Note on power measured at OFI s-pol rejected light monitor

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Scope

- s/p ratio was measured to be ~2% at LLO with full lock

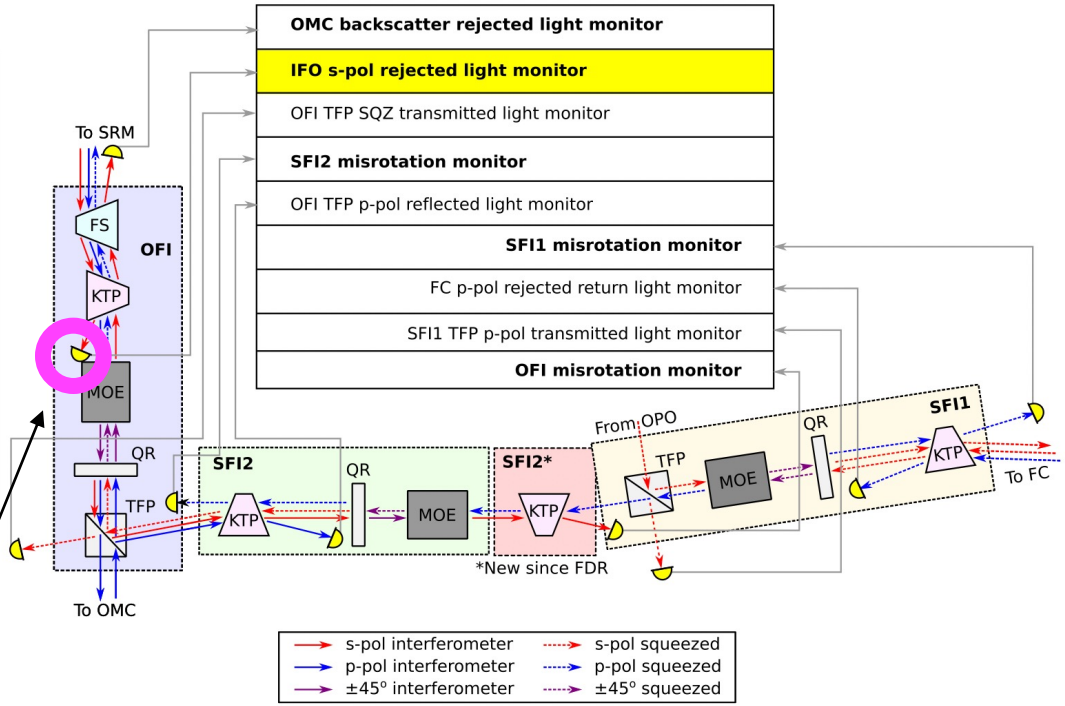
- This document summarizes the measurements and discussions to reveal the cause of excess s-pol, and discusses possible additional measurements

IFO s-pol rejected light monitor

- Named OFI_B in HAM5

IFO s-pol rejected light monitor

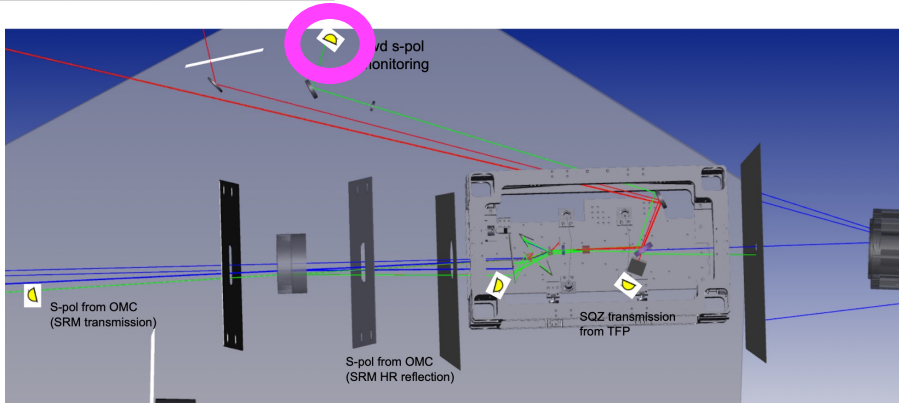
- **LLO experienced p-pol to s-pol ratio of 222:1 at the BS AR surface (c.f. LLO aLOG 22751)**
- **Propose we should be able to monitor this to ~100x lower and 10x higher:**
  - **200mW/222~1mW.**
  - ***Upper level: 10mW.***
  - ***Lower level: 10μW.***



LIGO-G2000723

L1:IOO-OFI_PD_B in CDS
(currently sampled at 16 Hz)
(LLO alog #59076)

