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Technical Note **LIGO-T2300300-v5**

SQZT0 PMC Motivation and a Potential Mode Matching Solution

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This is an internal working note of the LIGO project.

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1 Motivation

Since O3 we haven't been able to increase the CLF power without destroying the amount of squeezing. Low CLF power results in a marginal SQZ 3MHz LO loop and a noisy 42 MHz squeezer ASC signal. A squeezer laser intensity noise measurement showed that our laser intensity noise was not as good as the Mephisto documentation claimed to be (alog68991). We then injected a frequency dependent squeezing with a high CLF power and showed that the squeezer laser intensity noise could indeed be the limiting factor (alog69084). **Hence, we proposed adding a mode cleaner on the SQZT0 to mitigate the CLF intensity noise.**

An ECR has been submitted E2300187.

2 PMC waist estimation

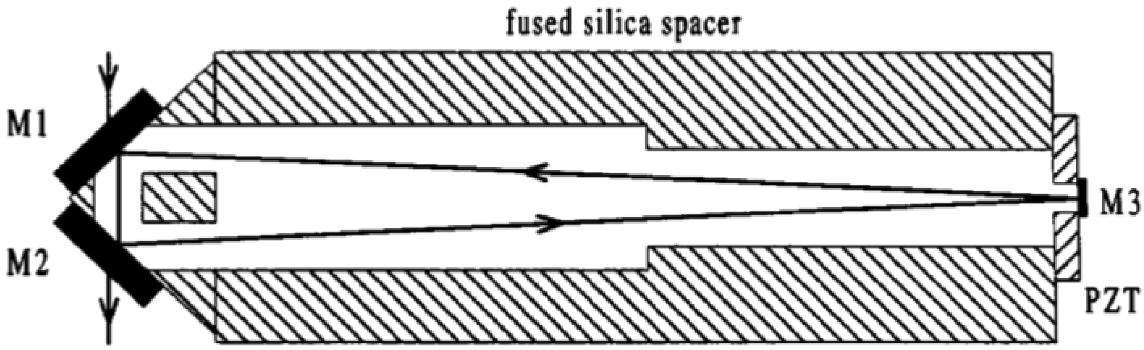


Figure 1: A drawing of iLIGO PMC Willke et al. [1998]

Table 1: Known parameters of the iLIGO PMC gathered from Willke et al. [1998] were used for the mode matching solution. Measurements of the PMC unit shipped to LHO was done by Vicky at MIT. The data can be found in appendix A.

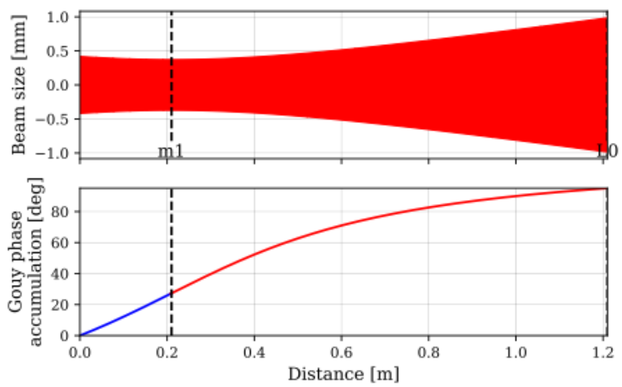
Cavity length (single trip)	21 cm
M3 Radius of Curvature	1 m
Input coupler reflectivity R (p-pol)	0.99
Finesse (p-pol)	220
Finesse (s-pol)	4440
Free Spectral Range (FSR)	713 MHz
Full Width at Half Maximum (FWHM, p-pol)	3.24 MHz
Full Width at Half Maximum (FWHM, s-pol)	160.6 kHz

The iLIGO PMC waist is estimated based on the information found in Willke et al. [1998] and King [1999]. Given a cavity length of 21 cm and a radius of curvature of 1m, Finesse model yields PMC waist of 371.41 um. For the details parameters used in Finesse and all other cross checking can be found in appendix A

```
# Add some curvatures to our mirrors.
#kat.m1.Rc = np.inf
#kat.m2.Rc = 1

# Define the cavity.
kat.parse("cavity cavity1 source=m1.p2.o via=m2.p1.i priority=1")

# Plot the beam trace, starting from cavity the eigenmode.
tsy = finesse.tracing.tools.propagate_beam(
    to_node=kat.L0.p1.i, from_node=kat.m2.p1.o, direction="y"
)
tsy.plot();
```




```
# this is telling me that the point I'm interested in sits -1m behind the waist and as the beam size of w
kat.beam_trace()
kat.L0.p1.o.qx
```

```
<BeamParam (w0=371.41 um, w=984.61 um, z=-1 m, nr=1, λ=1.064 um) at 0x169336f80>
```

Figure 2: PMC waist calculated by Finesse

3 A Proposed SQZT0 Table Layout: A Quick Summary of What Changes

The goal is to find a path and a mode matching solution into iLIGO PMC that would disturb the rest of the table a little as possible using LHO SQZ spare lenses. In this solution the beam is picked of from the existing path after reflecting off BS1 and rerouted further down to give space for the iLIGO LSPD (35.5 MHz). The new mode matching solution requires L2 to be replaced with a 100 mm ROC and moved further down the path towards the SHG while the rest of the table remains the same. The solution works at both LHO and LLO although the exact placements of the optics are slightly different. The LHO optical layout can be found in Figure 3. The LLO optical layout can be found in Figure 8.

EOM1 will be used to generate sidebands for the PMC locking and will continue to be used for SQZ-PSL laser stabilization actuation (TTFSS loop). **A new EOM4** will be added prior to the SHG to generate SHG locking sidebands.

Table 2 includes a list of additional optics we are going to need for the PMC path and the TTFSS beat box path. **This list is for both LHO and LLO except for the ROC 350 mm**.

Table 2: Optics required for the PMC and TTFSS beat box path.

Optics	Quantity	Where
ROC 350 mm lens	1	L1 to PMC (LHO only)
ROC 150 mm lens	1	L1 to PMC
ROC 100 mm lens	1	PMC to CLF L3
ROC 75 mm lens	2	PMC to CLF L3
ROC 154 mm lens	1	TTFSS beat box
99:1 Beamsplitter	1	Replace BS1 (currently .1% transmits)
Steering Mirror	8	Four for PMC path, another four for TTFSS path.
Thorlabs PDA100A	1	PMC trans power monitor
PAF-X-5-C Fiber coupler	1	For coupling SQZ laser into TTFSS beat box
APC fiber	1	For coupling SQZ laser into TTFSS beat box

4 Mode Matching Solution (LHO)

Figure 3 shows the current set up (top) and a proposed LHO SQZT0 layout (bottom).

