

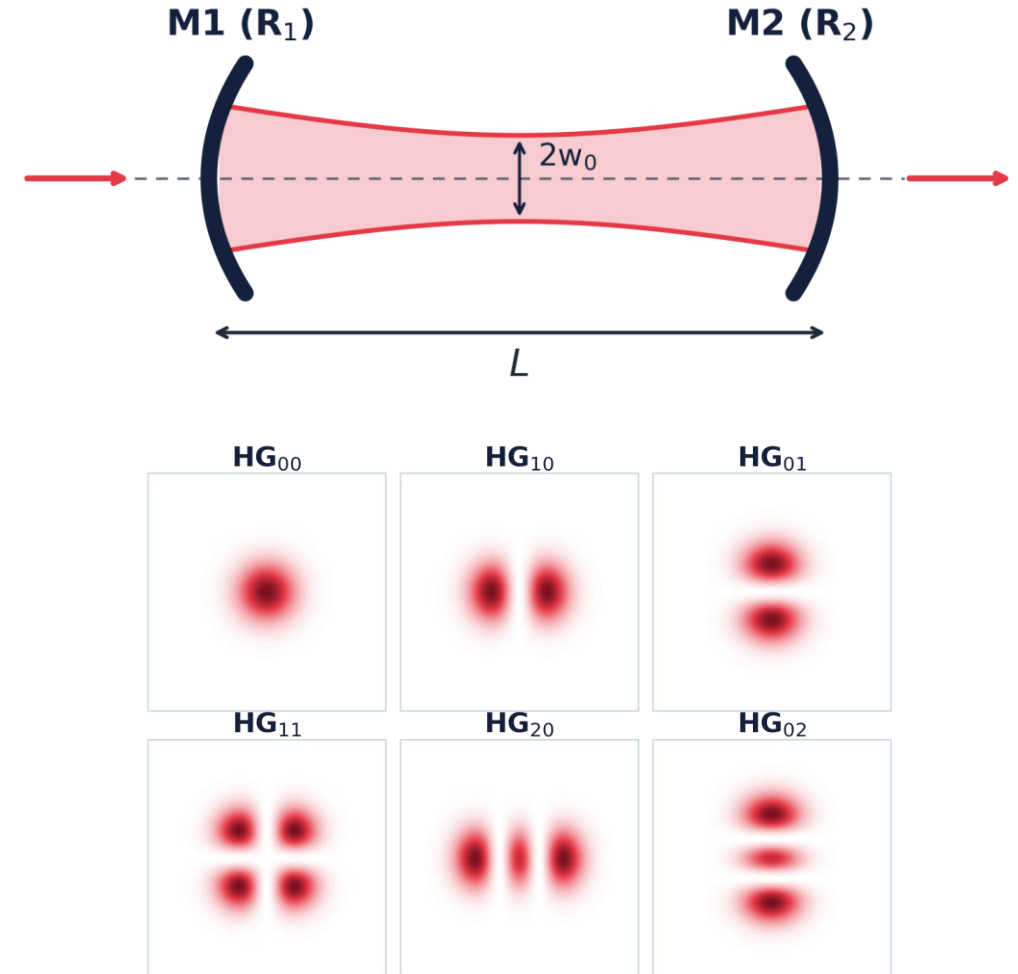
Investigating Astigmatism in the Stable Folded Recycling Cavities of Virgo

Jue Zhang , M. Boldrini, A. Goodwin-Jones, S. Melo, M. Mantovani, J. Casanueva Diaz

Optical cavities & transverse modes

The basic element of every recycling cavity and arm cavity in GWD

- **Longitudinal resonance**
 - Light bounces between two mirrors and power builds up when the round-trip phase is a multiple of 2π
 - $\nu_q = q \times \text{FSR}$ – resonant frequency of the carrier, HG_{00}
 - $\text{FSR} = c / 2L$
- **Transverse modes**
 - The field is described by Hermite Gaussian modes HG_{mn}
- **Gouy phase sets where HOMs resonate**
 - $\nu_{qmn} = \text{FSR} \times [q + (n+m+1) \psi / \pi]$ – resonant frequency of HG_{mn}
 - Stable cavity (large ψ): HOMs stay off resonance and are filtered
 - Marginally stable ($\psi \rightarrow 0$): HOMs resonate together with HG_{00}

