Cosmic Explorer Laser and Input Optics Power Requirements

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Contents

1 Introduction

Due to the enhanced requirements on frequency, intensity, and beam jitter noise, more input optics will likely be required for Cosmic Explorer-type interferometers compared to Advanced LIGO [1]. More input optics will inflict higher power losses on the pre-stabilized laser beam while the beam traveled to the power-recycling mirror. This will lead to a higher required power output of the pre-stabilized laser, while still maintaining good beam quality, polarization, and stability.

The Cosmic Explorer laser and input optics must be capable of delivering the necessary main carrier power and RF sidebands with the required noise levels and beam quality. This technical note focuses on the input power requirement for Cosmic Explorer, using the measured performance of Advanced LIGO to inform this requirement. Cosmic Explorer is currently aiming for 1.5 MW of resonant 1064 nm laser power in each of its arms in order to achieve its quantum noise goals [2, 3], similar to the A$^\sharp$ optical power goals [4].

The arm finesse is planned to be around 450 [5], similar to Advanced LIGO. PRM reflectivities and lengths are not yet decided for the main interferometer, nor is the overall coupling of the power into the interferometer for dealing with frequency noise [1, 6, 7].

2 Executive Summary

The Cosmic Explorer Pre-Stabilized Laser system shall deliver at least $P_\mathrm{psl} = 375$ W of laser power to the start of the input optics chain.

The equation calculating the required PSL power is

$$P_\mathrm{psl} = \frac{2P_\mathrm{arm}}{q_0 \eta_\mathrm{io} G_\mathrm{prc} G_\mathrm{arm} \left(1 - \frac{\Gamma^2}{2}\right)^n} \tag{1}$$

where P_psl is the total power out of the Pre-Stabilized Laser, P_arm is the target power in the arms of 1.5 MW, q_0 is the carrier mode matching (assumed to be 95 %), η_io is the throughput power efficiency of the CE input optics chain (assumed to be 65 %), G_{prc} is the power-recycling gain (assumed to be 50), G_{arm} is the arm gain (taken as 287), Γ is the modulation depth for the RF sidebands taken as 0.2 rad, and n is the number of sidebands applied to the main beam, taken to be five.

This requirement is driven by the arm power requirement for $P_{\mathrm{arm}} = 1.5$ MW, planned CE arm finesse $\mathscr{F} = 450$ [5], and power recycling gain of around 50. The total carrier power required to be coupled into the main interferometer to be around 210 W. All other losses due to throughput inefficiencies, mode mismatch, pickoffs, and RF sideband generation must be accounted for. Table 1 attempts to account of these inefficiencies in Advanced LIGO. The accounting done in Eq. 1 is justified in this document.

Stage	**Optical Element**	**Input (W)**	**Efficiency**	**Output (W)**
PSL: Amplification Chain				
	NPRO seed	—	—	1.8
	Amplifier 1 (neoVan-4S)	1.8	39×	70
	Amplifier 2 (neoVan-4S)	70	2×	140
PSL: Table Losses				
	AOM (ISS 4 % pickoff)	140	96 %	134
	Pre-Mode Cleaner (PMC)	134	77 % - 82 %	103–110†
PSL table loss η_{psl}		140	74 % - 79 %	103–110
Input Optics: Table-mounted				
	EOM (5 % into RF sidebands)	103–110	—	103–110
	Rotation stage (power control)	103–110	variable	62†
Input Optics: Suspended in-vacuum				
	Input Mode Cleaner (IMC)	62	94 %	58
	Input Faraday Isolator (IFI)	58	97 – 98 %	57
Suspended IO loss η_{io}		62	92 %†	57
Power at PRM (O4c)				**57**

Table 1: Advanced LIGO power budget from the NPRO seed laser to the power-recycling mirror (PRM). Values are for LIGO Hanford from O4c. The AOM and PMC combined throughput is 75 % of the 140 W amplifier output. The suspended IO throughput reported in [8] is 85 %; the more recent O4c measurement gives 92 %.

2.1 Current Efficiency of Advanced LIGO Laser and Input Optics

The *input optics* in Advanced LIGO are often considered all optical components that interact with the main high power pre-stabilized laser (PSL) beam *after* the pre-mode cleaner (PMC) cavity [8]. This includes several critical optics on the PSL table, including the rotation stage for laser power control, mode matching optics, a beam-steering PZT mirror for aligning to the input mode cleaner (IMC), the main high power electro-optic modulator (EOM) for imparting the sidebands for IMC and main interferometer Pound-Drever-Hall (PDH) controls.

For our purposes, we will consider the efficiency of the PSL table-mounted pre-mode cleaner as well. This gives us valuable information about the total throughput we may expect for table-mounted four-mirror pre-mode cleaner-type cavities, given difficulties with ultra-high spatial beam quality and input impedance matching for tabletop fixed-spacer cavities [9, 10].

The Advanced LIGO PSL provides the initial input power to the input optics chain, which then passes to the main interferometer. Figure 1 shows the PSL layout, while Figure 2 shows the PSL MEDM screen with labeled power monitor ports. Figure 3 shows the values of those monitors between June 2022 and June 2026.