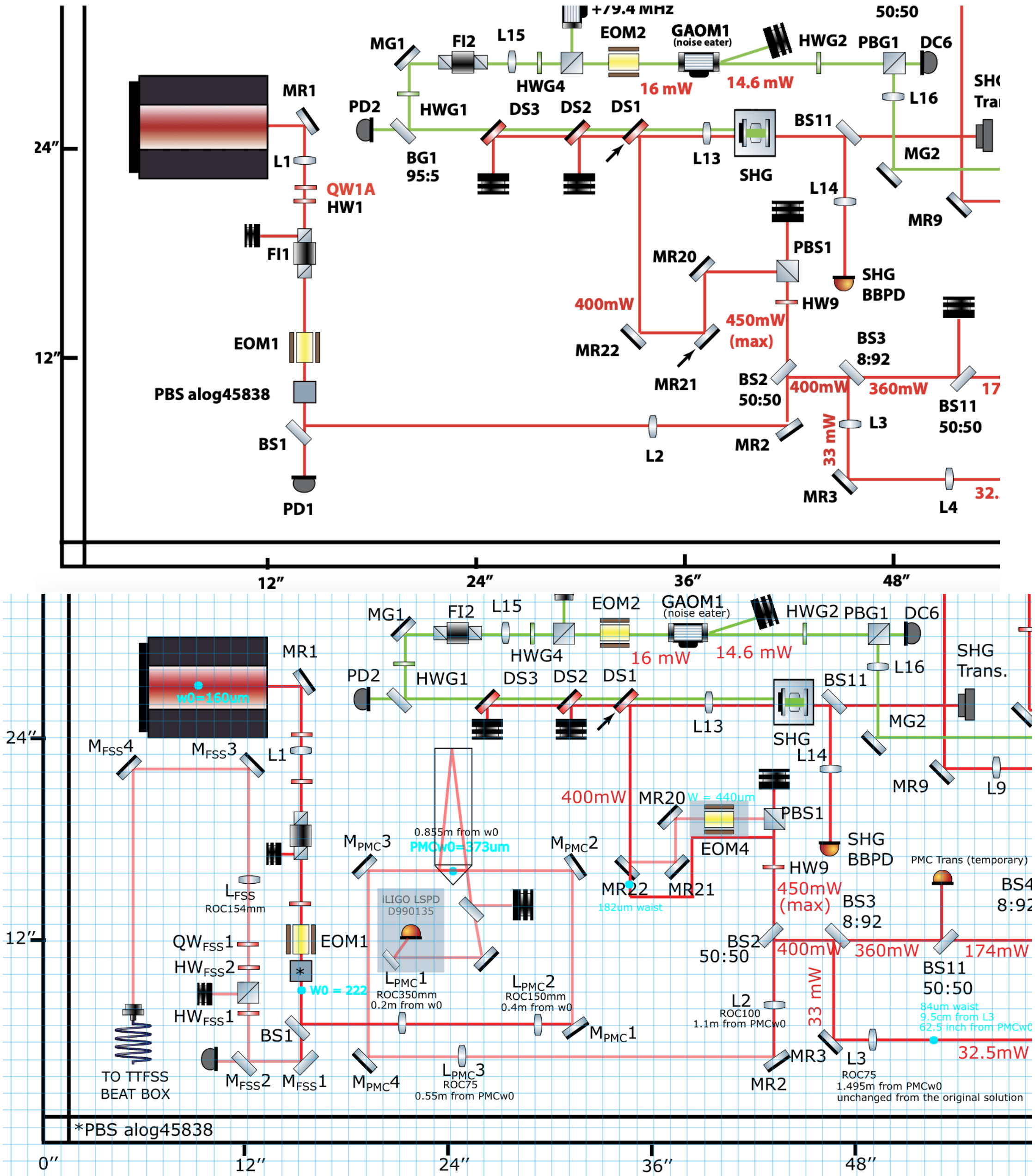


Figure 3: The current vs. the proposed LHO SQZT0 layout zooming in around the iLIGO PMC. New paths are shown with lighter red beam. A full table layout can be found in Appendix A. A small sample of 1-2 mW is picked off behind BS1 for the TTFSS locking. Please refer to section 5 for more details. Note that the components in this diagram is accurately placed on the 1x1 inch grid up until MR2. The SQZT0 enclosure specifications can be found on D2000493

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4.1 L1 waist to PMC

A 222um waist after l1 is used as a starting point for the PMC mode matching. The exact position of the 222um waist can be found in an existing CLF mode matching solution.

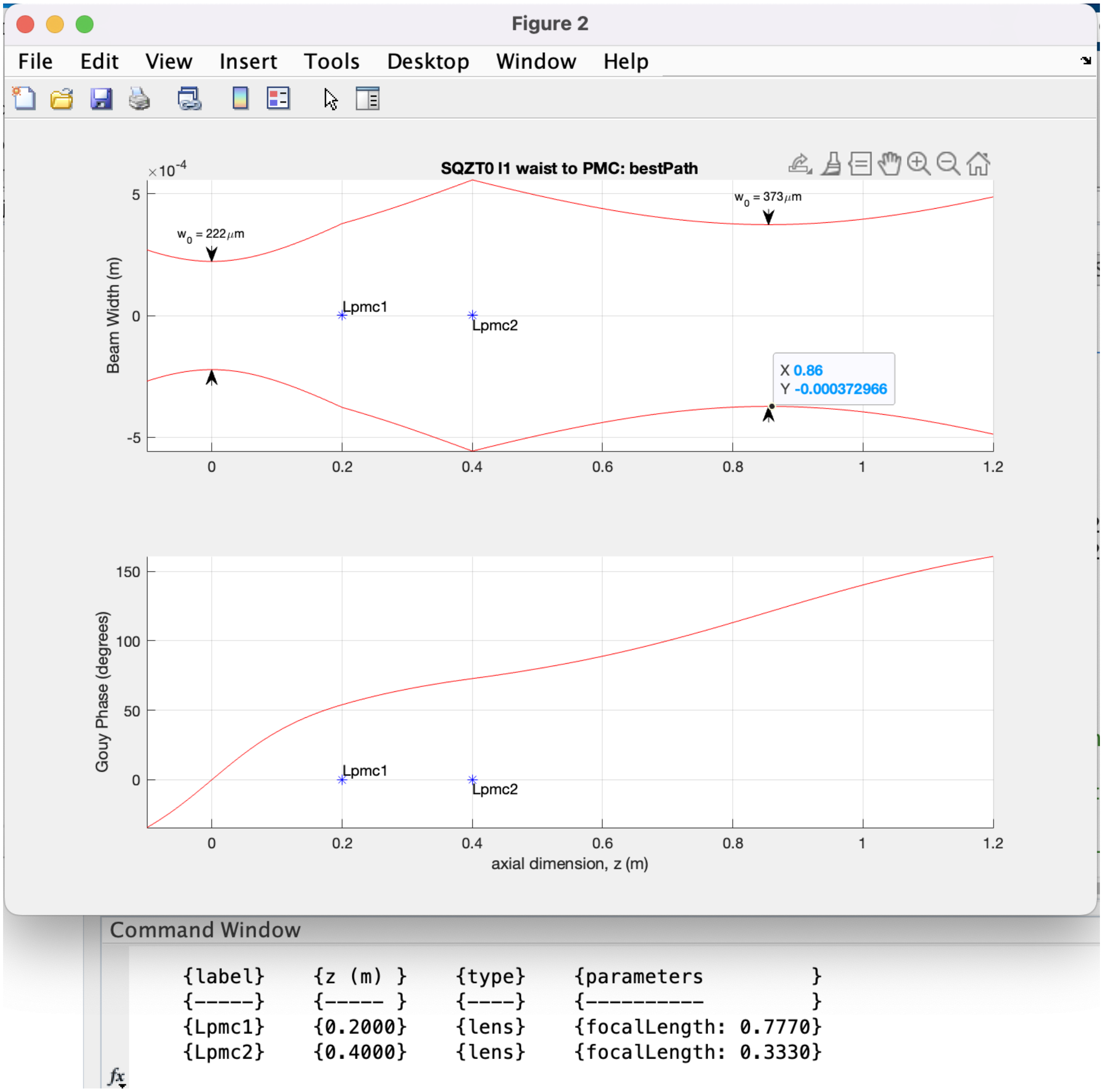


Figure 4: SQZT0 l1 waist to PMC waist solution. The PMC waist locates 0.85-0.86 m away from SQZT0 l1 waist.

4.2 PMC waist to CLF l3 waist

It's easier to mode match waist to waist in alamode so the planned PMC waist is mode matched into an existing CLF l3 waist. This solution requires L2 in Fig.3 to be replaced with 100mm ROC and move further to the right (closer to the SHG).