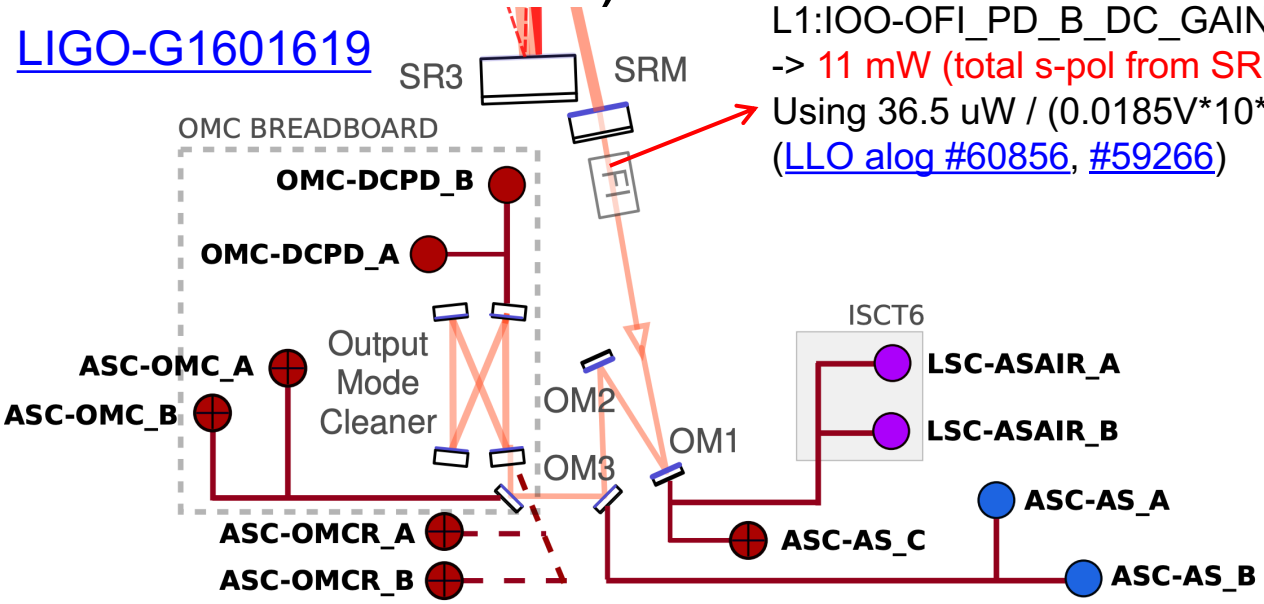
LIGO-T2200018



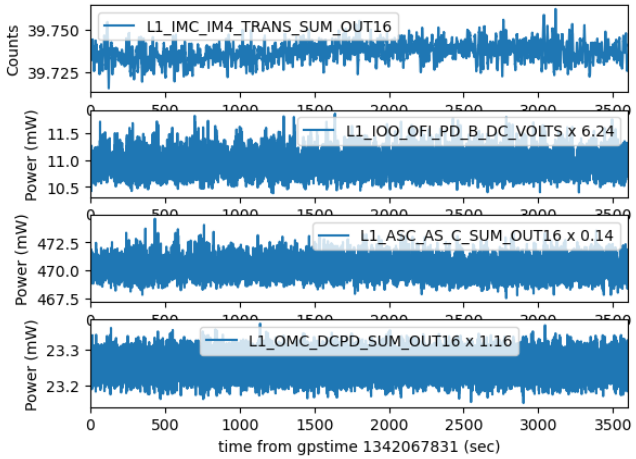
Power at AS port with Full Lock

- Estimated from LLO, ~40W at PRM (GPS time: 1342067831)

LIGO-G1601619



L1:IOO-OFI_PD_B_DC_VOLTS = 1.75
L1:IOO-OFI_PD_B_DC_GAIN = 1 (0 dB)
-> 11 mW (total s-pol from SRM to OFI)
Using 36.5 uW / (0.0185V*10**(-10/20)) = 6.24 mW/V @ 0 dB
(LLO alog #60856, #59266)



OM1 T=800ppm
OM3 T=1.5%
OMC QPD pickoff=0.7%
OMC MM = 93.2%
OMC loss = 4%
QE = 99%

L1:ASC-AS_C_SUM_OUT_DQ = 3350cnts
L1:ASC-AS_A_SUM_OUT_DQ = 36200cnts
-> 470 mW or 485 mW before OM1 (total OFI transmission (p-pol))
Using 149.8/21 cnts/mW for AS_C, 1568/21 cnts/mW for AS_A
(LLO alog #55225)

L1:OMC-DCPD_SUM_OUT_DQ= 20 mA
-> 23 mW at OMC transmission in total (p-pol carrier TEM00)
Using 0.86 A/W (LLO alog #60885)

Estimating s/p Ratio

- s/p ratio of light going to OFI can be estimated using OFI_B and AS_C_SUM
  - L1:IOO-OFI_PD_B_DC_VOLTS * 6.24 gives mW when gain is 0 dB. (It was 10 dB before June 22 (around 1339924767))
  - L1:ASC-AS_C_SUM_OUT_DQ * 0.14 gives mW
- OFI_B / ITM input
  - L1:IMC-IM4_TRANS_SUM_OUT gives input power in W
  - PRM transmission: 3.1% (PhysRevD.102.062003)
  - SRM transmission: 32.4 % (PhysRevD.102.062003)
  - BS is 50:50 for p-pol (~80:~20 for s-pol)
  - Power recycling gain: 44 (LLO alog 60702)

Mode Content with Full Lock

- In OFI_B, 8.4 mW out of 10.5 mW is carrier (*We cannot conclude that it is not 00 mode from DC chopping test; see following slides*)
- s/p ratio is about 2%

OFI Rejected Beam (wrong pol) too high power

- Beam goes to PD in HAM5, at 220kW arm power we have 10.5 mW
- Test of RF reduction says it's mostly carrier (8.4 out of the 10.5 mW)
- Test of chopping DC current says it's not 00 mode
- Quick crosscheck assuming same calibration at H1, they have 0.3V versus our 1.7 V
- Also measured HAM6 total loss ~17% and OMC MM ~7%