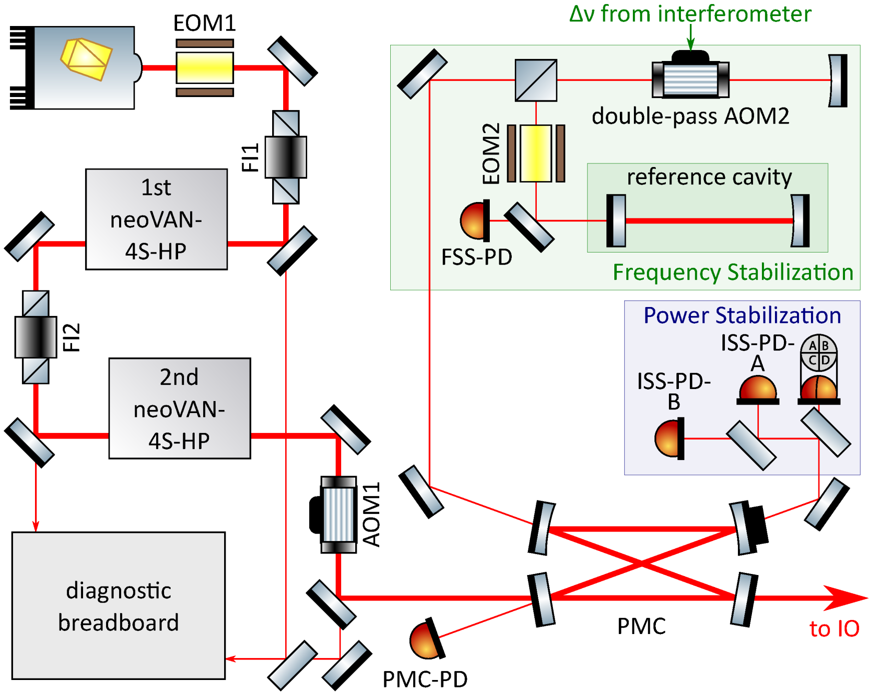
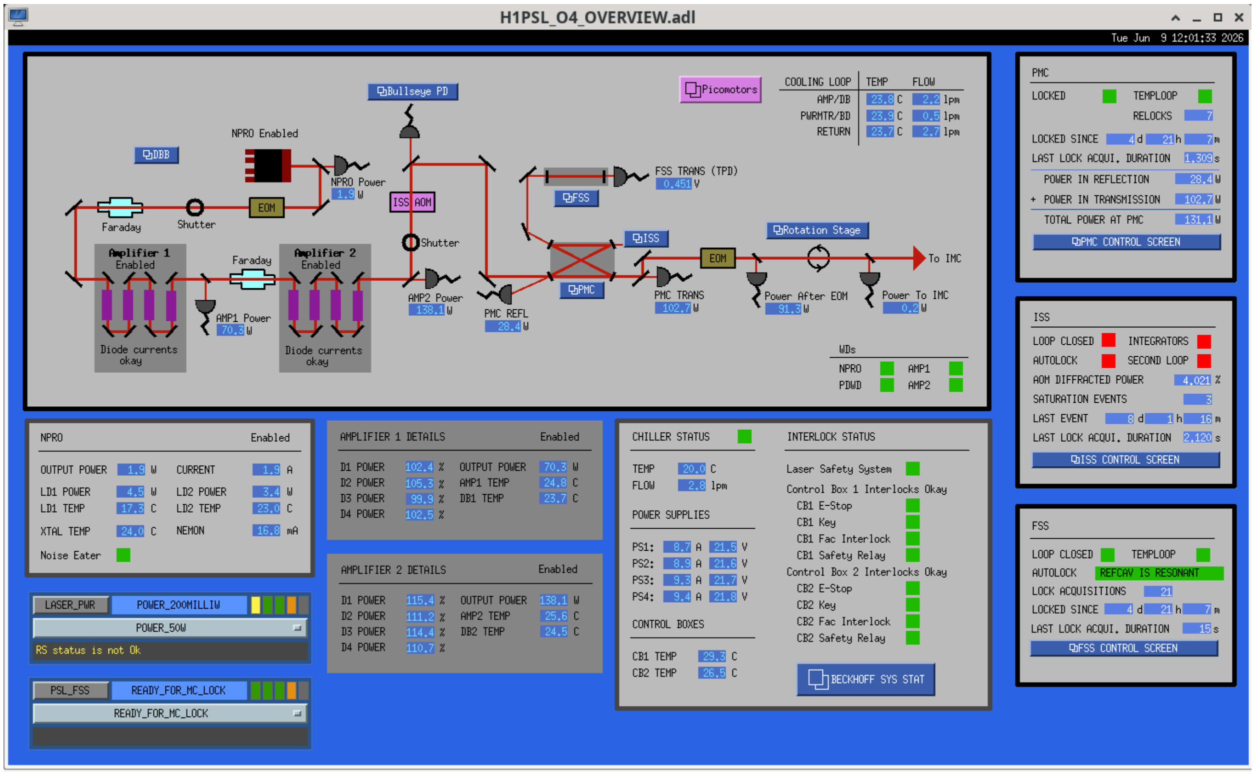


Figure 1: Pre-stabilized laser table diagram, taken from Figure 6 of [11]. A 2W Nd:YAG NPRO laser seeds two neoVAN-4S-HP laser amplifiers. The laser is amplified from 1.8 W to 70 W, then to 140 W. Then the beam is sent through the Pre-Mode Cleaner (PMC) to stabilize the beam spatially. This beam is then sent through the Input Optics (IO) chain, see Figures 4 and 5.

Advanced LIGO relies on a 2 W 1064 nm NPRO laser to generate a low-noise laser beam with good intrinsic stability and beam quality [12]. The excellent beam temporal and spatial quality lowers the requirements of all of the subsequent beam stabilization optics.