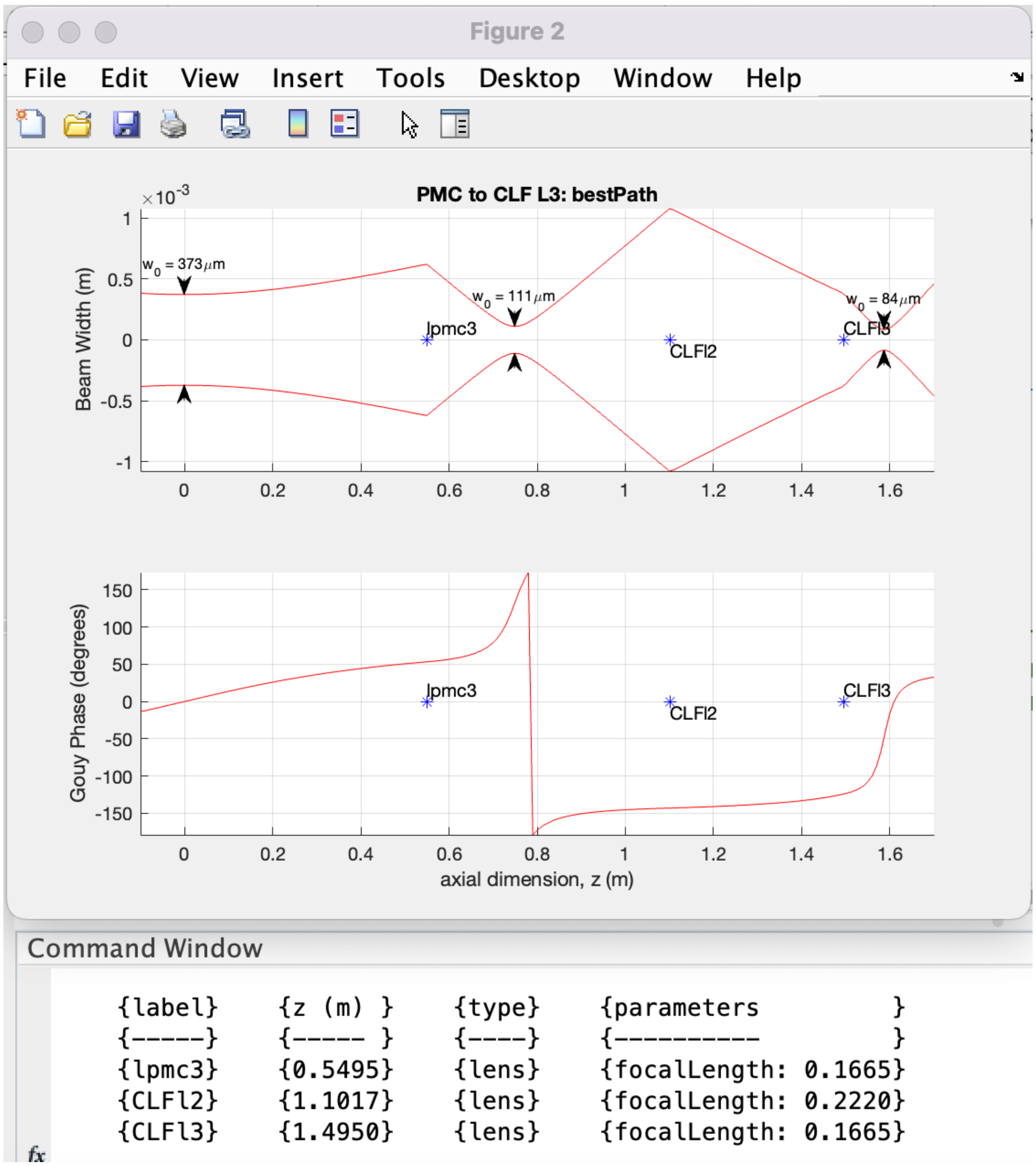
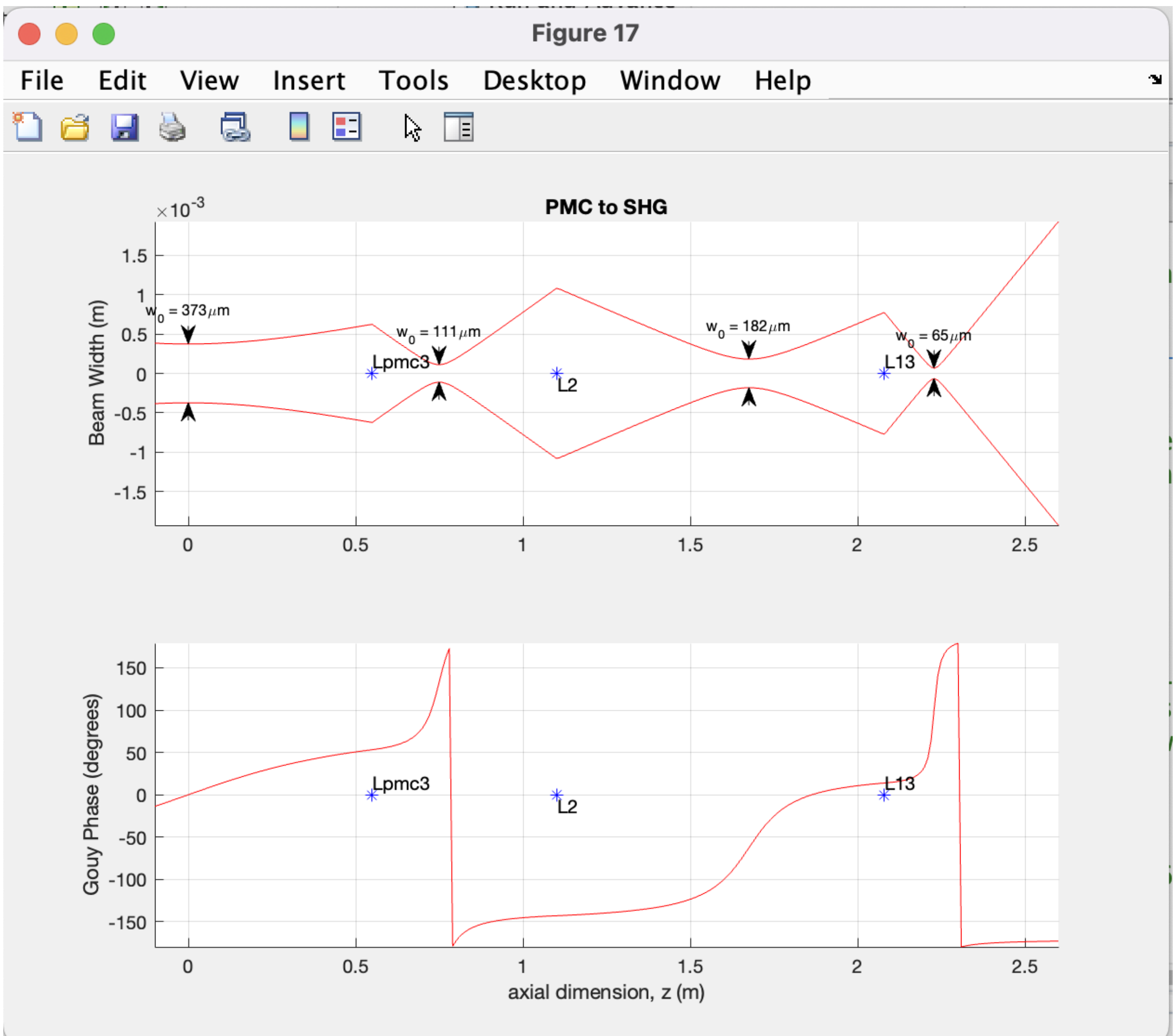


Figure 5: A PMC waist to CLF l3 waist solution. The starting waist is 373 um based on the outcome of the 222um to PMC mode matching solution. The 111 um waist locates 0.75 m away from the PMC waist and the 84 um waist locates 1.59 m away.

