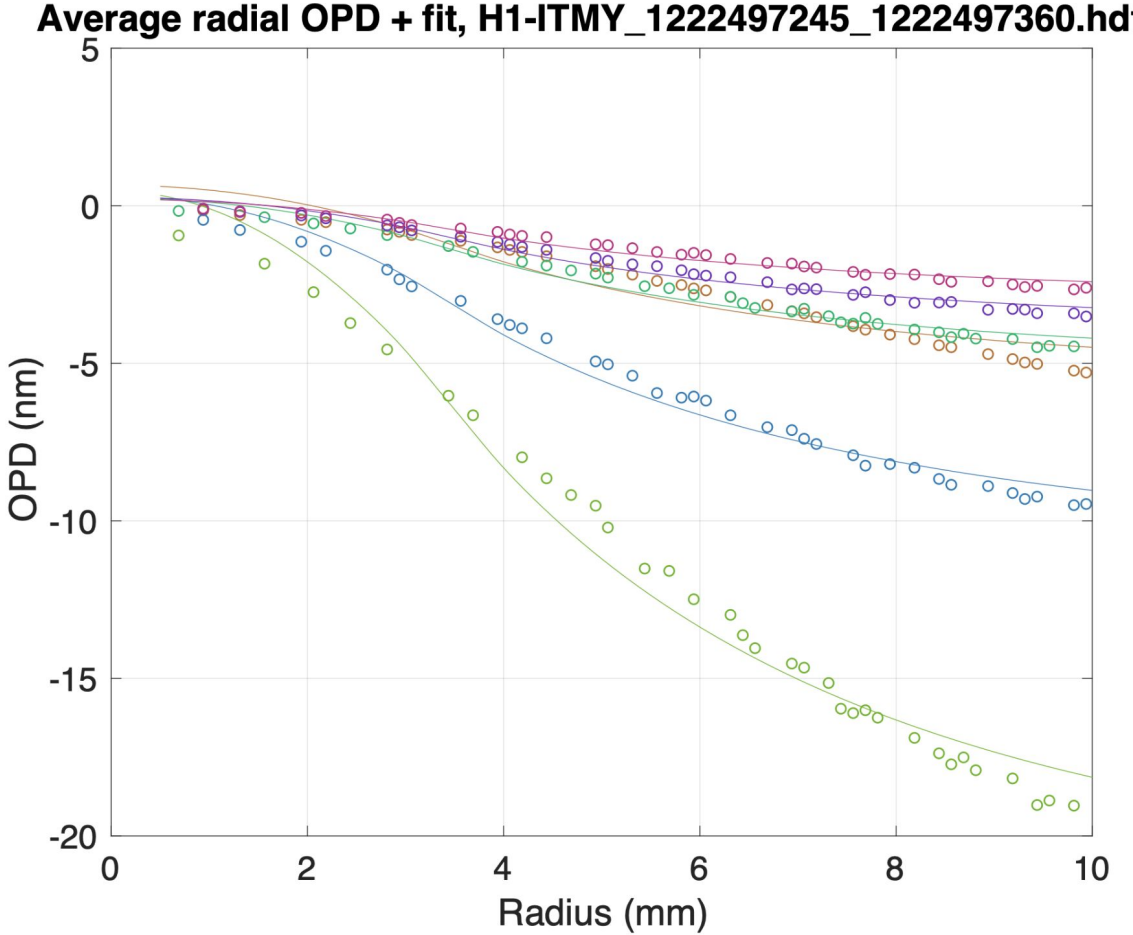
- Short duration heating of optic to isolate individual points
- Assume heating beam centered on largest point +/- 10mm
- Parameters assumed for intensity
  - IMC input power ramped from 5.3W to 14W over about 80s
  - PRG = 55
  - BS = 50%
  - Arm gain = 265

