Selected technical challenges for Cosmic Explorer

Evan Hall

LIGO MIT

July 6, 2017

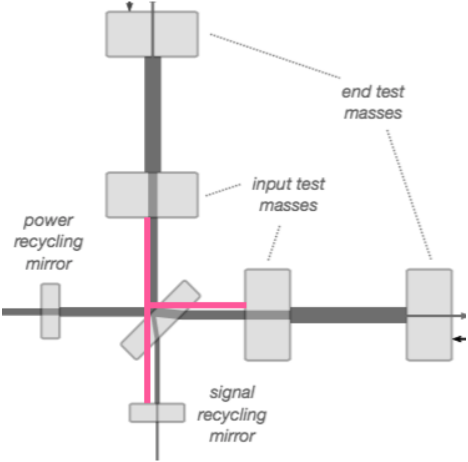
List

- Signal recycling cavity design
- Frequency control
- Test mass size and figure
    - Clipping loss
    - Radius of curvature tolerance
    - Scattering from surface figure errors

Signal recycling cavity design

How should we choose the transmissivity of the signal recycling mirror and its distance from the arms?

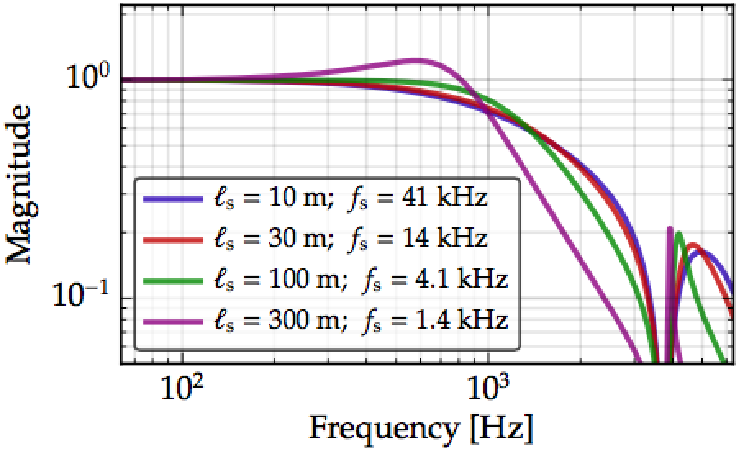
What is the signal recycling cavity?



Once the arm bandwidth is fixed (by fixing the ITM transmission), the bandwidth of the detector's GW response is set by choosing the SRM transmission.

Effect on GW response

Unlike Advanced LIGO, the choice of SRC length noticeably affects the detector's GW response:



Frequency control

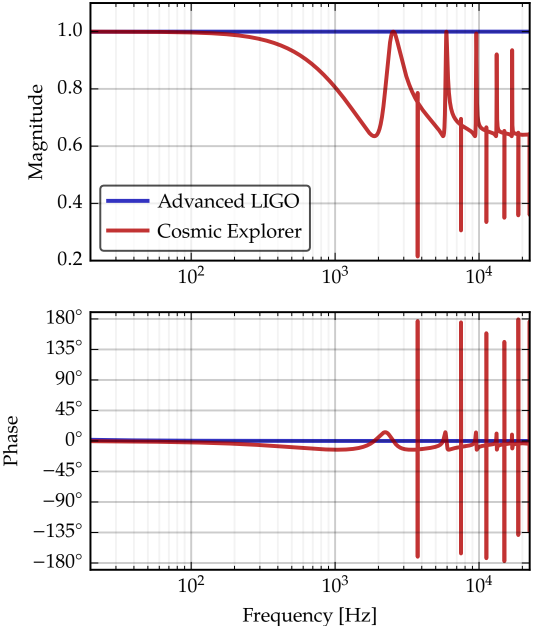
How should we control the laser so as to keep light resonant in the interferometer and suppress laser frequency fluctuations?