If this solution is successfully executed, the mode matching solution to the rest of the table shouldn't have to change.

4.3 PMC waist to SHG waist

Just to confirm that L13 and SHG doesn't have to move. The original SHG mode matching solution can be found https://dcc.ligo.org/DocDB/0096/D1201210/015/SummaryModematch.pdf. The original SHG waist was 71 um. A small discrepancy could have come from the fact that I don't know the distance to the SHG very well.




```
{label}    {z (m) }   {type}    {parameters          }
{-----}    {----- }   {----}    {----------          }
{Lpmc3}    {0.5495}   {lens}    {focalLength: 0.1665}
{L2    }   {1.1017}   {lens}    {focalLength: 0.2220}
{L13   }   {2.0797}   {lens}    {focalLength: 0.1110}
```

Figure 6: Double check that the same solution can still mode matched into the SHG without having to move L13 or the SHG. The 182 um waist locates 1.67 m away from PMC waist and 65 um waist locates 2.23 m away.

5 TTFSS beatnote pick-off point changes: TTFSS Fiber Mode Matching Solution

The pick off for the TTFSS-PSL beatnote currently locates at the top right corner of the SQZT0 (see Fig.15). Once the PMC is installed the pick-off will have to move before the PMC. Otherwise, the SQZ laser noise we try to mitigate with the TTFSS loop will be cleaned up by the PMC. Hence, we are picking off a SQZ laser sample at BS1 transmission, mode matched the beam into a fiber coupler (PAF-X-5-C), then send the SQZ laser sample light to the TTFSS beat note detector (please let's just call it a 'beat box') locates at the top of the enclosure. The PSL fiber will also be re-routed and sent into the TTFSS beat box. Refer to E2300333 for the more details on the TTFSS beat box layout and electronics.

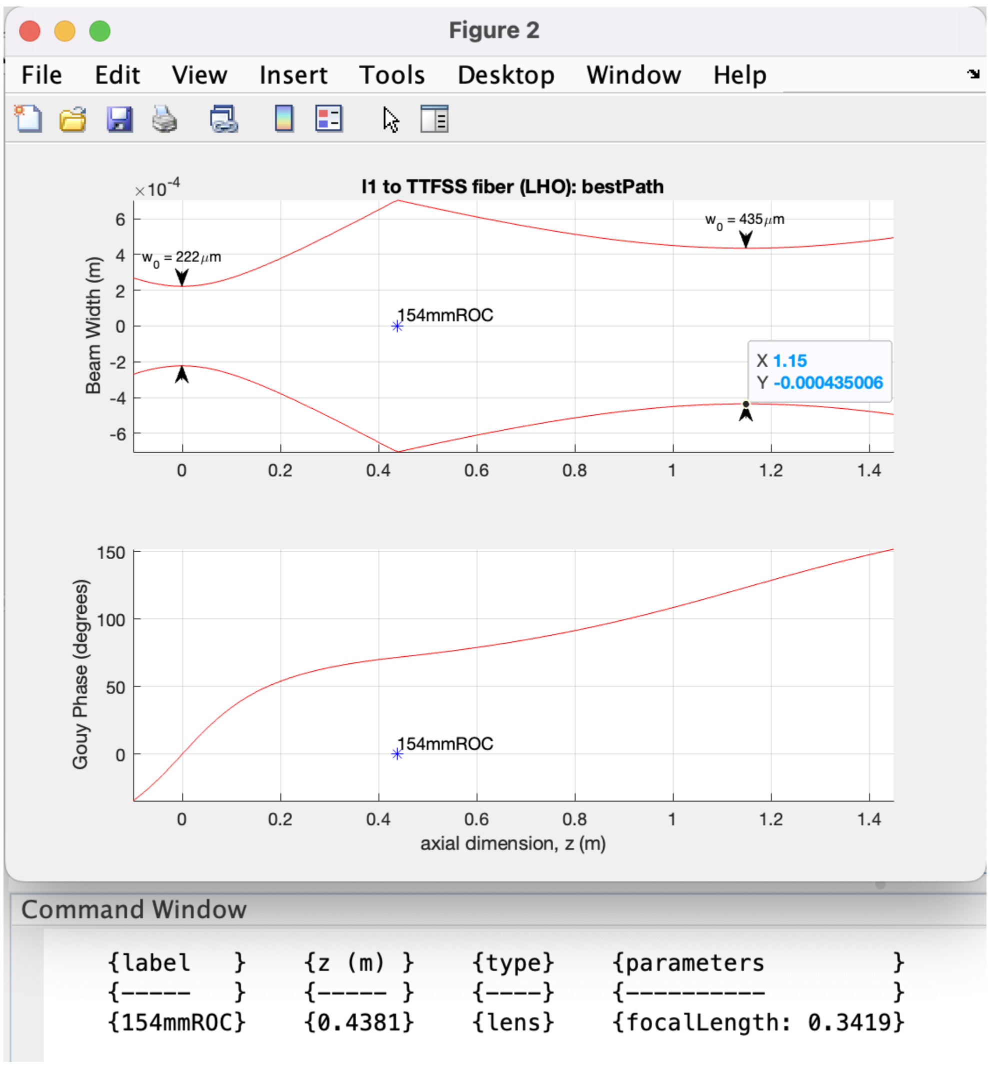


Figure 7: A mode matching solution from L1 waist to the TTFSS fiber. We will be using a Thorlabs PAF-X-5-C fiber coupler. The specified waist for the fiber coupler is 0.87 mm in diameter.

6 Mode Matching Solution (LLO)

Figure 8 shows the current set up (top) and a proposed LLO SQZT0 layout (bottom). The PMC and TTFSS fiber mode matching solutions are very similar between LHO and LLO except for the missing $L_{pmc}1$.