Point	Fitted absorption	Estimated intensity +/- 10mm beam center uncertainty	Equivalent point diameter
1	2.3mW	2.6 ± 1.6 W/mm^2	39 ± 15 μm
2	8.2mW	10.8 ± 1.3 W/mm^2	31 ± 2 μm
3	2.0mW	4.3 ± 2.1 W/mm^2	27 ± 8 μm
4	4.1mW	8.7 ± 2.2 W/mm^2	25 ± 4 μm
5	1.5mW	1.8 ± 1.3 W/mm^2	40 ± 18 μm
6	1.1mW	4.5 ± 2.1 W/mm^2	20 ± 6 μm





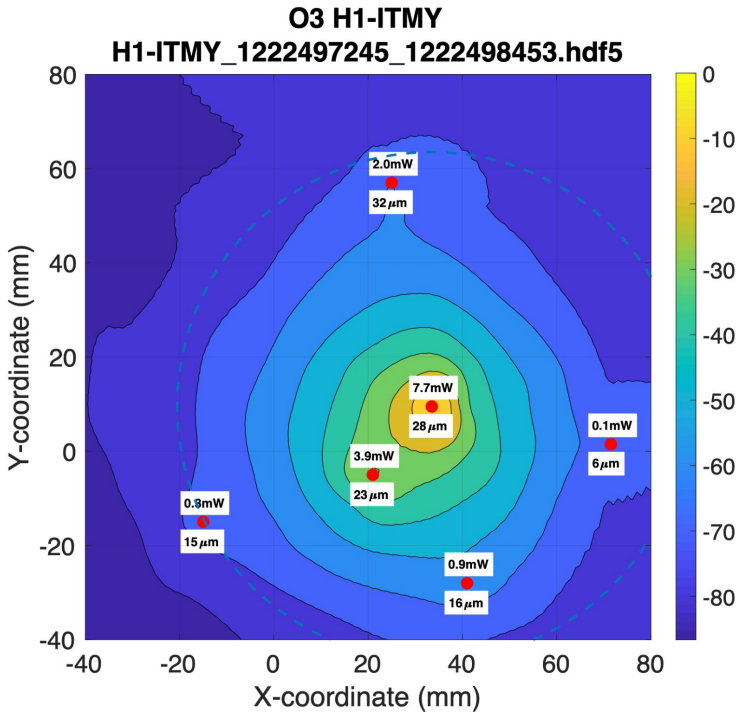
Fitting COMSOL OPD model to average OPD(r) for points



H1ITMY - long duration fit

- Same measurement setup but for 1200s longer heating duration
- Highlighted orange rows disagree with short duration by more than uncertainty

Point	Fitted absorption	Estimated intensity +/- 10mm beam center uncertainty	Equivalent point diameter
1	2.0mW	2.6 ± 1.6 W/mm^2	32 µm
2	7.7mW	10.8 ± 1.3 W/mm^2	28 µm
3	0.1mW	4.3 ± 2.1 W/mm^2	6 µm
4	3.9mW	8.7 ± 2.2 W/mm^2	23 µm
5	0.3mW	1.8 ± 1.3 W/mm^2	15 µm
6	0.9mW	4.5 ± 2.1 W/mm^2	16 µm

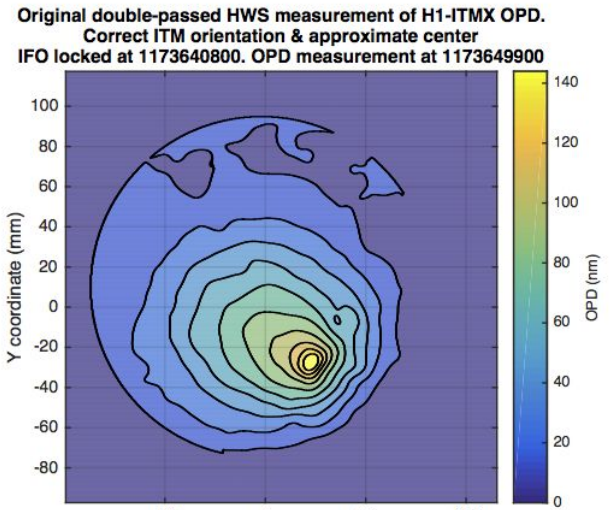


H1-ITMX (O1,O2)

