

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY  
- LIGO -  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
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Technical Note	LIGO-T1000247-v2	2010/08/06
<b>ISC In-vacuum Gouy phase telescopes</b>		
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## 1 Introduction

The Advanced LIGO wavefront sensors are located at the Transmission port (Transmon), Reflection port (REFL), Pick-Off Port (POP), and AntiSymmetric port (AS). At each port alignment information is required in both the near field and far field or equivalently, at two Gouy phases separated by 90 degrees. In practice, we aim to position the two wavefront sensors at each port symmetrically one Rayleigh range around a  $250\text{ }\mu\text{m}$  waist. This configuration gives a spot size at the sensor of  $350\text{ }\mu\text{m}$ , appropriate for the infrared photodetectors: OSI Optoelectronics Q3000 3 mm quadrant photodiodes with  $45\text{ }\mu\text{m}$  gaps.[9] This configuration is relatively insensitive to errors in the optic positions and deviations of the input beam from the model. Because there is no mode cleaner or other spatial discriminator after these Gouy telescopes, the lateral and angular coupling described in Ref. [8] is not relevant.

Some of the optics described here serve double duty as elements in the alignment control of a beam. For alignment, mirrors (either flat or curved) will be mounted in 2" diameter, voice coil actuated Tip/Tilt suspended mounts. In order to simplify the alignment control matrix, the Tip/Tilt mounts must be separated by a significant Gouy phase,  $\phi_G \geq 60^\circ$ . To meet this requirement, the phase accumulated between the telescope elements must itself exceed  $60^\circ$  and we choose an acceptable range of  $70^\circ \leq \phi_G \leq 110^\circ$ .

This note describes workable Gouy phase telescopes for each of the four ports of the H1 interferometer, based on the interferometer configuration described in Ref. [1]. For all ports, the beam is propagated from the last optic for which Ref. [1] specifies the beam radius and the radius of curvature. ISC table layouts are based on the block diagrams shown in Ref. [4] and related documents.

## 2 References

### References

- [1] M. Arain and G. Mueller; *Optical Layout and Parameters for the Advanced LIGO Cavities*; T0900043-10
- [2] P. Fritschel; *Advanced LIGO H1 Optical Layout*; D0902838-v2
- [3] D. Coyne and M. Smith; *Advanced LIGO H1 Optical Layout, ZEMAX*; D0901920-v6
- [4] J. Fishner; *Top Level ISC Block Diagram*; D1000653
- [5] P. Fritschel; *List of ISC Photodetectors in Advanced LIGO* T1000264
- [6] M. Arain et al.; *Pre Mode Matching Telescope Parameters, Adaptive Mode matching, and Diagnostics*; T0900407-v4
- [7] M. Arain et al.; *Optical Layout of POP/ALS beams*; Presented at the January 29, 2010 ISC meeting
- [8] K. Kawabe; *Mode Matching Telescope for Advanced LIGO Output Mode Cleaners* T1000317
- [9] R. Abbott and P. Fritschel; *Transmission Monitor Quadrant Photodetector Design* T0900423
- [10] J E Chavez; *AdvLIGO Systems, HAM2-H1 Top Level Chamber Assembly* D0901083
- [11] S J Waldman; *The Advanced LIGO ETM transmission monitor* T0900385

### 3 Telescope requirements

Three major considerations drive the selection of the telescopes. First, the geometry of the telescope must fit on a HAM-ISI table. We interpret this constraint as requiring a minimum distance between optical elements of 0.1 m and a maximum distance of 1.8 m. The minimum length is based on the assumption that the optics are lenses and can be placed in series as for lenses. The maximum length is the diameter of the ISI table. Obviously, both lengths could be exceeded with minor layout gymnastics.

Second, alignment telescopes must accumulate at least  $60^\circ$  of Gouy phase between the first and last optic. This ensures that the Tip/Tilt control matrix will not be degenerate.