The beam then proceeds through two sequential neoVan-4S free-space amplifiers from neoLase (see Figure 1). The laser is amplified from 1.8 W to 70 W at the output of the first amplifier, then to 140 W at the output of the second amplifier.

The beam then passes through an AOM, which picks off 4 % of the beam power for the intensity stabilization servo (ISS).



NPRO Power 1.9 W
AMP1 Power 70.3 W
AMP2 Power 138.1 W
PMC REFL 28.4 W
FSS TRANS (TPD) 0.451 V
PMC TRANS 102.7 W
Power After EOM 91.3 W
Power To IMC 0.2 W

COOLING LOOP	TEMP	FLOW
AMP/DB	23.8 C	2.2 lpm
PWRMTR/BD	23.9 C	0.5 lpm
RETURN	23.7 C	2.7 lpm

WDs

NPRO	🟩	AMP1	🟩
PDWD	🟩	AMP2	🟩

PMC

LOCKED 🟩 TEMPLOOP 🟩
RELOCKS 7
LOCKED SINCE 4 d 21 h 7 m
LAST LOCK ACQUI. DURATION 1.309 s
POWER IN REFLECTION 28.4 W
+ POWER IN TRANSMISSION 102.7 W
TOTAL POWER AT PMC 131.1 W

ISS

LOOP CLOSED 🟥 INTEGRATORS 🟥
AUTOLOCK 🟥 SECOND LOOP 🟥
AOM DIFFRACTED POWER 4.021 %
SATURATION EVENTS 3
LAST EVENT 8 d 1 h 16 m
LAST LOCK ACQUI. DURATION 2.120 s

FSS

LOOP CLOSED 🟩 TEMPLOOP 🟩
AUTOLOCK REFCAV IS RESONANT
LOCK ACQUISITIONS 21
LOCKED SINCE 4 d 21 h 7 m
LAST LOCK ACQUI. DURATION 15 s

NPRO Enabled

OUTPUT POWER	1.9	W	CURRENT	1.9	A
LD1 POWER	4.5	W	LD2 POWER	3.4	W
LD1 TEMP	17.3	C	LD2 TEMP	23.0	C
XTAL TEMP	24.0	C	NEMON	16.8	mA
Noise Eater	🟩				

AMPLIFIER 1 DETAILS Enabled

D1 POWER	102.4	%	OUTPUT POWER	70.3	W
D2 POWER	105.3	%	AMP1 TEMP	24.8	C
D3 POWER	99.9	%	DB1 TEMP	23.7	C
D4 POWER	102.5	%			

AMPLIFIER 2 DETAILS Enabled

D1 POWER	115.4	%	OUTPUT POWER	138.1	W
D2 POWER	111.2	%	AMP2 TEMP	25.6	C
D3 POWER	114.4	%	DB2 TEMP	24.5	C
D4 POWER	110.7	%			

LASER_PWR POWER_200MILLIW
POWER_50W
RS status is not Ok

PSL_FSS READY_FOR_MC_LOCK
READY_FOR_MC_LOCK

CHILLER STATUS 🟩
TEMP 20.0 C
FLOW 2.8 lpm

POWER SUPPLIES

PS1:	8.7	A	21.5	V
PS2:	8.9	A	21.6	V
PS3:	9.3	A	21.7	V
PS4:	9.4	A	21.8	V

CONTROL BOXES
CB1 TEMP 29.3 C
CB2 TEMP 26.5 C

INTERLOCK STATUS
Laser Safety System 🟩
Control Box 1 Interlocks Okay
CB1 E-Stop 🟩
CB1 Key 🟩
CB1 Fac Interlock 🟩
CB1 Safety Relay 🟩
Control Box 2 Interlocks Okay
CB2 E-Stop 🟩
CB2 Key 🟩
CB2 Fac Interlock 🟩
CB2 Safety Relay 🟩

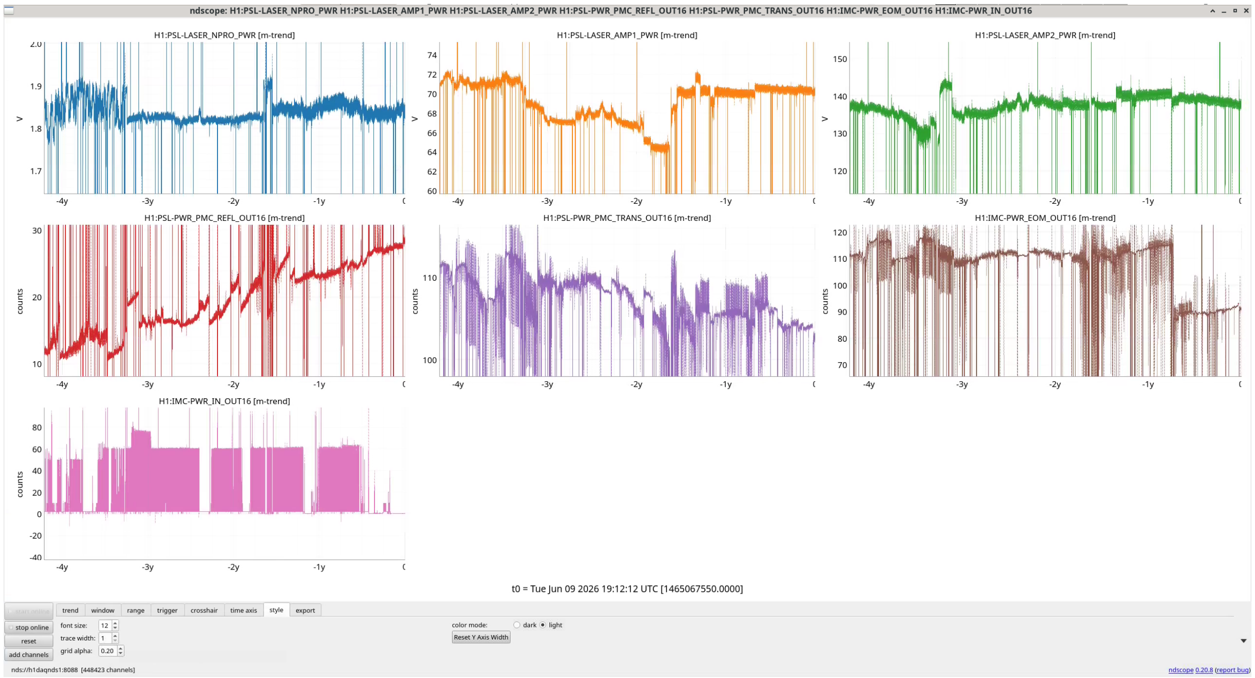
Figure 2: MEDM screen of the LIGO Hanford PSL, with power monitors labeled. Credit to Jason Oberling and Jenne Driggers.