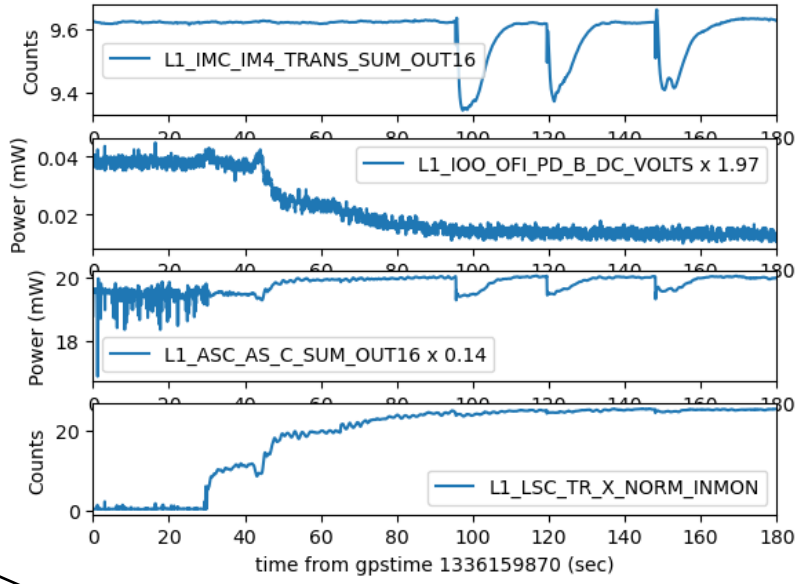
DCPD	AS_C	AS_A	OFI PD	OMCR_A	OMCR_B
20	3353	36149	1.73	8615	10006
20	3344	36049	1.74	8592	9983
30	3437	37100	1.71	8620	10015
30	3435	37072	1.71	8614	10009
30	3433	37056	1.72	8610	10005
15	3304	35594	1.74	8595	9981
15	3303	35586	1.74	8592	9979
15	3301	35562	1.74	8587	9975

LIGO-G2201281, LLO alog #60883, LLO alog #60878

alogs:60856 6

Single X-arm Lock

- s/p ratio reduced with Xarm locked, compared with ITMX single bounce (0.2% -> 0.07%)
- Suggests non-uniform ITMX birefringence is causing this; see Section IV in LIGO-T2200272



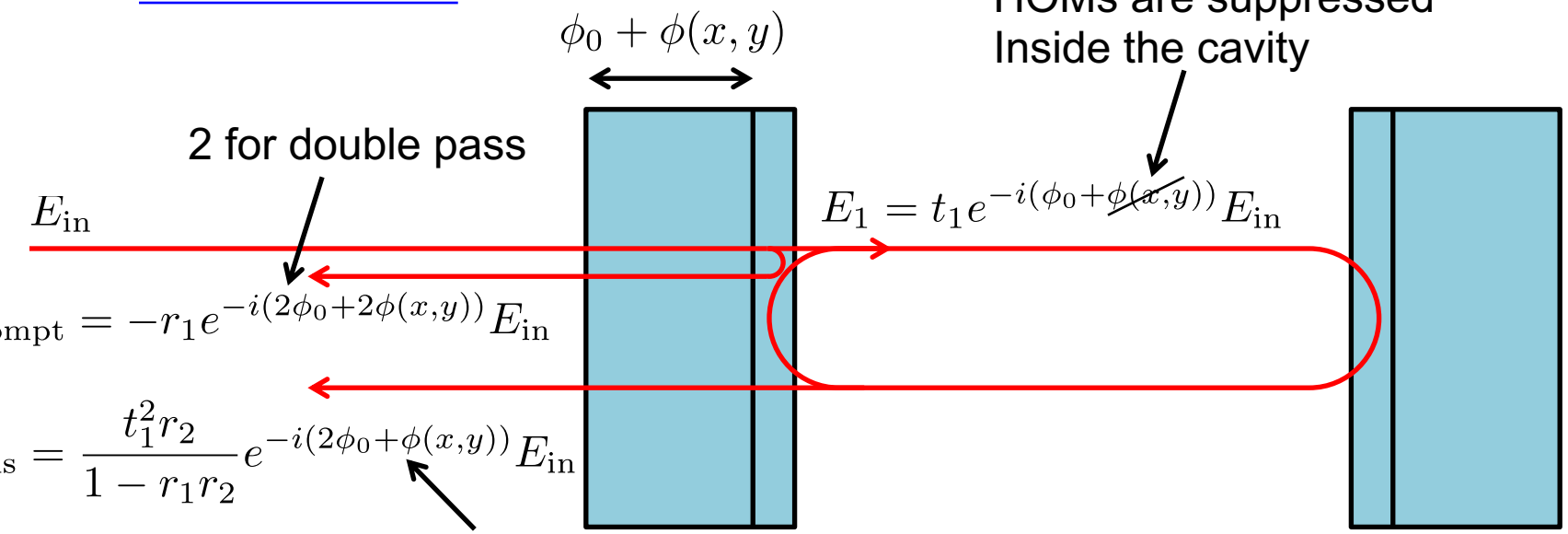
Corrected ratio for BS unbalance

	IM4_TRANS	OFI_B	AS_C_SUM	s/p ratio
ITMX single bounce	9.6 W to IFO ~150 mW to ITM	0.019 @ 10 dB (0.038 mW)	138 (19.4 mW)	0.20% (AS) 0.14 mW / 120 mW = 0.12 % (ITM refl)
Xarm locked	9.6 W to IFO ~150 mW to ITM	0.0061 @ 10 dB (0.013 mW)	142 (19.9 mW)	0.065% (AS) 0.050 mW / 120 mW = 0.041 % (ITM refl)
Full lock	39.7 W to IFO ~870 W to ITM	1.74 @ 0 dB (10.8 mW)	3350 (470 mW)	2.3% (AS) * Note that p-pol is RF sideband dominated