Finally, the  $250\ \mu\text{m}$  output waist must be separated from the last optic by at least  $0.18 + 0.1\ \text{m} = 0.47\ \text{m}$ . This length gives enough separation from the waist, one Rayleigh range plus 0.1 m, so that we can put a beam splitter and sensor in the beam path.

## 4 Reflection Port

The input parameters for the REFL port telescope are listed in Table 1. The beam must be propagated from the Power Recycling Mirror (PRM), through the steering mirrors and Pre Mode Matching Telescope (PMMT), to HAM1. The distance to HAM1 is taken as the distance from HAM1 to HAM2 as listed in Ref. [3], 2.5 m.

Parameter	Ref.	Symbol	Straight	Folded
Beam radius at PRM	[6]	$\omega_{PRM}$	2.24 mm	2.08 mm
PRM radius of curvature	[1]	$R_{PRM}$	-11.0 m	-8.87 m
PRM thickness	[2]	$t_{PRM}$	75 mm	
Distance PRM to SM2	[3]	$x_{sm2}$	490 mm	
Distance SM2 to PMMT2	[3]	$x_{pmmt2}$	1210 mm	
PMMT2 radius of curvature	[2]	$R_{PMMT2}$	-6.24 m	
Distance PMMT2 to PMMT1	[3]	$x_{Far}$	1170 mm	
PMMT2 radius of curvature	[2]	$R_{PMMT2}$	12.8 m	
Distance PMMT2 to HAM1		$x_{HAM1}$	2.5 m	
Beam parameter in HAM1		$q_{HAM1}$	1.03 + 13.1 i	

Table 1: The REFL port input parameters. The values are defined for the straight and folded interferometer configurations. Where folded IFO parameters are not explicitly stated in the references, they are assumed identical to the straight configuration. Distances are between the HR faces, unless otherwise noted. Unless specifically noted, the optics are flat. Negative ROC is convex.

The beam in HAM1 has a size of 2.1 mm with the waist located about 1 m before the HAM1 chamber. We separate the optics in HAM1 by function. One set of optics is a telescope that produces a collimated beam with a Rayleigh range  $> 5$  m ( $\omega_0 > 1.4$  mm) and output waist located in HAM1. The telescope includes (at least) two mirrors in Tip/Tilt mounts which are used for alignment control and must be spaced by at least  $60^\circ$  of Gouy phase. A second set of optics, the Gouy phase telescope, produces the 250  $\mu$ m waist and associated  $90^\circ$  of Gouy phase for the QPDs.

The alignment telescope is physically constrained by the size of the HAM1 iLIGO-style optics table, 170 cm by 190 cm. To accumulate sufficient Gouy phase requires a small waist between alignment controlled optics, while the telescope output should have a relatively large waist. These two requirements are best met with a three element telescope. We calculated all of the 3 element telescopes with reflective optics ranging in 0.1 m ROC intervals that fit on the HAM1 table. We selected only the solutions with: a) at least  $60^\circ$  degrees of Gouy phase between a pair of optics; b) one of the optics as a 1.7 m ROC mirror (to match the optic used in the AS port solutions), and c) a good combination of forgiving length. For the solution described by M1, M2 and M3 in Table 2, the alignment control is accomplished between the second two optics which must be reflective mirrors mounted in Tip/Tilts. Note that this telescope uses two of the 1.7 m ROC mirrors. The QPD sled has two lenses, L1 and L2, and 2 QPDS, QPD1 and QPD2. The beam waist and Gouy phase propagation are shown in Fig. 1, and a plausible layout for the QPD sled shown in Fig. 2.

Optic	Position	Gouy phase
M1 R = 1.7 m	0	0
M2 R = -0.6 m	831 mm	66°
M3 R = 1.7 m	1686 mm	161°
L1 f = 343 mm	2686 mm	166°
L2 f = -172 mm	2896 mm	171°
QPD1	3258 mm	188°
QPD2	3627 mm	278°

Table 2: REFL port telescope parameters.