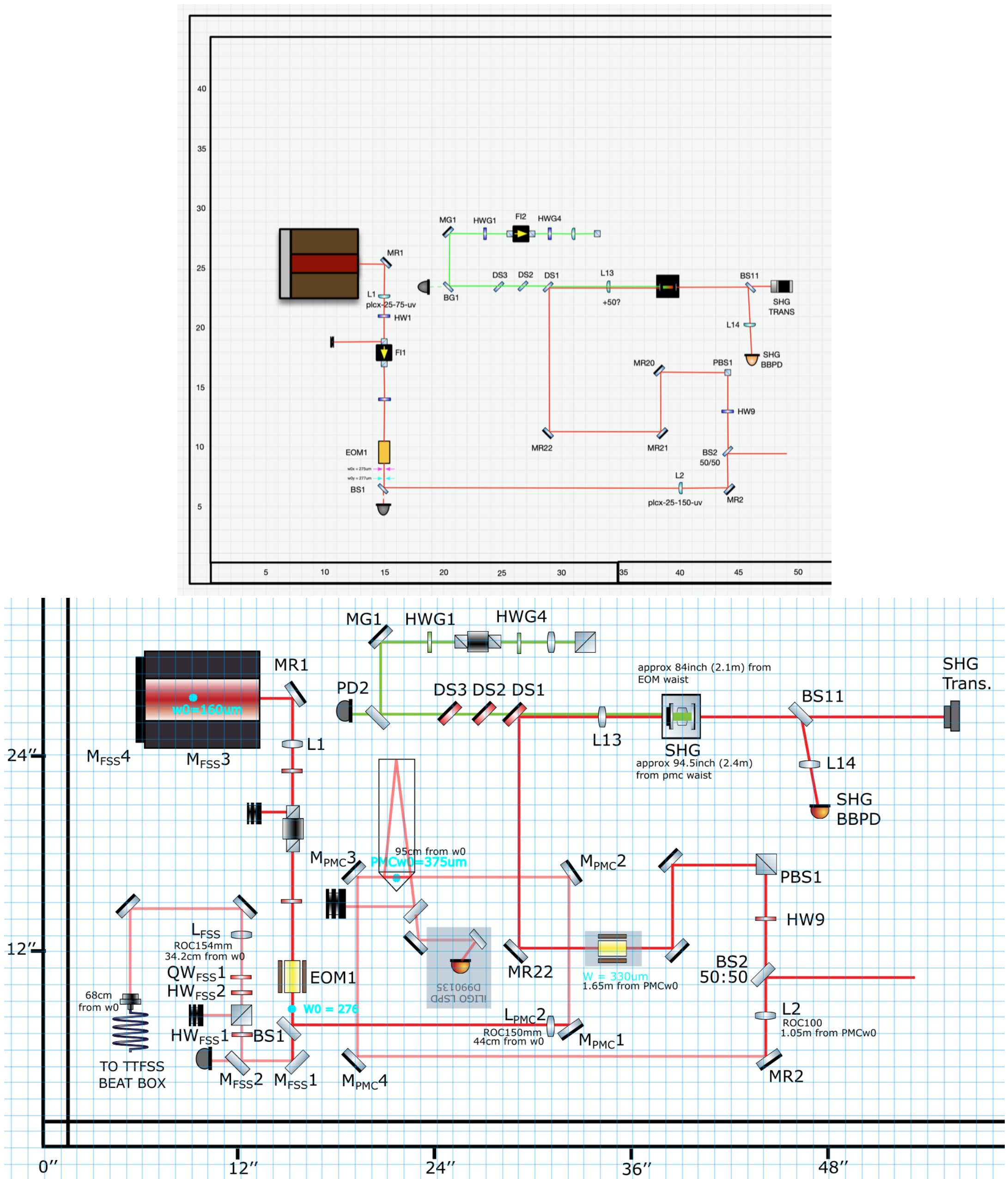


Figure 8: The current SQZT0 set up at LLO (top) and a proposed LLO SQZT0 layout (bottom). Although the layout is a bit different between LHO and LLO but the distance from w0 to the SHG is roughly the same between both sites.

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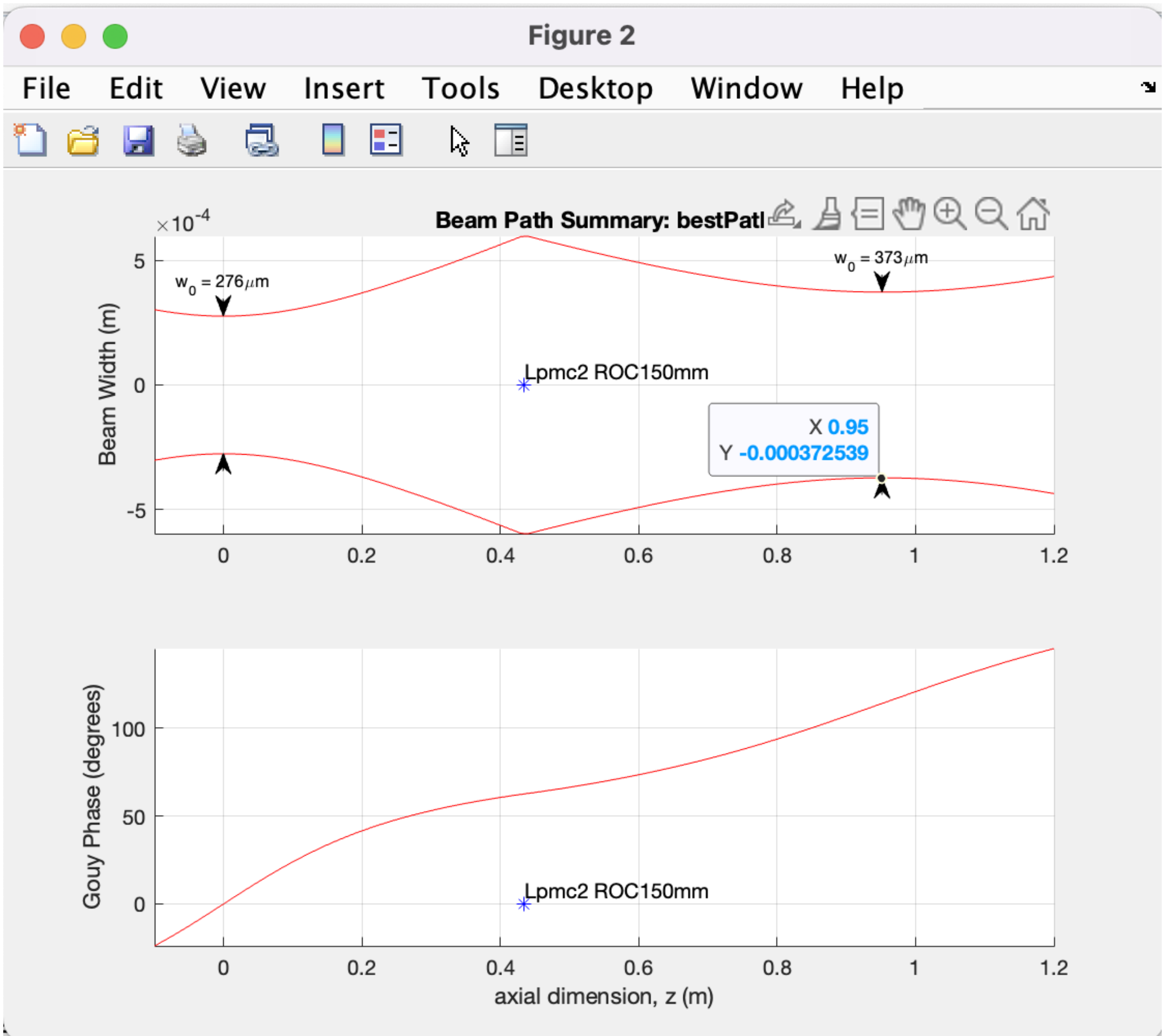
6.1 I1 waist to PMC

The starting waist at LLO is slightly larger than LHO. Together with a slight different table layout allows for a single-lens solution into the PMC.