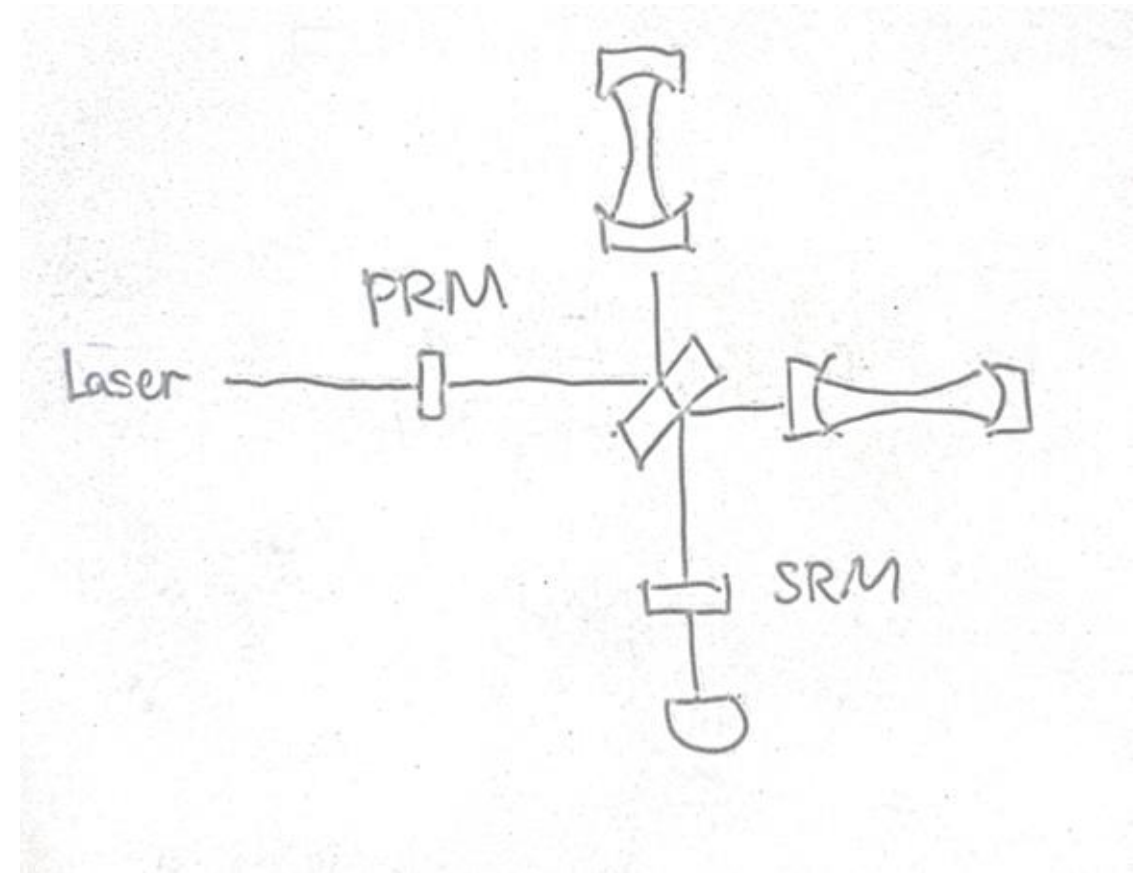


Virgo O5 upgrade: Stable recycling cavities

Why the stable-cavity upgrade needs a controllability study

The O4 limitation

- Broadband noise with a $\sim 1/f^{2/3}$ spectrum of still-unexplained origin.
- Likely linked to the marginally stable Signal Recycling cavity, where higher-order Hermite–Gauss modes (HOMs) can resonate.
- Control noise: HOMs and thermal effects pollute sensors used by the control loops.