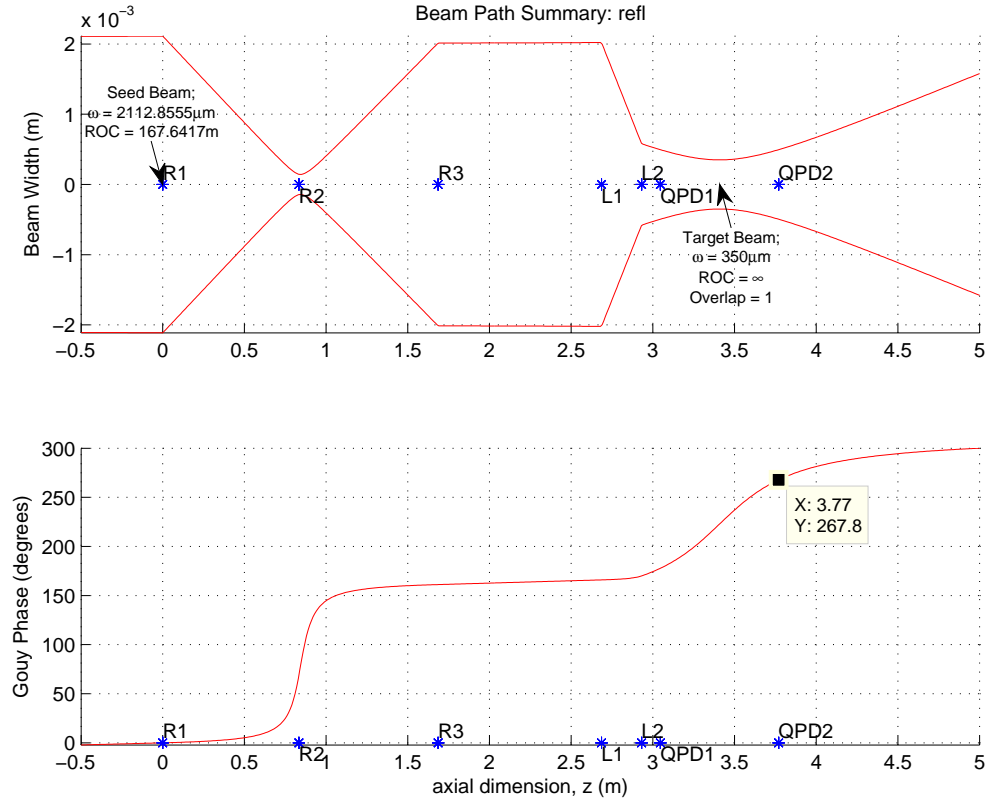


Figure 1: The REFL port telescope beampath.

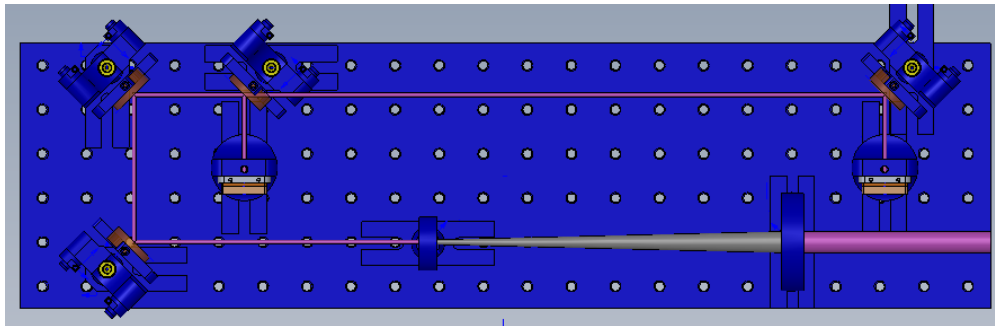


Figure 2: The REFL port QPD layout.

## 5 Pick-Off Port

The input parameters for the Pick-Off Port (POP) telescope are listed in Table 3. The beam from the PRM must be propagated through the second Power Recycling cavity mirror (PR2) in HAM3, through the steering mirrors to a QPD sled. There is no tip/tilt alignment at the POP port. The Rayleigh range of the beam after PR2 is quite long, 5.2 m, hence the exact position of the QPD optics is not critical. We take 2.5 m as a reasonable distance between PR2 and the first of the QPD sled optics (including steering mirrors).