Lawrence Effect: ITM Substrate

- Lawrence effect (conjugation effect; mode healing) also works for birefringence

See Table I in LIGO-T2200272



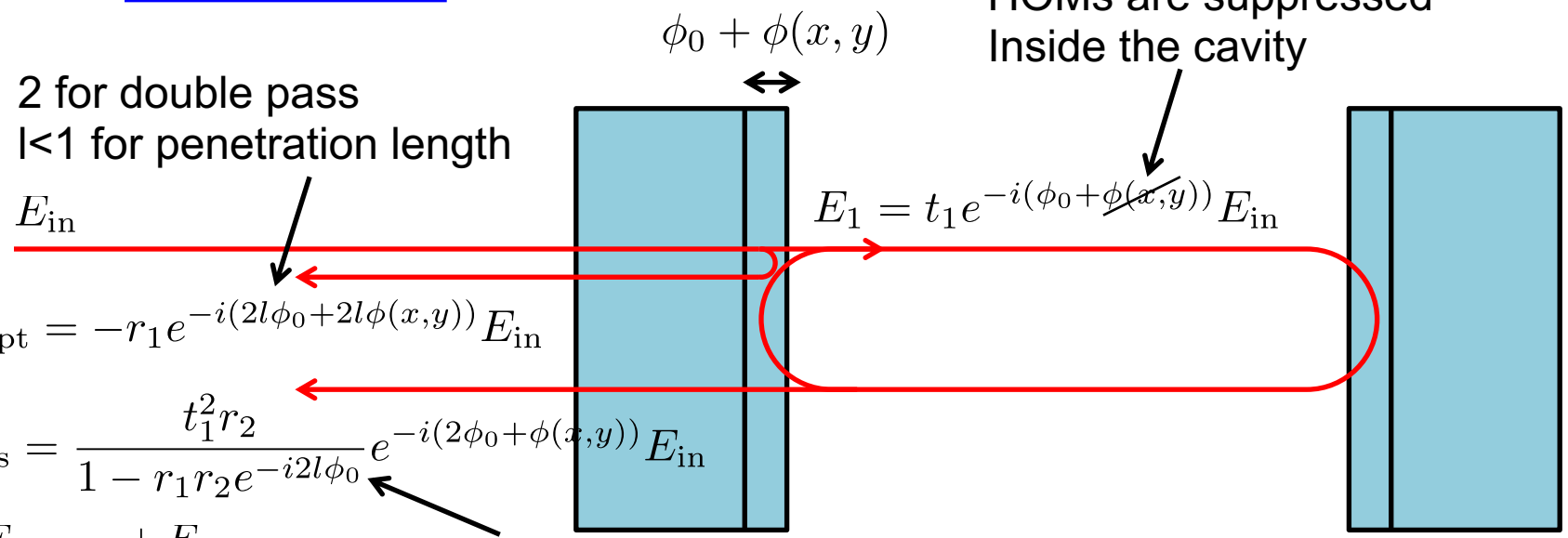
$$E_{\rm refl} = E_{\rm prompt} + E_{\rm cavtrans}$$
$$\simeq \left[-r_1\left(1 - 2i(\phi_0+\phi(x,y)) + \frac{1}{2}(2i(\phi_0+\phi(x,y)))^2\right)\right.$$
$$\left.+(1+r_1)\left(1 - i(2\phi_0+\phi(x,y)) + \frac{1}{2}(i(2\phi_0+\phi(x,y)))^2\right)\right] E_{\rm in}$$
$$\simeq -(1 + 2i\phi_0 - 2(i\phi_0)^2 + (i\phi(x,y))^2) E_{\rm in}$$

s-pol TEM00 remains, HOM suppressed to O(φ(x,y)^2)

Lawrence Effect: ITM Coating

- Not perfectly for ITM coating, as penetration length is not equal to coating thickness

See Table I in LIGO-T2200272



$$E_{\rm refl} = E_{\rm prompt} + E_{\rm cavtrans}$$
$$\simeq \left[-r_1\left(1-2li(\phi_0+\phi(x,y))\right)\right.$$
$$\left.+(1+r_1)\left(1-i(2\phi_0+\phi(x,y))+\frac{\mathcal{F}}{2\pi}2li\phi_0\right)\right]E_{\rm in}$$
$$\simeq -\left(1+2(2-l)i\phi_0-2(l-1)i\phi(x,y)+\frac{2\mathcal{F}}{\pi}li\phi_0\right)E_{\rm in}$$

s-pol TEM00 enhanced by cavity, HOM not suppressed completely

S-pol from Arm is 90 deg Off

- s-pol generated in arm reflection is always 90 deg out of phase from p-pol in small birefringence limit
- This is always the case, arm locked/unlocked or with small arm detuning
- DARM offset will change MICH fringe and amount of s-pol carrier TEM00 in AS port, but AS port could be bright for s-pol, depending on axis orientation of both arms