Then the beam encounters the tabletop Pre-Mode Cleaner (PMC) [9]. The PMC is critical for cleaning up the beam spatial quality prior to sending into the input optics, while still passing most of the input power. The PMC finesse is typically kept low (finesse $\mathscr{F} = 125$) to avoid excessively high power causing thermal deformations. Additionally, pickoffs from the extra PMC ports are used as a part of the intensity and frequency stabilization servos (ISS and FSS). From Figure 3, somewhere between 110 W to 103 W makes it through the PMC in transmission, compared with around 140 W of input power. Thus the PMC throughput is around 75 %.

After the PMC, the beam officially enters the input optics chain. This includes some pickoffs of the ALS and Squeezer phase-locked loop systems, the rotation stage, and the periscope for sending the beam into vacuum to the suspended and isolated optics in-chamber.

It also includes the electro-optic modulator (EOM) for imposing the RF-sideband phase modulated sidebands. The RF sidebands are used to Pound-Drever-Hall lock the input mode cleaner (IMC) and main interferometer. Between 2015 and 2026, the EOM was on the PSL optical table, like in Figure 4. Since the install of the Jitter Attenuation Cavity (JAC) at LIGO Hanford in Spring 2026, the EOM is now suspended in-vacuum after the JAC, but before the IMC [13, 14]. Because the effects of the JAC on throughput have not yet been measured, we will not consider it in this document.

The RF sidebands are remotely controllable in their amplitude, and are stabilized using an amplitude RF-stabilization box [15, 16]. The RF sidebands with the current EOM can have a max modulation depth of up to around 0.25 rad, although typically we run with much less modulation



font size: 12
trace width: 1
grid alpha: 0.20
color mode: ○ dark ● light
Reset Y Axis Width

Figure 3: LIGO Hanford PSL power trends from 2022 to June 2026. The NPRO power (blue) and amplifier outputs (orange and green) are very stable over the years. The pre-mode cleaner reflection (red) does appear to climb from 10 W to nearly 30 W, but the PMC transmission (purple) appears to not suffer an equivalent drop, going from 110 W to about 103 W.

(around 0.15 rad or so).

The EOM applies four different sidebands to the laser, with different levels of modulation depth. One is for locking the input mode cleaner (24 MHz). Three are for controlling the main interferometer (9.1 MHz, 45.5 MHz, 118.3 MHz). Around 5 % of the light is scattered out of the carrier into the RF sidebands.

The input optic on the PSL optical table is the rotation stage. The rotation stage is a remotely controllable half-wave plate (HWP) with two thin-film polarizers (TFPs) mounted at Brewster's angle. The output of the rotation stage is sent directly up the periscope and into the vacuum.

The suspended input optics chain includes the input mode cleaner (IMC), the input Faraday isolator (IFI), and several steering optics (See Figure 5). The input mode cleaner is 16 meters long, with an free spectral range of 9.1 MHz to pass all of the main interferometer sidebands. The input optics paper [8] cites a total power throughput of around 85%. Using O4c data from November 2025 at LIGO Hanford in Figure 7, we see around $57\,\mathrm{W}/62\,\mathrm{W} = 92\%$ total throughput through the entire suspended IO chain, indicating some improvement in the input optics chain throughput efficiency.

From [8], the input Faraday isolator measured optical throughput efficiency was between 97 % – 98 %. Assuming an IFI throughput efficiency of 98 %, this means the rest of the input optics chain, including the IMC, has a throughput efficiency of 94 %.