Parameter	Ref.	Symbol	Straight	Folded
Beam radius at PRM	[6]	$\omega_{PRM}$	2.24 mm	2.08 mm
PRM radius of curvature	[1]	$R_{PRM}$	-11.0 m	-8.87 m
Distance PRM to PR2	[1]	$x_{prc}$	16.6 m	15.8 m
Beam radius at PR2	[2]	$\omega_{PR2}$	6.2 mm	6.3 mm
Beam curvature at PR2	[1]	$R_{PR2}$	24.86 m	?? m
PR2 radius of curvature	[2]		-4.55 m	
PR2 thickness	[2]	$t_{PR2}$	75 mm	
Distance PR2 to QPD	[7]	$x_{M1}$	2.5 m	

Table 3: The POP input parameters. The values are defined for the straight and folded interferometer configurations. Where folded IFO parameters are not explicitly stated in the references, they are assumed identical to the straight configuration. Distances are between the HR faces, unless otherwise noted. Unless noted, the optics are flat. Negative ROC is convex.

A solution for the POP DC QPD telescope is shown in Fig. 3. The optics' positions and Gouy phase with respect to PR2 are enumerated in Table. 4. The beam size on each QPD is  $350 \mu\text{m}$ .

The folded geometry has not yet been calculated.

Optic	Specification	Z [m from PR2]	Gouy Phase
PRM	ROC = -11 m	-16.60	-24°
PR2	ROC = -4.56 m	0	0
L1	f = 343 mm	2.425	1.5°
L2	f = -57 mm	2.708	2.7°
QPD1	3mm QPD	3.101	30°
QPD2	3mm QPD	3.470	120°

Table 4: The POP DC optics, positions and Gouy phases.

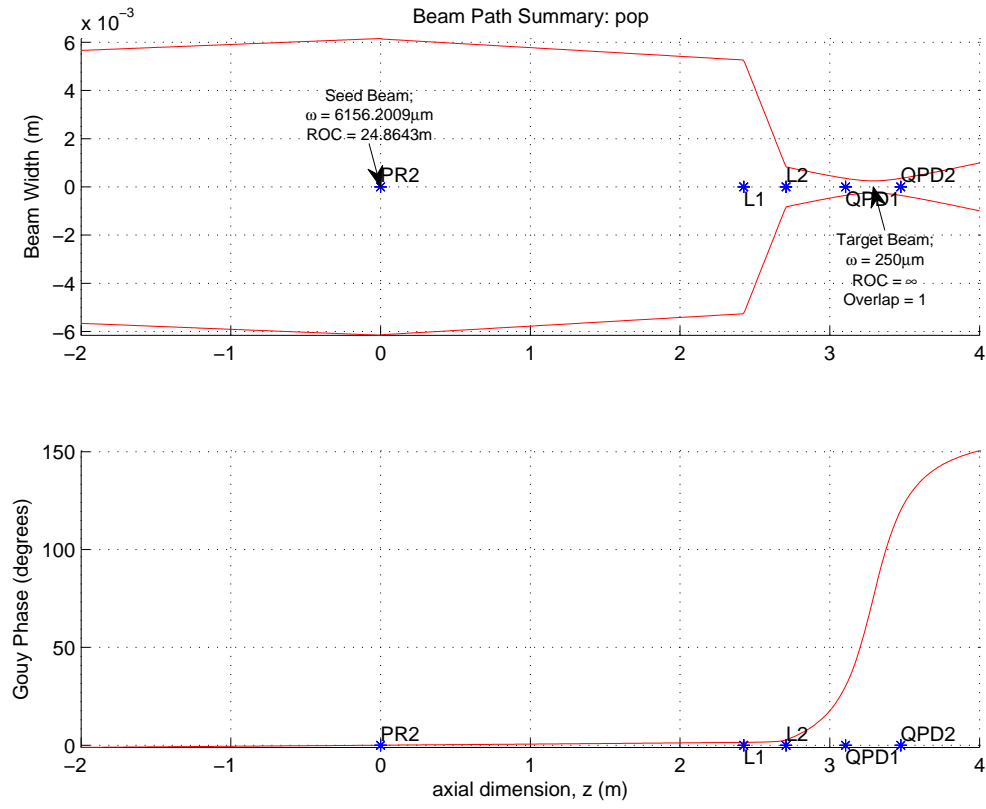


Figure 3: A solution for the POP DC QPD Gouy phase telescope.