If we consider arm cavity as a waveplate which makes small phase shift δ<<1, and its axis is rotated by θ from input polarization, reflected light is

Input pol

$$\vec{v}_{\mathrm{refl}} = W_{\mathrm{FP}}\vec{v}_{\mathrm{in}} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} e^{i\delta} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\simeq \begin{pmatrix} 1 - i\delta\cos^2\theta \\ i\delta\cos\theta\sin\theta \end{pmatrix}$$

Orthogonal polarization have *i*, which means its phase is off by 90 deg (+90 or -90, depending on axis orientation)

Resonant condition of arm cavity will change the amount of δ and θ, and thus amplitude of orthogonal polarization, but it will not change the phase of orthogonal polarization

BS Messes Up s-pol

- BS is ~80:~20 for s-pol, and phase in reflection/transmission is different from p-pol by O(10) mrad (LIGO-G1501374), which makes MICH reflection/transmission phase difference by ~100 mrad

PRC linewidth is 2*pi/Finesse ~ 50 mrad

- This is enough to shift s-pol resonance away from p-pol resonance, and MICH fringe away from bright/dark fringe

With zero DARM/CARM offsets and no PRM/SRM, electric field of AS beam and REFL beam will be

Different for s-pol from BS effects

$$E_{\mathrm{AS}} = \sqrt{2(1-\cos(\phi_x-\phi_y))}\, r_{\mathrm{BS}} t_{\mathrm{BS}} E_{\mathrm{in}} e^{i(\omega t-(\phi_x+\phi_y)/2-\pi/2)}$$

$$E_{\mathrm{REFL}} = \sqrt{1-2(1-\cos(\phi_x-\phi_y))r_{\mathrm{BS}}^2 t_{\mathrm{BS}}^2}\, E_{\mathrm{in}} e^{i(\omega t-(\phi_x+\phi_y)/2+\varphi)}$$

$$\tan\varphi = (t_{\mathrm{BS}}^2 - r_{\mathrm{BS}}^2)\tan(\phi_x-\phi_y)$$

DIFF and COMM mixed in PRC

x-y = -76 mrad for AS and REFL
(x+y)/2 = -184 mrad for AS
(x+y)/2-φ = -146 mrad - 22 mrad = -168 mrad for REFL

Discussion

- Why DARM offset didn't change power in OFI_B much?
  - It is possible because contrast of s-pol is probably worse than that of p-pol, and MICH fringe is different for s-pol (AS port can be dark or bright for s-pol, depending on axis orientations of both arms, and shifted from perfect dark or bright from additional phase in BS). For example, if ITMX birefringence is very large compared with ITMY, DARM offset does not change s-pol power at AS.
- Why s-pol is carrier dominant?
  - Resonant condition in PRC/SRC is different for s-pol because of BS, and RFSB (and carrier TEM00) are suppressed?
  - ITM non-uniform coating birefringence can create carrier HOMs in s-pol (ITM substrate birefringence cannot make much due to Lawrence effect; See previous slides and Table I in LIGO-T2200272), but it also makes more carrier 00 mode when the arm is locked than unlocked.
  - Can be also explained if uniform coating birefringence is small
  - It could also be that birefringence in the coating mainly on substrate side (because of stress from mirror-coating boundary?)
- Why s/p ratio increased to 2%, compared with single arm lock?
  - With full lock RFSB dominates p-pol, but for single arm, carrier dominates p-pol
  - Also, higher power creates larger birefringence (LLO alog #61099)
  - Additionally, some HOM s-pol might be resonating in PRC/SRC?