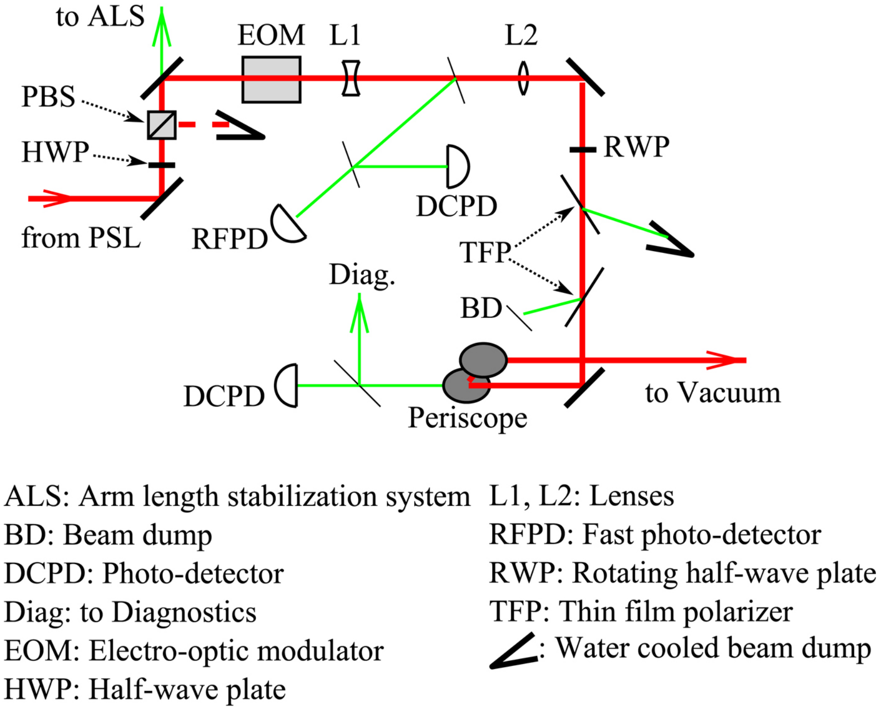


Figure 4: Input-optics on PSL table, taken from Figure 3 of [8].

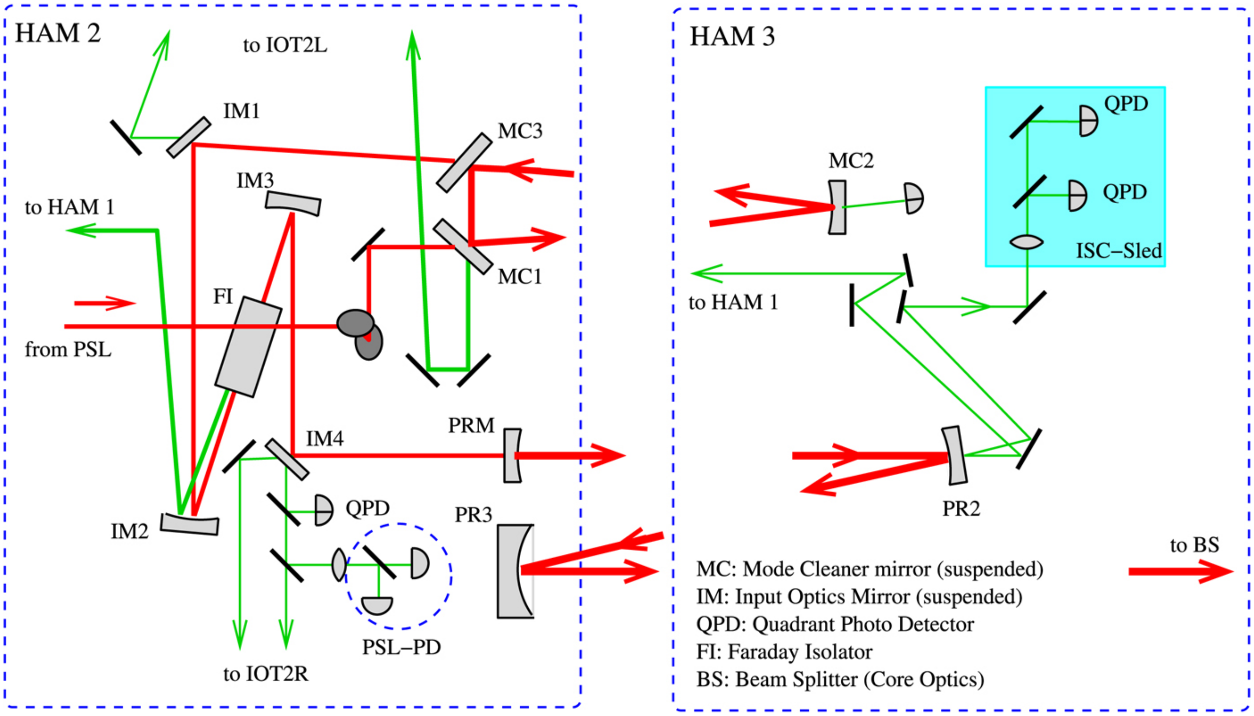
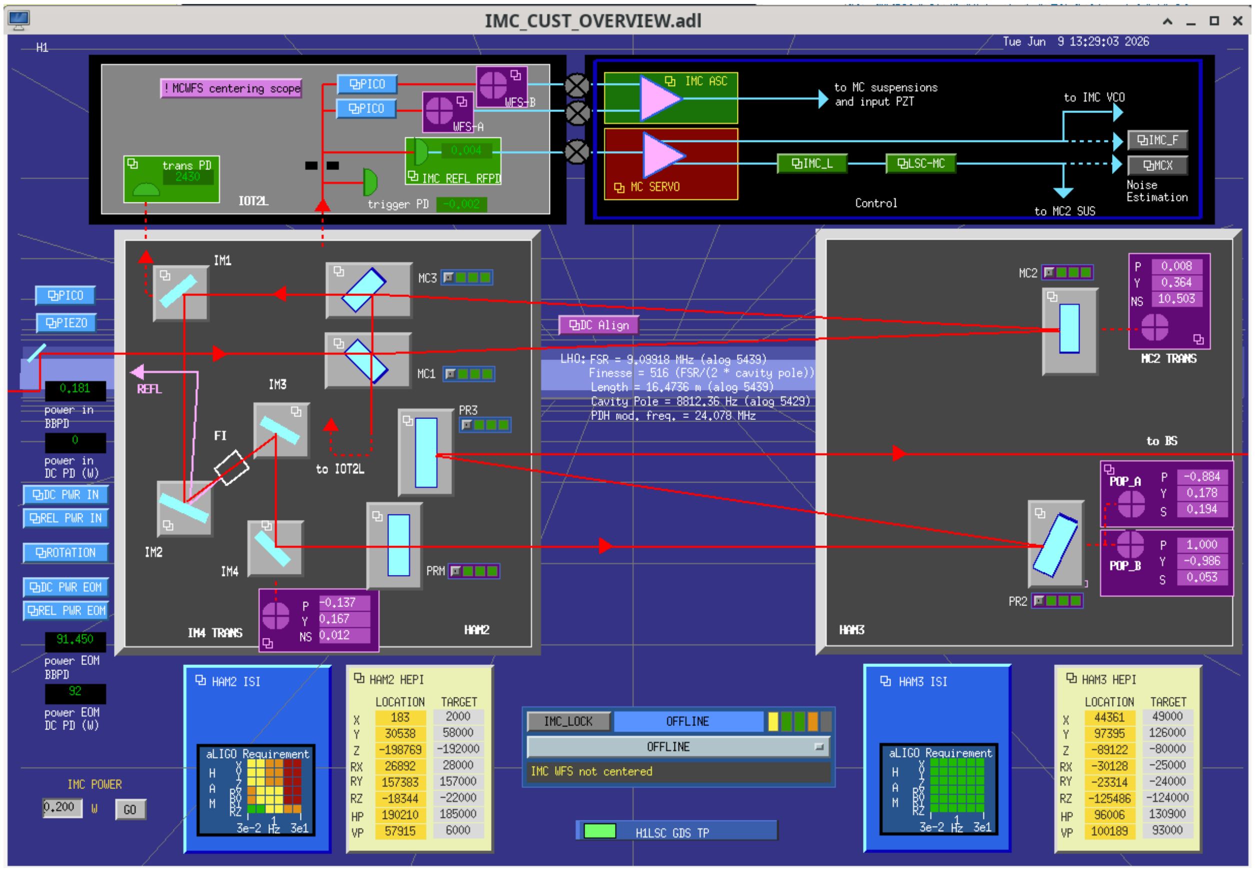