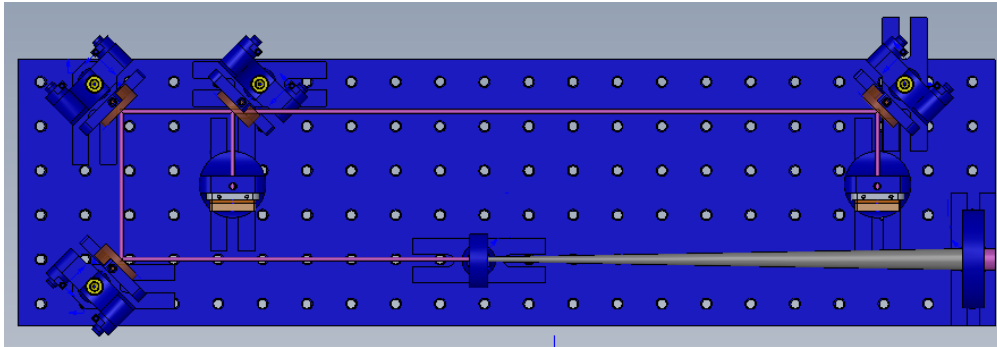


Figure 4: Layout the POP DC QPD Gouy phase telescope.

## 6 Antisymmetric port

The input parameters for the Anti-Symmetric port (AS) telescope are listed in Table 5 and shown in Fig. 5. The 3-mirror OMC mode matching telescope is described in Ref. [8]. We assume that the beam for the AS port QPDs is transmitted through the third mirror of the mode matching telescope and delivered to the QPD sled through two steering mirrors 0.5 m apart. Because the AS port beam is already reduced to 0.5 mm in order to match the OMC waist, the AS QPD sled is the simplest yet, consisting only of a single 343 mm lens. This simplicity comes at the cost of a requirement placed on the QPD sled placement, but the beam’s Rayleigh range, 74 cm, is sufficiently long that this requirement is lax. Since the AS port optics are in the more-readily accessible HAM6, we don’t present a detailed QPD sled layout.

Parameter	Ref.	Straight	Folded
Beam radius at SRM	[2]	2.1 mm	2.6 mm
SRM radius of curvature	[1]	-5.7 m	-11.4 m
SRM thickness	[2]	75 mm	
Distance SRM to TT1	[8]	3.646 m	
TT1 ROC		4.6 m	
Distance TT1 to TT2		1.395 m	
TT2 ROC		1.7 m	
Distance TT2 to TT3		0.708 m	
TT3 ROC		$\infty$	

Table 5: The AS port input parameters. The values are defined for the straight and folded interferometer configurations. Where folded IFO parameters are not explicitly stated in the references, they are assumed identical to the straight configuration. Distances are between the HR faces, unless otherwise noted. Unless noted, the optics are flat. Negative ROC is convex.

Optic	Position [mm]	Gouy phase
TT3	-605	-42
L1 f = 343 mm	0	0
QPD1	193	21
QPD2	301	111

Table 6: A solution for the AS port Gouy phase telescope.