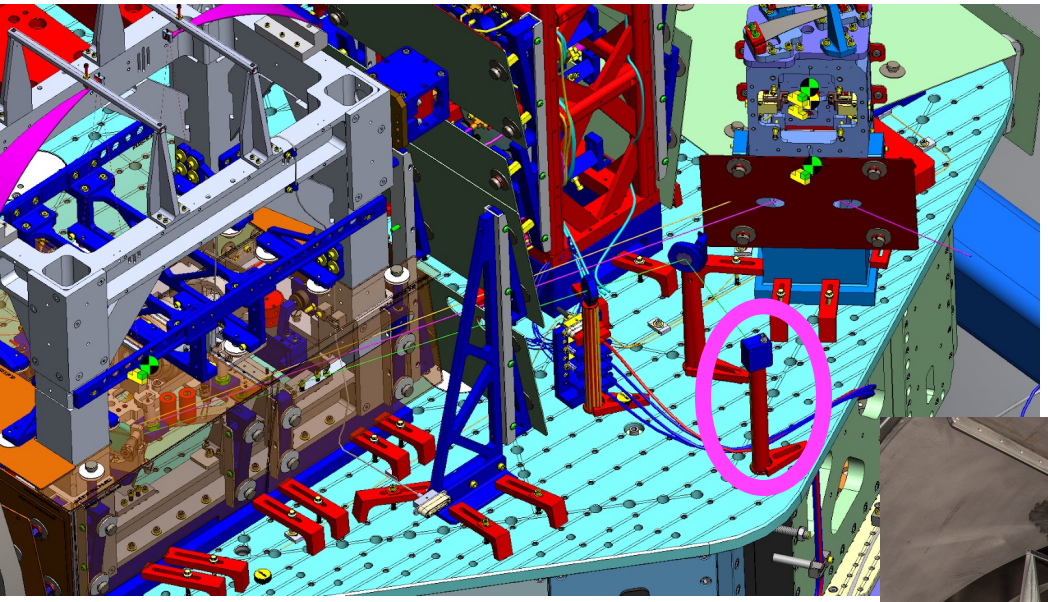
Possible Additional Measurements

- PRXarm/SRXarm locked and unlocked
  - Gives the effect of PR and SR
- Single arm detuned, RF modulation depth scanned
  - To see mode content for single arm lock
- FPMI and single arm
  - To check if s-pol generated is common or not
- ITM/ETM ring heater on/off
  - To confirm if the effect is from ITM, and if ETM contributes
- Power high/low
  - To check power dependence on ITM birefringence
- Arm/PRC/SRC cavity scan
  - to see mode content in OFI_B (better to have fast ADC synced with other channels)
- Use other in-air ports? (POP? HWS port?)
- TRX/Y gives polarization modes in the arm (assuming ETM substrate birefringence is small)