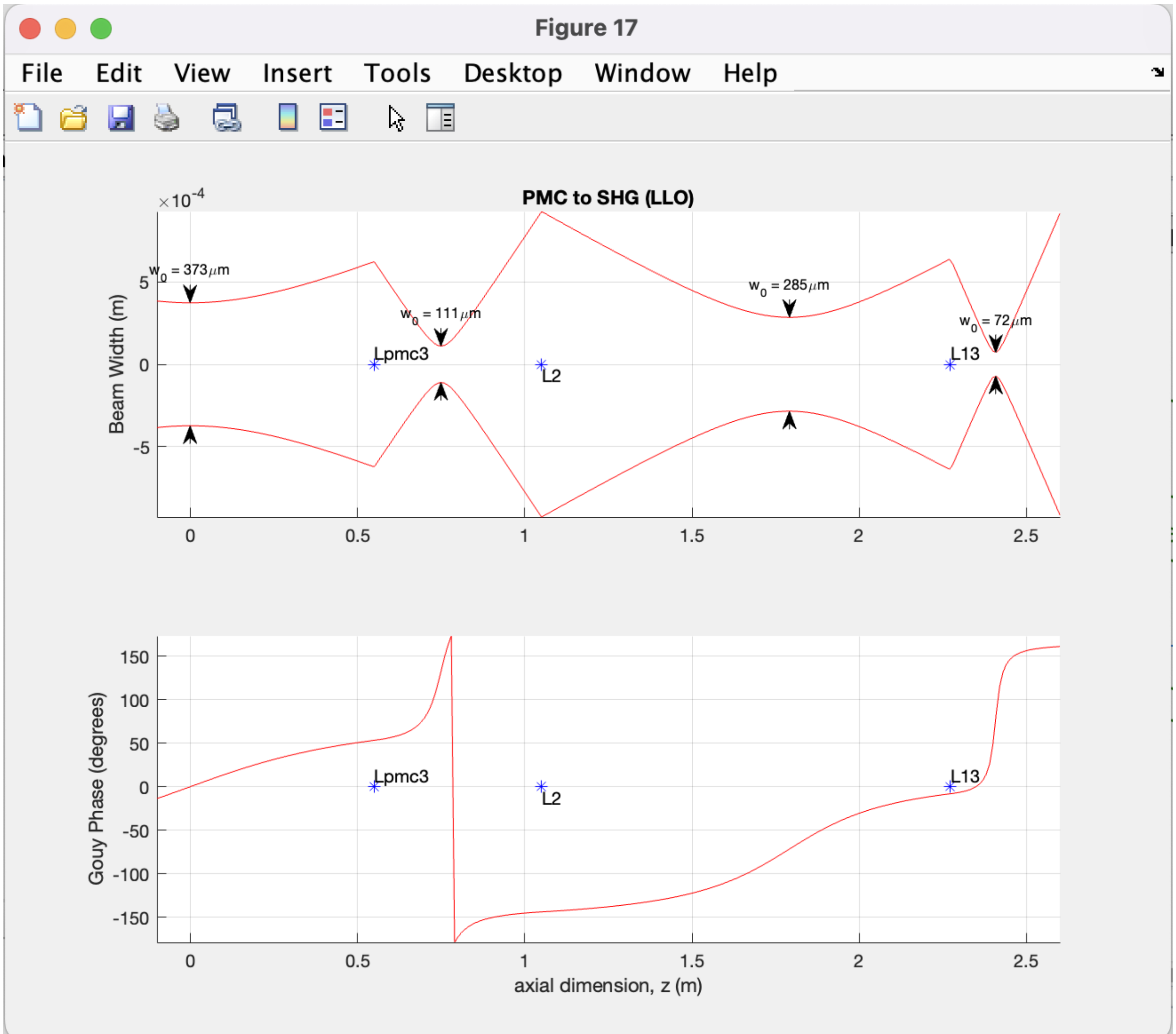



```
{label          }    {z (m) }    {type}    {parameters         }
{-----          }    {----- }    {----}    {----------         }
{Lpmc2 ROC150mm}    {0.4344}    {lens}    {focalLength: 0.3330}
```

Figure 9

6.2 PMC waist to SHG

LLO SHG may be placed a bit further away from L1 waist compared to LHO. A more accurate distance is needed. Here's a solution I came up with by counting table grids. Should be close enough.



{label}	{z (m) }	{type}	{parameters }
{-----}	{----- }	{----}	{---------- }
{Lpmc3}	{0.5495}	{lens}	{focalLength: 0.1665}
{L2 }	{1.0500}	{lens}	{focalLength: 0.2220}
{L13 }	{2.2730}	{lens}	{focalLength: 0.1110}

Figure 10

A Appendix

```
: kat = finesse.Model()
kat.parse(
    """
    # Add a Laser named L0 with a power of 1 W.
    l L0 P=1

    # Space attaching L0 <-> m1 with length of 0 m (default).
    s s0 L0.p1 m1.p1 L=1

    # Input mirror of cavity.
    m m1 R=0.99 T=0.01

    # Intra-cavity space.
    s CAV m1.p2 m2.p1 L=0.21

    # End mirror of cavity.
    m m2 R=1 T=0 Rc=1


    # Power detectors on reflection, circulation and transmission.
    pd refl m1.p1.o
    pd circ m2.p1.i
    pd trns m2.p2.o

    # Scan over the detuning DOF of m1 from -180 deg to +180 deg with 400 points.
    xaxis(m1.phi, lin, -180, 180, 10000)
    """
)
```

Figure 11: finesse code simplifying PMC into 2-mirror cavity. Reflectivity used is likely specified for p-pol.

```
plt.plot(xfreq/1e6,out["circ"])
plt.xlim([-1000, 1000])
plt.xlabel("freq")
plt.ylabel("circ power")
```

```
Text(0, 0.5, 'circ power')
```

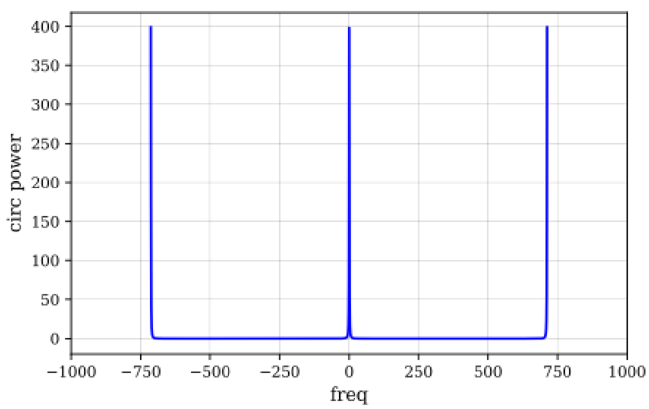


Figure 12: A plot confirming FSR of 713 MHz

```
plt.plot(xfreq,out["circ"])
plt.xlim([-5e6, 5e6])
plt.xlabel("freq")
plt.ylabel("circ power")
```

```
Text(0, 0.5, 'circ power')
```

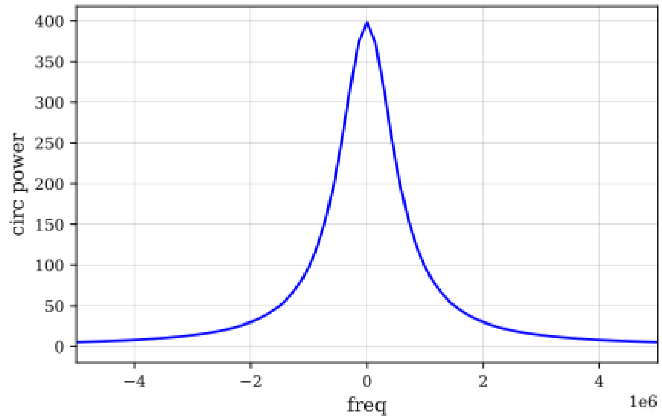


Figure 13: FWHM showing 3MHz attenuation (using p-pol reflectivity).