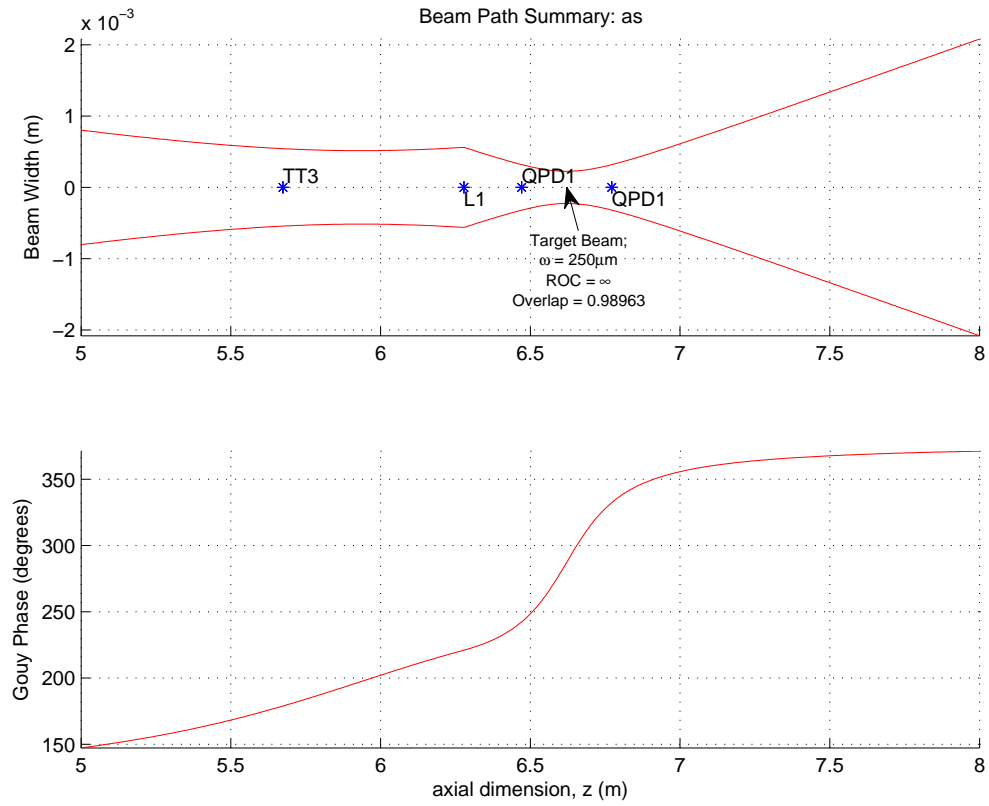


Figure 5: A solution for the AS QPD Gouy phase telescope.

## 7 Transmission monitor

The transmission monitor QPD has been discussed at length in Ref. [11]. Here we list the IR QPD sled solution for completeness.

Optic	Specification	Z [m from PR2]	Gouy Phase
L1	$f = 343$ mm	0	$0^\circ$
L2	$f = -114$ mm	246	$2^\circ$
QPD1	3mm QPD	685	$30^\circ$
QPD2	3mm QPD	1054	$120^\circ$

Table 7: The Transmon QPD optics, positions and Gouy phases.