Figure 5: Input-optics in vacuum, taken from Figure 4 of [8].



trans PD 2450

trigger PD -0.002

IMC REFL RFPD 0.004

power in BBPD 0.181

power in DC PD (W) 0

power EOM BBPD 91.450

power EOM DC PD (W) 92

IMC POWER 0.200 W

MC2 TRANS: P 0.008, Y 0.364, NS 10.503

IM4 TRANS: P -0.137, Y 0.167, NS 0.012

POP_A: P -0.884, Y 0.178, S 0.194

POP_B: P 1.000, Y -0.986, S 0.053

LHO: FSR = 9.09918 MHz (alog 5439)
Finesse = 516 (FSR/(2 * cavity pole))
Length = 16.4736 m (alog 5439)
Cavity Pole = 8812.36 Hz (alog 5429)
PDH mod. freq. = 24.078 MHz

HAM2 HEPI

	LOCATION	TARGET
X	183	2000
Y	30538	58000
Z	-198769	-192000
RX	26892	28000
RY	157383	157000
RZ	-18344	-22000
HP	190210	185000
VP	57915	6000

IMC_LOCK OFFLINE
OFFLINE
IMC WFS not centered

HAM3 HEPI

	LOCATION	TARGET
X	44361	49000
Y	97395	126000
Z	-89122	-80000
RX	-30128	-25000
RY	-23314	-24000
RZ	-125486	-124000
HP	96006	130900
VP	100189	93000

Figure 6: LIGO Hanford input optics MEDM screen, illustrating the layout and power monitor locations

2.2 Estimated Efficiency of Cosmic Explorer Input Optics Chain

The input optics for Cosmic Explorer are only largely designed around satisfying the laser frequency stabilization requirements in the face of the 40 km long arms [1]. The drastically lowered free-spectral range for an overcoupled interferometer will impose a strong limitation on the frequency stabilization loop to less than around 2 kHz [17].

Currently, the reference design employs a suspended pre-mode cleaner, two linear input mode cleaners, six total input Faraday isolators, and three Pockels cells (see Figure 8).

The suspended pre-mode cleaner is to clean the beam for entry into the first input mode cleaner, in order to ensure the shot noise limit achieved is not limited by junk light. The first input mode cleaner is used for high-bandwidth laser frequency stabilization to the shot noise limit. The first IMC's shot noise limit is not anticipated to be sufficient for stabilization at high frequencies, so the second input mode cleaner will passively stabilize the laser frequency, as well as the intensity and beam jitter [1].

The reference design uses linear mode cleaners, rather than triangular. This is proposed in order to avoid small beam spots causing significant thermalization inside the input mode cleaners, and to avoid an uncontrolled backpropagating beam caused by the small angle on the far mirror for the long mode cleaners causing scattering noise from a parasitic interferometer.