Virgo O5 upgrade: Stable recycling cavities

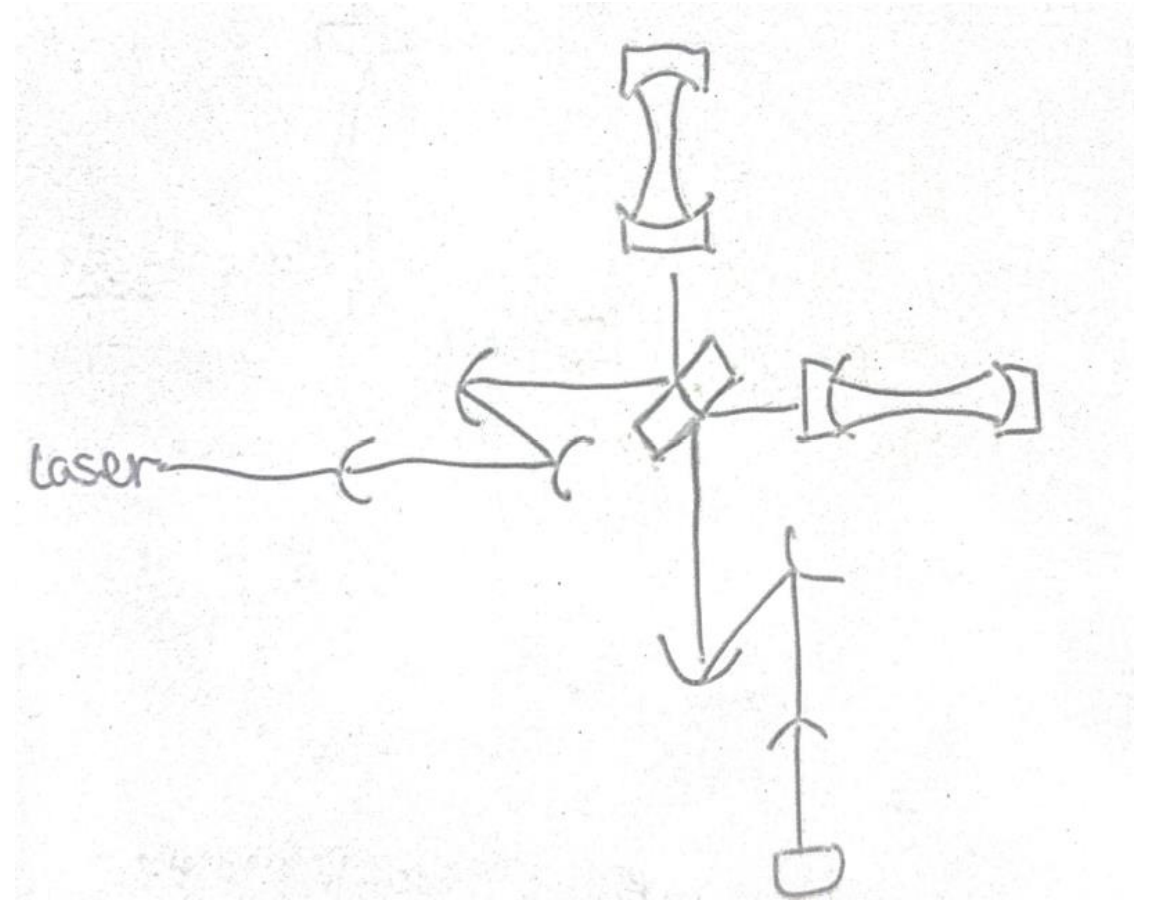
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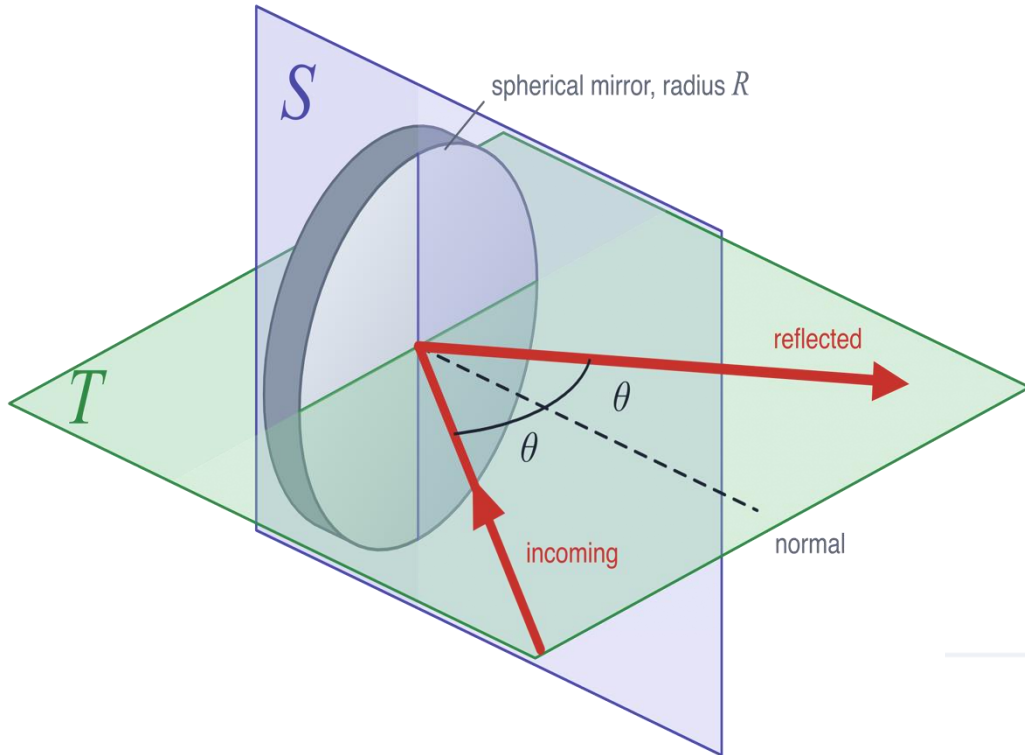
The O5 upgrade