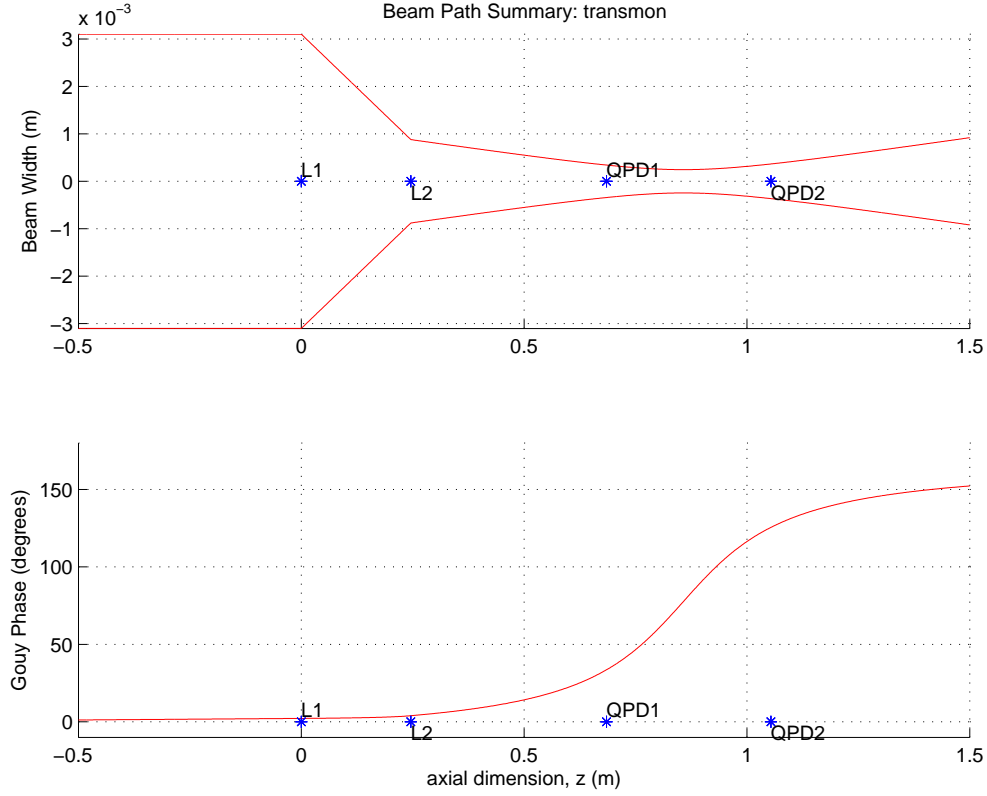


Figure 6: A solution for the Transmon QPD Gouy phase telescope.

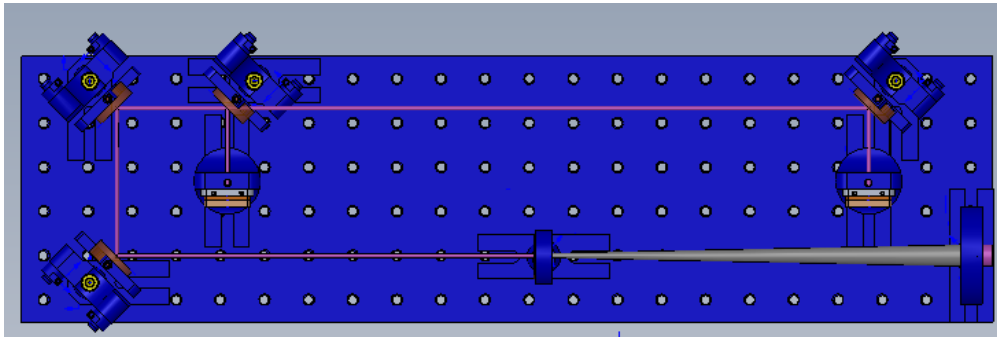


Figure 7: Layout the Transmon QPD Gouy phase telescope.

## 8 Transmission monitor Green

The transmission monitor green QPDs have not been discussed at length in Ref. [11]. Because the green QPDs have a large gap,  $250\text{ }\mu\text{m}$ , and a larger diameter,  $7\text{ mm}$ , a different spot size is required. Instead of  $350\text{ }\mu\text{m}$  as for IR, we aim for  $1\text{ mm}$ . Because the telescope must still fit on the QPD sled, this implies a somewhat different design. We choose here a three lens design. The first lens is a convex lens the begins focusing. The second concave lens produces a waist such that the lens is approximately one Rayleigh range from the focus. The third concave lens is one Rayleigh range after the focus and expands the beam to be the correct size on the second QPD. Note that the first QPD is before the first lens. The solution is described in Table 8, and Figs. 8 and 9.

Optic	Specification	Z [m from PR2]	Gouy Phase
L1	$f = 343\text{ mm}$	0	$0^\circ$
QPD1	7mm QPD	190	$1^\circ$
L2	$f = -57\text{ mm}$	291	$4^\circ$
L3	$f = -57\text{ mm}$	850	$86^\circ$
QPD2	7mm QPD	990	$91^\circ$

Table 8: The Transmon Green QPD optics, positions and Gouy phases.