Details

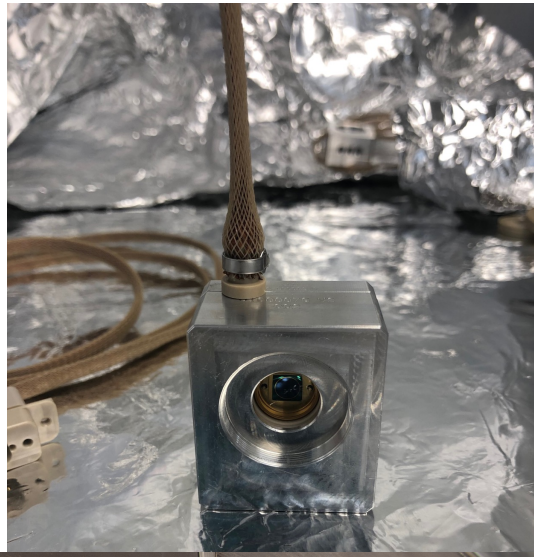
IFO s-pol rejected light monitor

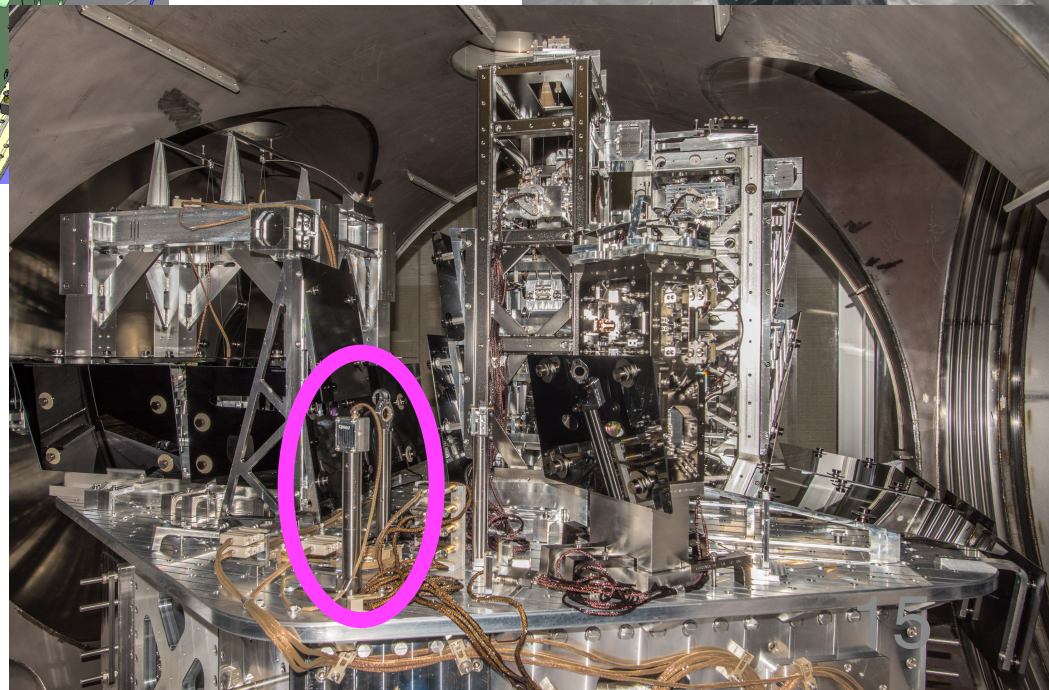
- Named OFI_B in HAM5



LIGO-T2200018

LIGO-E2100030



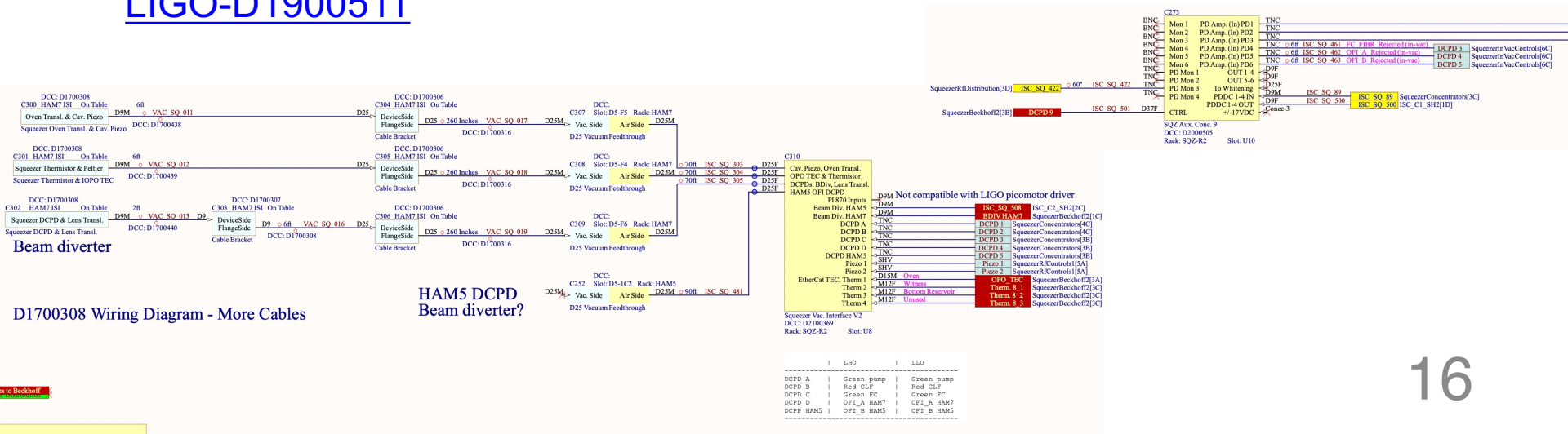


LLO alog #59282

Current OFI_B Signal Chain

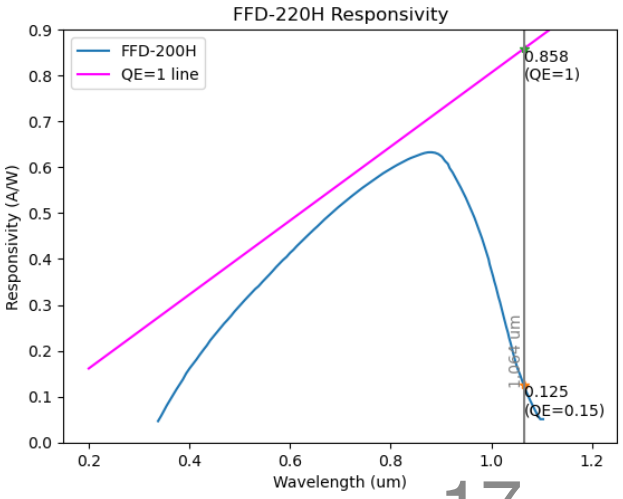
- Excelitas FFD-200H (E2100030)
- A+ Squeezer Interface Chassis (D2100369)
- Auxiliary Signals Concentrator 9 (D2000505)
  Dual DC Photodiode Amplifier (D1200543)
  - Trans-impedance switchable from 1k, 3.16k, 10k 31.6k
  - Has extra x(-2) gain
- No whitening
- ADC-ed with Beckhoff (16 Hz)
- L1:IOO-OFI_PD_B in CDS (LLO alog #59076)