Frequency control

Advanced LIGO: laser frequency is locked to the average arm length using Pound–Drever–Hall (PDH) reflection locking.

Servo loop needs a bandwidth $> 10\,\mathrm{kHz}$ in order to adequately suppress frequency noise below 1 kHz.

PDH frequency response



Frequency control for CE?

Presence of right-handed zeros above a few kilohertz limits the bandwidth of a PDH frequency-locking loop

Could blend the PDH signal with another signal (perhaps a single non-resonant sideband)

Test mass size and figure

How large should the test masses be, and how finely must we control their radius of curvature and surface figure?

Mirrors for CE

Compared to Advanced LIGO, Cosmic Explorer will have mirrors that...

- are **wider** (diameter ~30 cm →??)
- are **flatter** (radius of curvature ~2 km → ~30 km)
- must accommodate **larger laser beams** (spot radius ~5 cm → ~15 cm)
- may be made of a **different material** (silica → silicon)

What challenges will we face as we fabricate these new mirrors?

Clipping loss

Clipping loss: outermost ring of the laser beam falls off the test mass.

Clipping loss reduces the power stored in the interferometer arms (and must be compensated with higher input laser power).

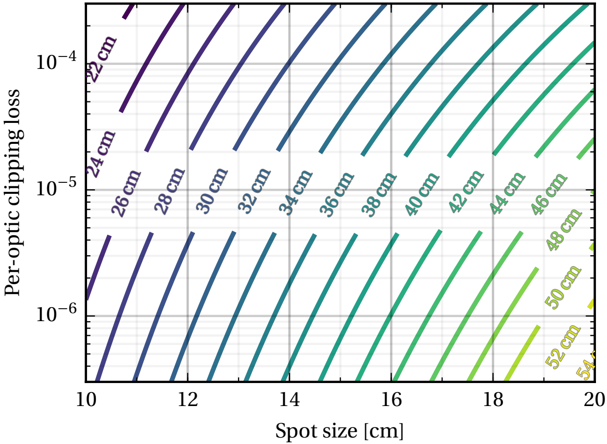
Simple expression: $\eta_{\mathrm{clip}} = \exp[-2(r_{\mathrm{TM}}/w)^2]$, where r_{TM} is the radius of the test mass, and w is the beam spot radius.

For Advanced LIGO: $r_{\mathrm{TM}} = 17\,\mathrm{cm}$ and $w_{\mathrm{ETM}} = 6.2\,\mathrm{cm}$, giving $\eta_{\mathrm{clip}} < 1\,\mathrm{ppm}$.

For CE, 15 ppm might be acceptable (Dwyer et al. [1]).

Clipping loss

For Cosmic Explorer:



Test mass radius $> 30\,\text{cm}$ required to achieve per-optic clipping loss below 15 ppm…

Radius of curvature tolerance

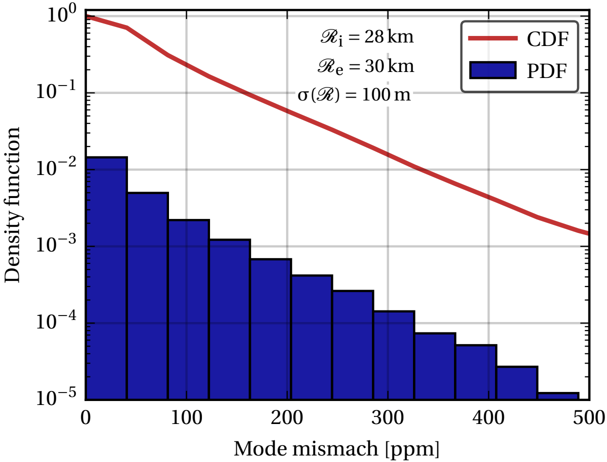
RoC mismatch between arms will cause junk light ("contrast defect") at the interferometer's GW readout.

For Advanced LIGO, the manufacturing tolerance on the **sagitta** is $\Delta s \simeq 5\,\mathrm{nm}$.