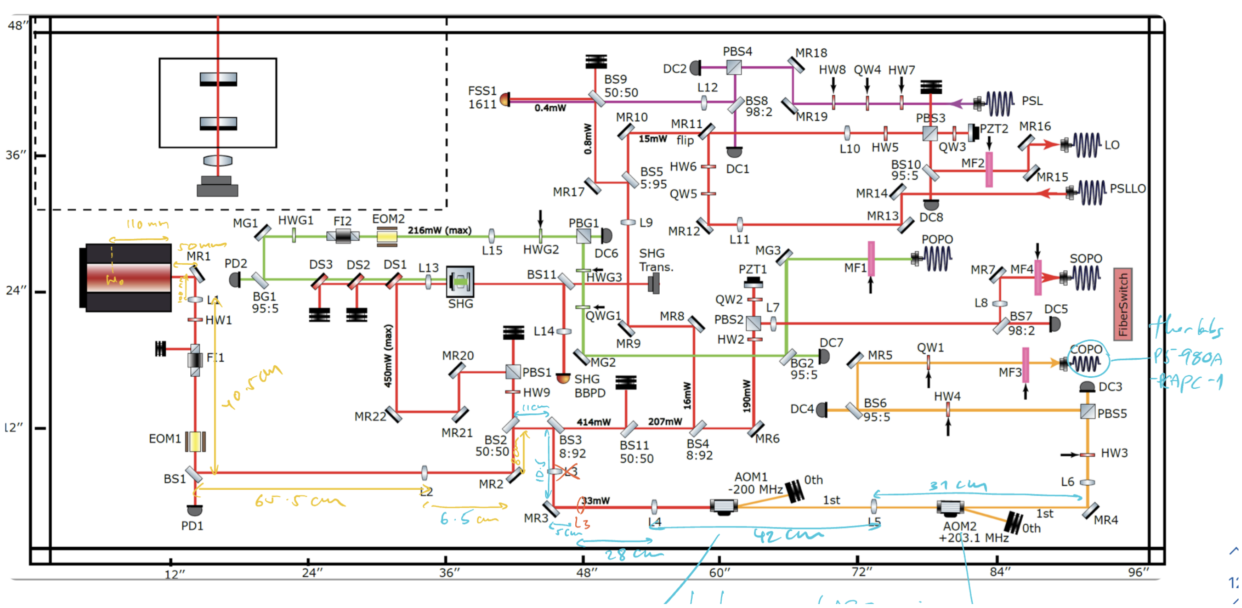


Figure 14: LHO sqzt0 measurement from 2017

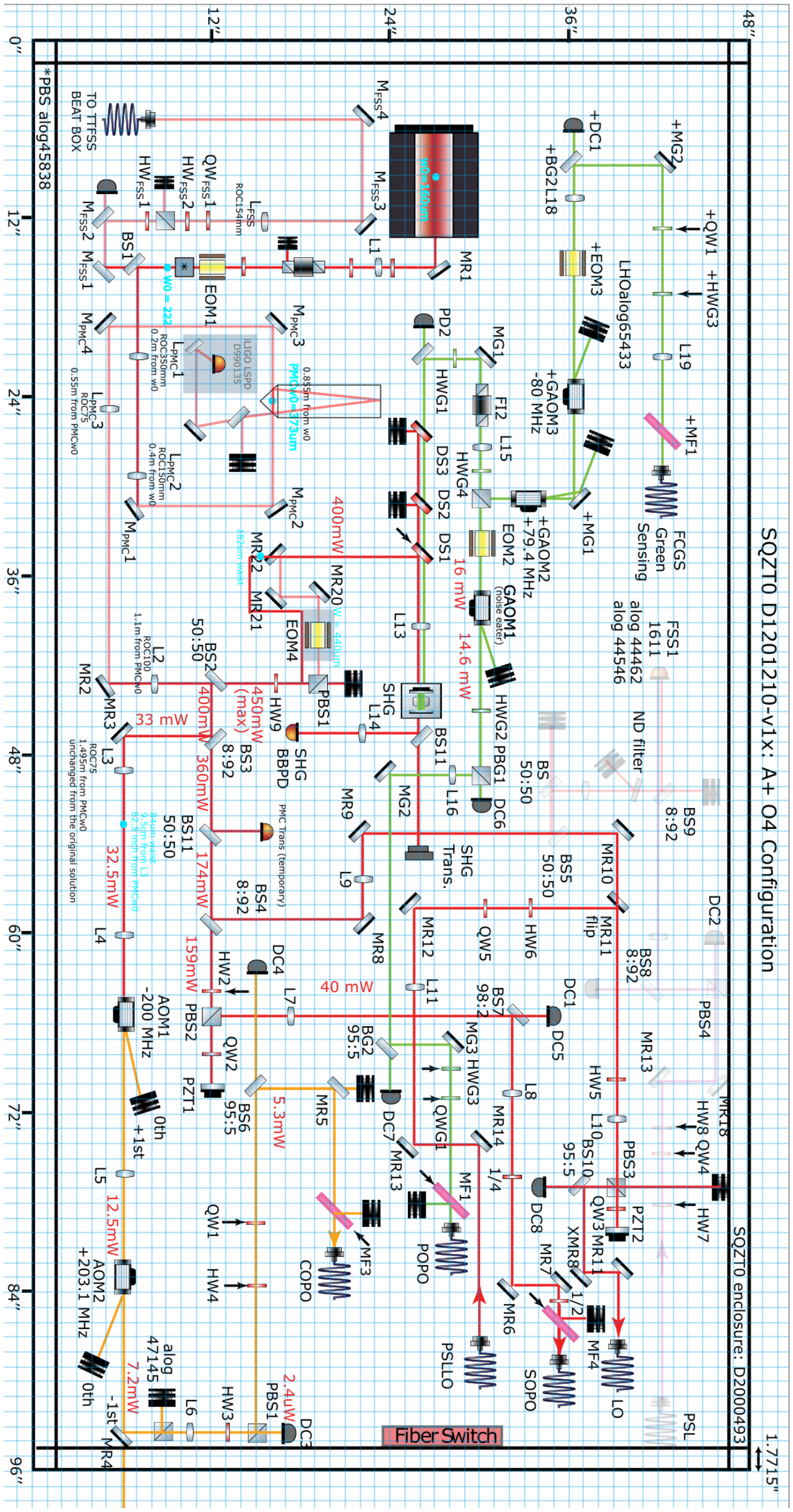


Figure 15: sqzt0 full layout (PMC path + current). Where things are in this diagram is somewhat accurate up until MR2 for the PMC mode matching purpose. The rest of the diagram roughly depicts where things are relative to each other.