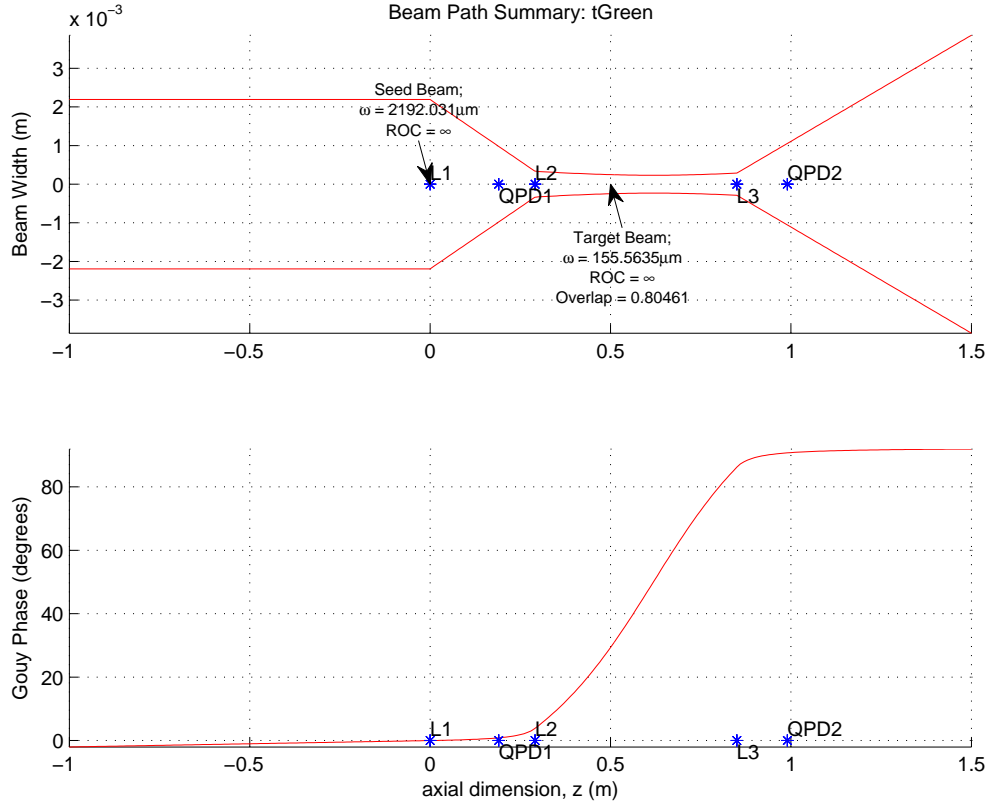


Figure 8: A solution for the Transmon Green QPD Gouy phase telescope.

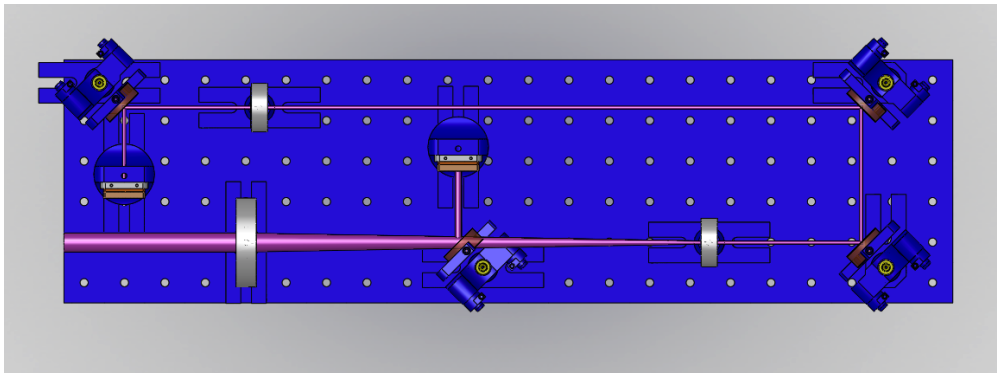


Figure 9: Layout the Transmon Green QPD Gouy phase telescope.