Assuming a similar tolerance for CE, if $\mathscr{R} = 30\,\mathrm{km}$, the resulting RoC error is $\Delta\mathscr{R} \simeq 100\,\mathrm{m}$.

Radius of curvature tolerance

Numerical simulation of mode mismatch:



Contrast defect $< 250\,\mathrm{ppm}$ for 95 % of realizations — too large by at least a factor of 10. Active modematching will be required.

Surface figure

Surface figure: spatial fluctuations across the optic surface *other than* the radius of curvature

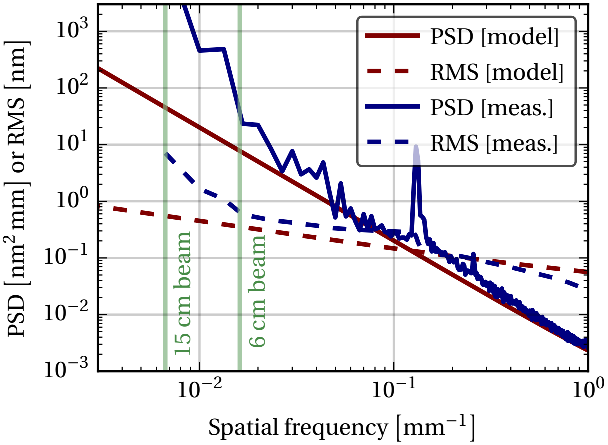
The figure of an isotropic surface is characterized by a **spatial power spectrum** $S_1(k)$, where k is the spatial wavenumber (units of m^{-1}).

Given a particular PSD $S_1(k)$, a larger laser beam will experience more scatter because it samples longer wavelengths.

Advanced LIGO mirror power spectrum

Advanced LIGO model after Yamamoto [2]:

$$S_1(k) = (0.2\,\mathrm{nm}^2\,\mathrm{mm}) \times \left(\frac{0.1\,\mathrm{mm}^{-1}}{k}\right)^2$$



Scatter from surface figure errors

Formula for power scattered out of a beam with spot size w [3]:

$$\eta_{\text{scat}}(w) = \left[\frac{4\pi\sigma_{\text{scat}}(w)}{\lambda_0}\right]^2 = \int_0^\infty \mathrm{d}k\, S_1(k)\, W_w(k). \tag{1}$$

$W_w(k)$ suppresses spatial modes larger than the spot size; $\sigma_{\text{scat}}(w)$ is the effective total rms surface roughness for the given spot size.

Some numbers for surface figure scattering

Note the scaling: if $S_1(k) \propto 1/k^2$, then $\eta \propto \sigma^2 \propto w$.

For Advanced LIGO: $\sigma(6.2\,\mathrm{cm}) = 0.35\,\mathrm{nm}$, so $\eta_{\mathrm{scat}} = 20\,\mathrm{ppm}$ per optic

For Cosmic Explorer: $\sigma(15\,\mathrm{cm}) = 0.55\,\mathrm{nm}$, so $\eta_{\mathrm{scat}} = 48\,\mathrm{ppm}$ per optic

Note the caveats: behavior of $S_1(k)$ for $k < 0.01\,\mathrm{mm}^{-1}$ not well known; optical cavity effects not yet included.

References

S. Dwyer, D. Sigg, S. W. Ballmer, L. Barsotti, N. Mavalvala, and M. Evans. Gravitational wave detector with cosmological reach. *Phys. Rev. D* **91**(8) (2015), p. 082001.

H. Yamamoto. *Guestimation of large angle scattering.* Tech. rep. LIGO-T1600463. LIGO, 2016.

W. Winkler, R. Schilling, K. Danzmann, J. Mizuno, A. Rüdiger, and K. A. Strain. Light scattering described in the mode picture. *Appl. Opt.* **33**(31) (1994), pp. 7547–7550.