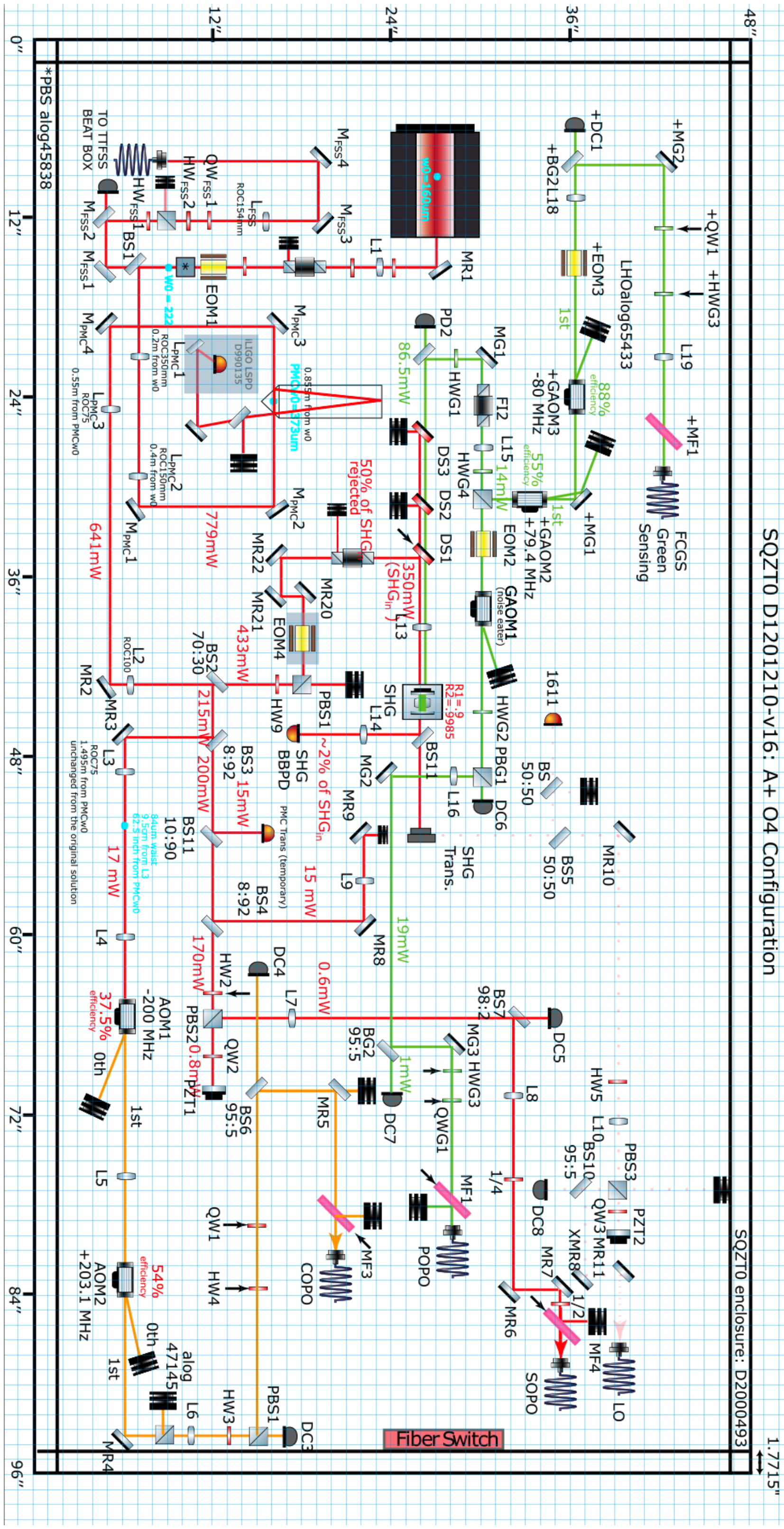


Figure 16: LHO SQZT0 full layout and the power budget as of March 2024.

PMC - **LHO004** (ship MIT→LHO)

FSR & FWHM quoted in units of PZT modulation voltage

	FSR	p-pol	s-pol
trans fsr	6.139141	NaN	NaN
refl fsr	6.139141	NaN	NaN
trans fwhm	NaN	0.034114	0.001508
refl fwhm	NaN	0.033891	0.001509
trans finesse	NaN	179.957609	4071.181168
refl finesse	NaN	181.145507	4069.406102

low-finesse p-pol: *F* ~ 180 *(should be ~220)*

high-finesse s-pol: *F* ~ 4070 *(should be ~4440)*

cavity pole = FSR / Finesse = 713e6/4070 ~ 175 kHz

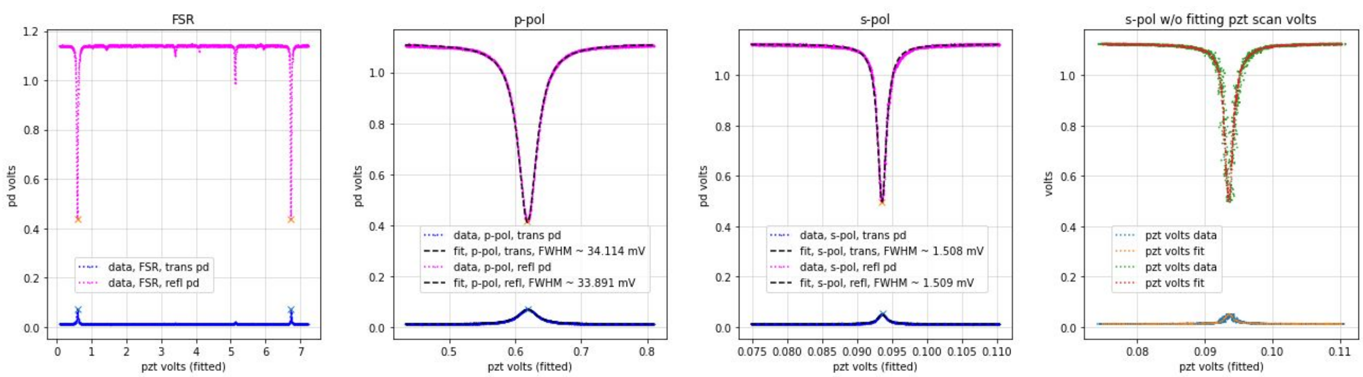


Figure 17: PMC p-pol finesse, s-pol finesse, and a cavity pole

```
0 FSR refl
FSR refl fsr = 6.139141 V

1 p-pol trans
x0, ampl, FWHM, y0 = 618.581, 3.143, 34.114, 12.439 mV
1 p-pol refl
x0, ampl, FWHM, y0 = 618.497, -37.314, 33.891, 1113.117 mV

2 s-pol trans
x0, ampl, FWHM, y0 = 93.589, 0.091, 1.508, 12.696 mV
2 s-pol refl
x0, ampl, FWHM, y0 = 93.579, -1.480, 1.509, 1122.145 mV

FSR & FWHM quoted in units of PZT modulation voltage
```

	FSR	p-pol	s-pol
trans fsr	6.139141	NaN	NaN
refl fsr	6.139141	NaN	NaN
trans fwhm	NaN	0.034114	0.001508
refl fwhm	NaN	0.033891	0.001509
trans finesse	NaN	179.957609	4071.181168
refl finesse	NaN	181.145507	4069.406102

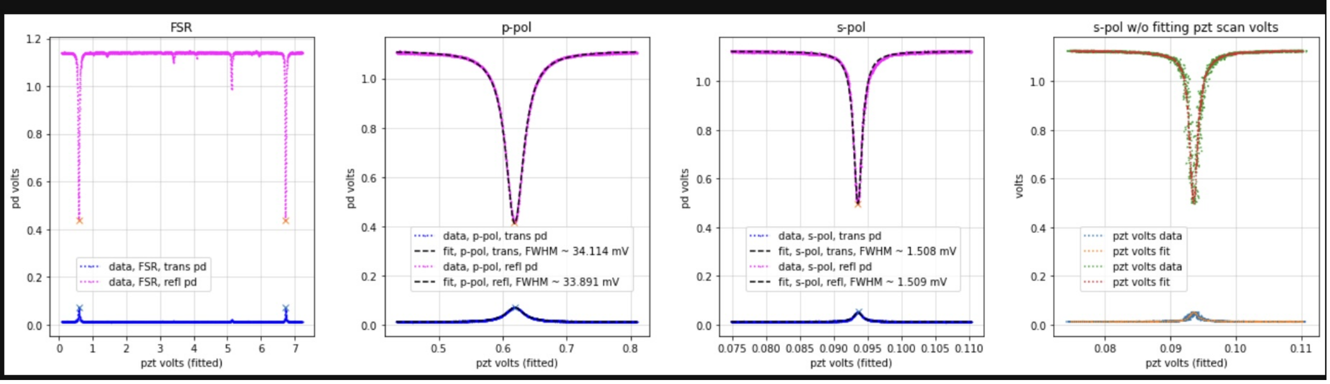


Figure 18

References

B. Willke, N. Uehara, E. K. Gustafson, R. L. Byer, P. J. King, S. U. Seel, and R. L. Savage. Spatial and temporal filtering of a 10-w nd:yag laser with a fabry–perot ring-cavity premode cleaner. Opt. Lett., 23(21):1704–1706, Nov 1998. doi: 10.1364/OL.23.001704. URL https://opg.optica.org/ol/abstract.cfm?URI=ol-23-21-1704.

Peter King. Pre-modecleaner body block. Technical report, https://dcc.ligo.org, 1999. URL https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?.submit=Identifier&docid=D980675&version=.