ITMX point was fitted in March 2017

- Best fit absorption: 25.5mW (aLOG 35069)
- For 23W power up
- Arm power = 137kW. Assume:
  - PRG = 45
  - Arm gain = 265
  - BS = 0.5
- Point is about 29mm from center of optic: T1800013
- Fitted diameter = 44μm

Point	Fitted absorption	Estimated intensity +/- 10mm beam center uncertainty	Equivalent point diameter
#1	25.5mW	17 ± 7 W/mm^2	44 + [13,-7] μm



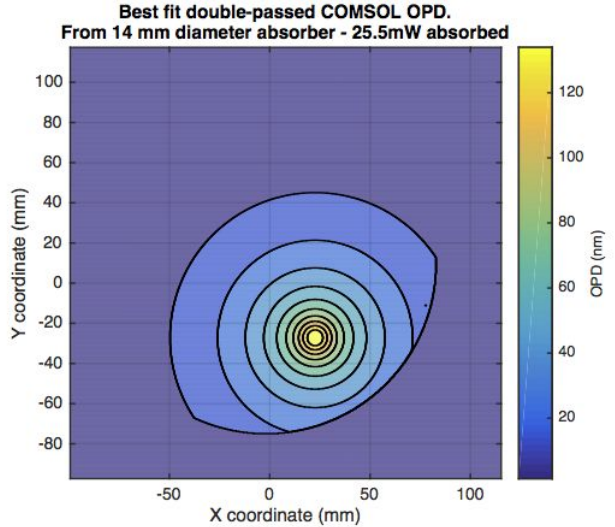


Table of point absorbers

OPTIC PT	P_{abs}	ΔP_{arm} or P_{HPAD}	ABS*	Relative or absolute intensity	Circular diameter	REF
H1-ETMX [A]	5.5mW	~90kW	~60ppb	Unknown [80%]	24μm	G2102068
L1-ETMX [α]	19.5mW	~210kW	~93ppb	~30%	49μm	aLOG 46090
L1-ETMX [β]	13.7mW	~210kW	~65ppb	~28%	42μm	aLOG 46090
L1-ETMY [main]	~5mW	~113kW	~45ppb	~60%	24μm	aLOG 54361
H1-ITMX [O1/O2]	25.5mW	~137kW	~190ppb	17 ± 7 W/mm^2	44 + [13,-7] μm	aLOG 34900, LDAS
H1-ITMY [1]	2.3mW	~137kW	~17ppb	2.6 ± 1.6 W/mm^2	39 ± 15 μm	This work
H1-ITMY [2]	8.2mW	~137kW	~60ppb	10.8 ± 1.3 W/mm^2	31 ± 2 μm	This work
H1-ITMY [3]	2.0mW	~137kW	~15ppb	4.3 ± 2.1 W/mm^2	27 ± 8 μm	This work
H1-ITMY [4]	4.1mW	~137kW	~30ppb	8.7 ± 2.2 W/mm^2	25 ± 4 μm	This work
H1-ITMY [5]	1.5mW	~137kW	~11ppb	1.8 ± 1.3 W/mm^2	40 ± 18 μm	This work
H1-ITMY [6]	1.1mW	~137kW	~8ppb	4.5 ± 2.1 W/mm^2	20 ± 6 μm	This work
ITM11 - i [HPAD]	0.47mW	95W	4.9ppm	1.2 - 2.4W/mm^2	16 - 22μm	This work
ITM11 - b [HPAD]	51μW	95W	0.54ppm	1.2 - 2.4W/mm^2	5 - 7μm	This work
ITM11 - g [HPAD]	48μW	95W	0.51ppm	1.2 - 2.4W/mm^2	5 - 7μm	This work