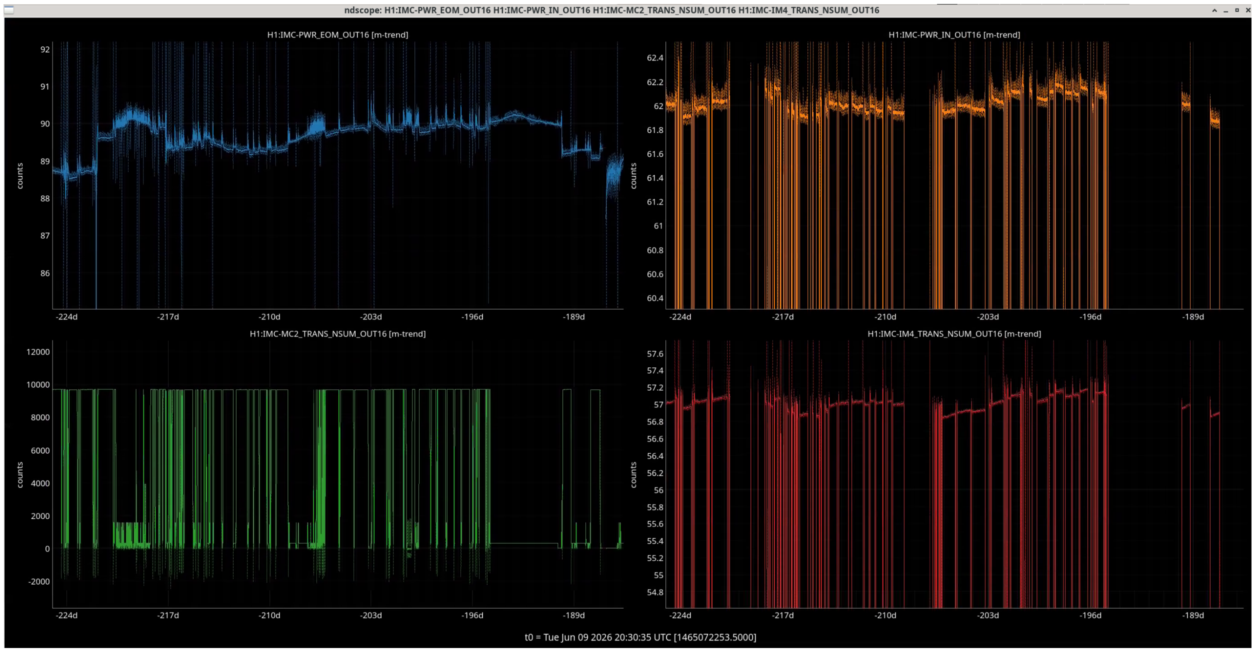


Figure 7: LIGO Hanford IO power trends from November 2025. The requested input power is the orange trace, set by the rotation stage to be around 62 W. The actual power making it to the PRM is the red trace, around 57 W. This makes the suspended IO chain throughput around 92 %.

The linear IMCs will need additional polarization and backscatter control *outside* the cavity. Therefore, we have two input Faraday isolators between the two input mode cleaners and two between the second input mode cleaner and the main interferometer.

Now, for the CE power budget, we estimate throughput efficiencies for the total suspended IO chain (η_{io} in Eq. 1). The values assumed are largely informed from the Advanced LIGO observed performances, assuming we can match those performances for Cosmic Explorer. The values are listed in Table 2.

The suspended pre-mode cleaner is assumed to be similar in form factor the current Advanced LIGO IMC (triangular, 16 m in length), so we use the LIGO IMC throughput efficiency for the CE suspended PMC.

For the Cosmic Explorer IMCs, there will be fewer mirrors for the linear cavities, leading to less losses, but they will be much longer with larger beam spots. We estimate the CE IMC throughput efficiency to be around 0.95% for both cavities.

There will be six total input Faraday isolators needed to handle the longer input optics chain and maintain a good polarization extinction ratio. For the input Faraday isolator efficiency, we assume $\eta_{\text{ifi}} = 98\,\%$ for each isolator.

For this CE power budget, we want to consider the *carrier* power delivered to the interferometer in the correct spatial mode. Recall that CE requires around 210 W of carrier power to be mode matched into the interferometer. So here we consider the Pockels Cell (PC) or EOM RF sideband creation out of light scattered from the carrier, and input beam mode matching to the main interferometer.

Each RF sideband is assumed to require a modulation depth $\Gamma = 0.2\,\text{rad}$. This does not cause a