LIGO-D1900511



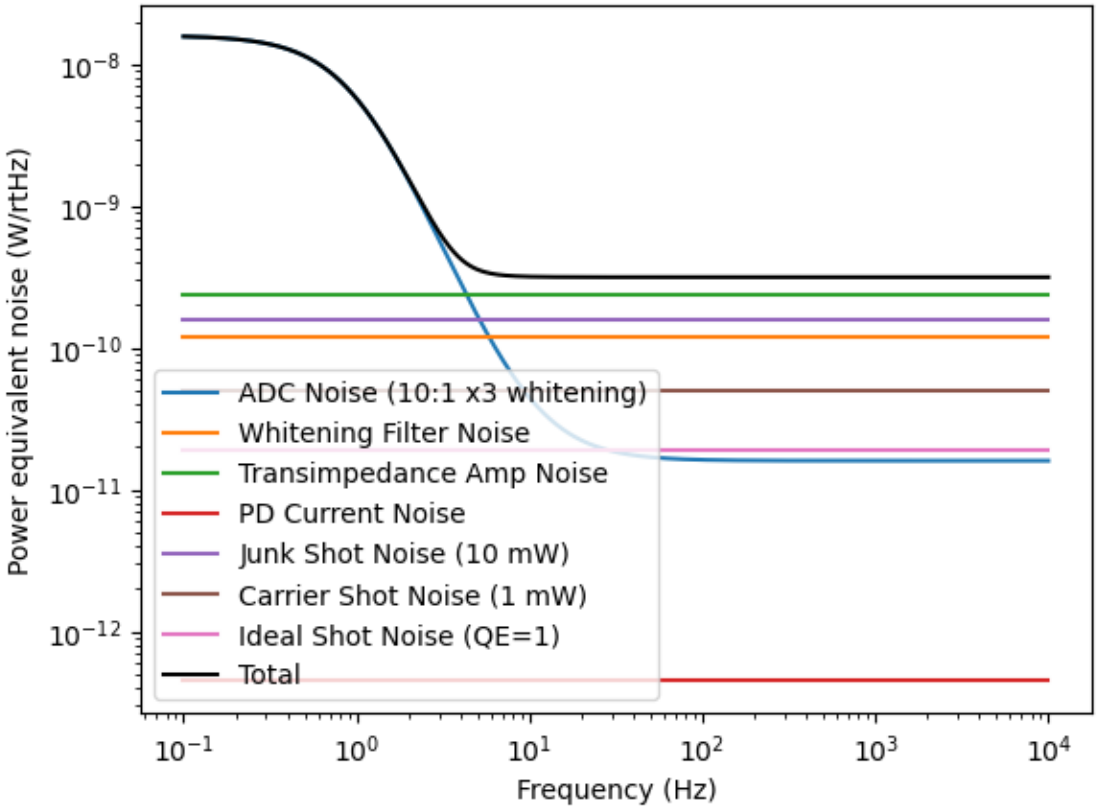
Noise Estimate

- PD dark noise / transimpedance amp noise
  - FFD-200H: 0.125 A/W at 1064 nm (Datasheet)
  - FFD-200H: Dark current 56 fA/rtHz @ 1 kHz (Datasheet)
  - OP97: 20fA/rtHz, 30nV/rtHz (Datasheet); assume 1 kOhm transimp
- Shot noise
  - Power at BS in O4: 2800 W? (400 kW at arm)
  - s-pol power at OFI_B: ~11 mW with ~40W at PRM (LLO alog #60856); assumed 1 mW to be TEM00, and 10 mW to be junk)
  - Assume no squeezing in s-pol
  - FFD-200H has QE=15%
- ADC noise
  - 4 uV/rtHz ? (assuming 16bit ADC)
  - Use 3-stage 10 Hz / 1 Hz whitening filter (e.g. LIGO-D1001530)
    - whitening filter noise: 3e-8 V/rtHz



Estimated Power Equivalent Noise

- Dominated by ADC noise at low frequencies
- Transimpedance amp noise and shot noise from junk light (HOMs, RFSBs) at high frequencies
  - Amp noise can be reduced further with modifications

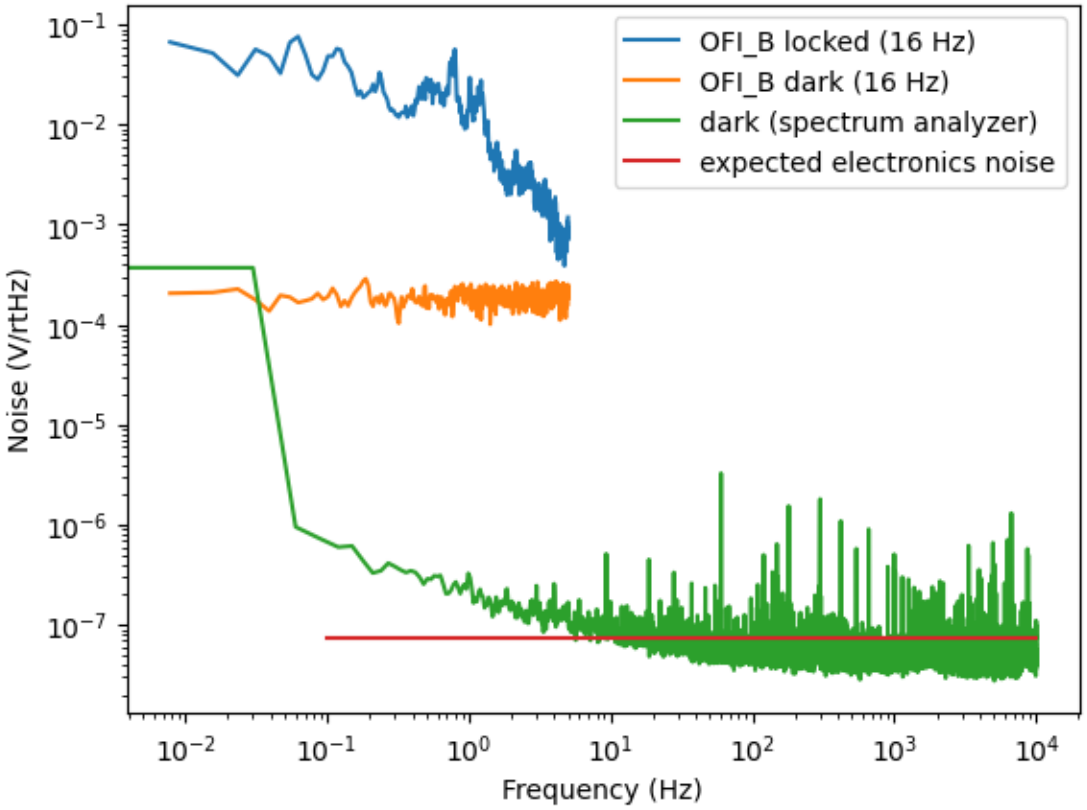


Assumed 1 mW of carrier TEM00 and 10 mW of junk light for s-pol

ADC noise: if we use usual fast ADC with whitening filter (not current Beckhoff ADC)

Measured Noise

- From L1:IOO-OFI_PD_B_DC_VOLTS (16 Hz)
- Dark noise also measured with spectrum analyzer by Masayuki



Currently Beckhoff ADC noise is limiting dark noise

Dark noise measured with a spectrum analyzer matches well with our electronics noise expectation

BS Phase

- Number from LIGO-G1501374