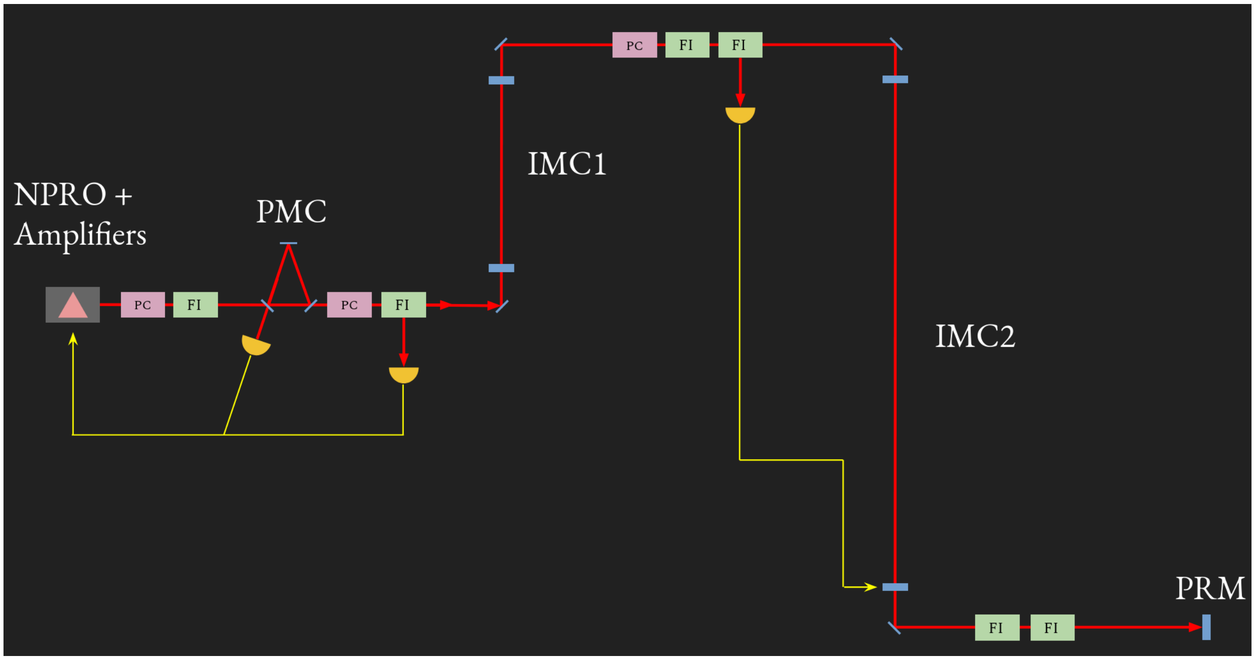


Figure 8: Rough initial draft of the Cosmic Explorer input optics chain. PC is a Pockel's Cell, and FI is a Faraday Isolator. PMC is the suspended Pre-Mode Cleaner, IMC1 is the first Input Mode Cleaner, IMC2 is the second. NPRO + Amplifiers represents the entire Pre-Stabilized Laser table. PRM is the Power Recycling Mirror of the main interferometer.

Optical Element	**Symbol**	**Efficiency**	**Quantity**
AOM	η_{aom}	96 %	1
Table PMC	η_{pmc}	80 %	0
Suspended PMC	η_{suspmc}	94 %	1
Input Mode Cleaners	η_{imc}	95 %	2
Input Faraday Isolators	η_{ifi}	98 %	6
RF sidebands	η_{rf}	98 %	5
Mode matching	q_0	95 %	1
Total	η_{io}	65 %	—

Table 2: Estimated carrier power throughput efficiencies for the Cosmic Explorer input optics chain. Values are informed by Advanced LIGO O4c performance. Efficiencies are per element. The RF sidebands count as lost power only for the carrier laser beam, this and mode matching should be considered for supplying sufficient carrier. We assume NO on-table Pre-Mode Cleaner in the reference design, and so list zero for its quantity, but emphasize that it could be added in later on.

loss of total power, but scatters light from the carrier into the RF sidebands. The amount of power lost per sideband is then $1 - \frac{\Gamma^2}{2} \approx 98$ %.

Finally, the input beam mode matching to the main interferometer is a big unknown. We believe that with mode sensing and control improvements in both the input chain and main interferometer, an input mode matching value of at least 95 % can be achieved.

Using Table 2, we can calculate the total CE input optics chain carrier power efficiency η_{io} as

$$\eta_{\mathrm{io}} = \eta_{\mathrm{aom}} \eta_{\mathrm{suspmc}} \eta_{\mathrm{imc}}^2 \eta_{\mathrm{ifi}}^6 \eta_{\mathrm{rf}}^5 q_0 \tag{2}$$

$$\eta_{\mathrm{io}} \approx 0.65 \tag{3}$$

3 Possible Methods for Power Output of the Pre-Stabilized Laser

The Cosmic Explorer Pre-Stabilized Laser (PSL) will operate at 1064 nm, and must be capable of delivering at least 375 W to the input optics subsystem.

The current LIGO PSL can deliver around 110 W of linearly-polarized ultra-stable laser power to the main interferometer [10, 11, 18]. This system relies on a 2 W Nd : YAG NPRO seed laser [12], amplified using two sequential free space Nd : $\mathrm{YVO_4}$ amplifiers to achieve around 138 W to be delivered to the input optics [19]. The pre-mode cleaner, input mode cleaner, and input Faraday isolator constitute the largest power loss components on the PSL table or in the input optics. An acoustic-optic modulator (AOM) also intentionally throws away 4 % of the input light for the laser intensity stabilization [10].

To achieve coherent continuous-wave laser powers at around 375 W that retain the high stability of the seed NPRO, new technology must be developed. The sequential free-space amplifiers cannot currently be used to amplify beyond 200 W with major system upgrades and high complexity [20].

For the Cosmic Explorer Pre-Stabilized Laser, we anticipate employing a single-seed 2 W 1064 nm NPRO with two parallel 200 W fiber-amplifier systems. These two parallel amplified fibers are then coherently combined using a Mach-Zender interferometer up to 400 W of stable laser power [21].

This should be sufficient to supply the Cosmic Explorer input optics chain with enough laser power to satisfy the maximum input power requirement. If a table-top pre-mode cleaner or additional IO chain optics are determined to be needed for additional beam cleaner, then this requirement will need to be revisited.

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