- Folded, stable recycling cavities: 25° Gouy phase in the PRC, 18° in the SRC.
- Allows higher input power: 13 W $\rightarrow$ 80 W.
- Expected factor ~ 3 sensitivity gain at 100 Hz: BNS range 55 $\rightarrow$ ~ 150 Mpc.

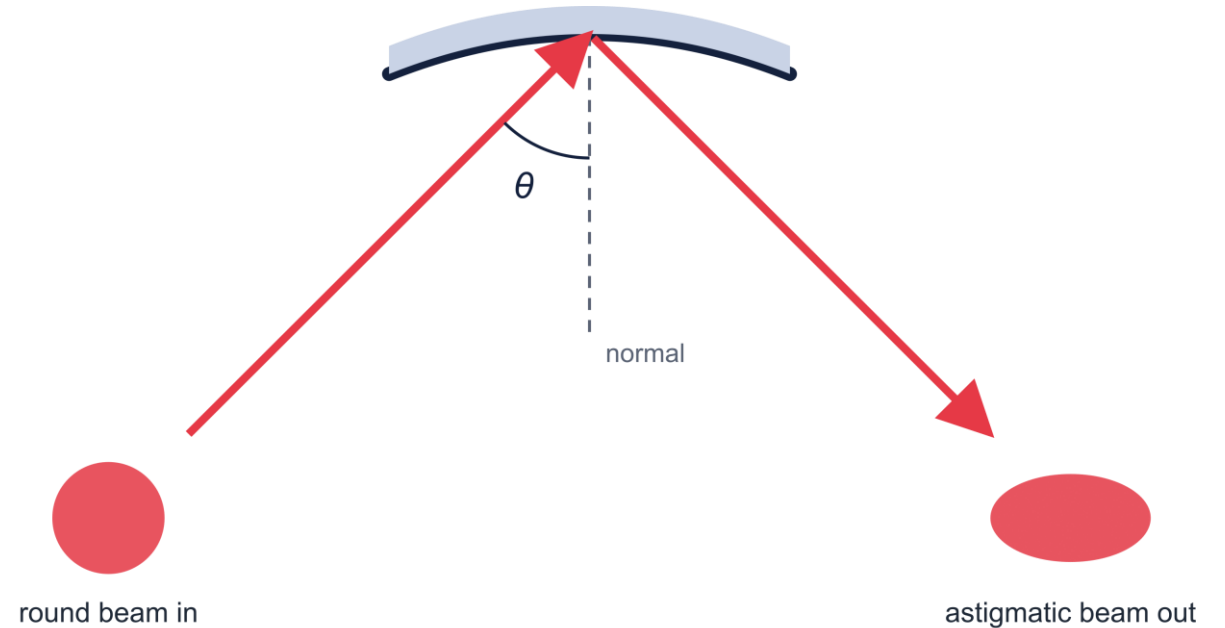


Astigmatism arising from angle of incidence

(a) Tangential and sagittal planes



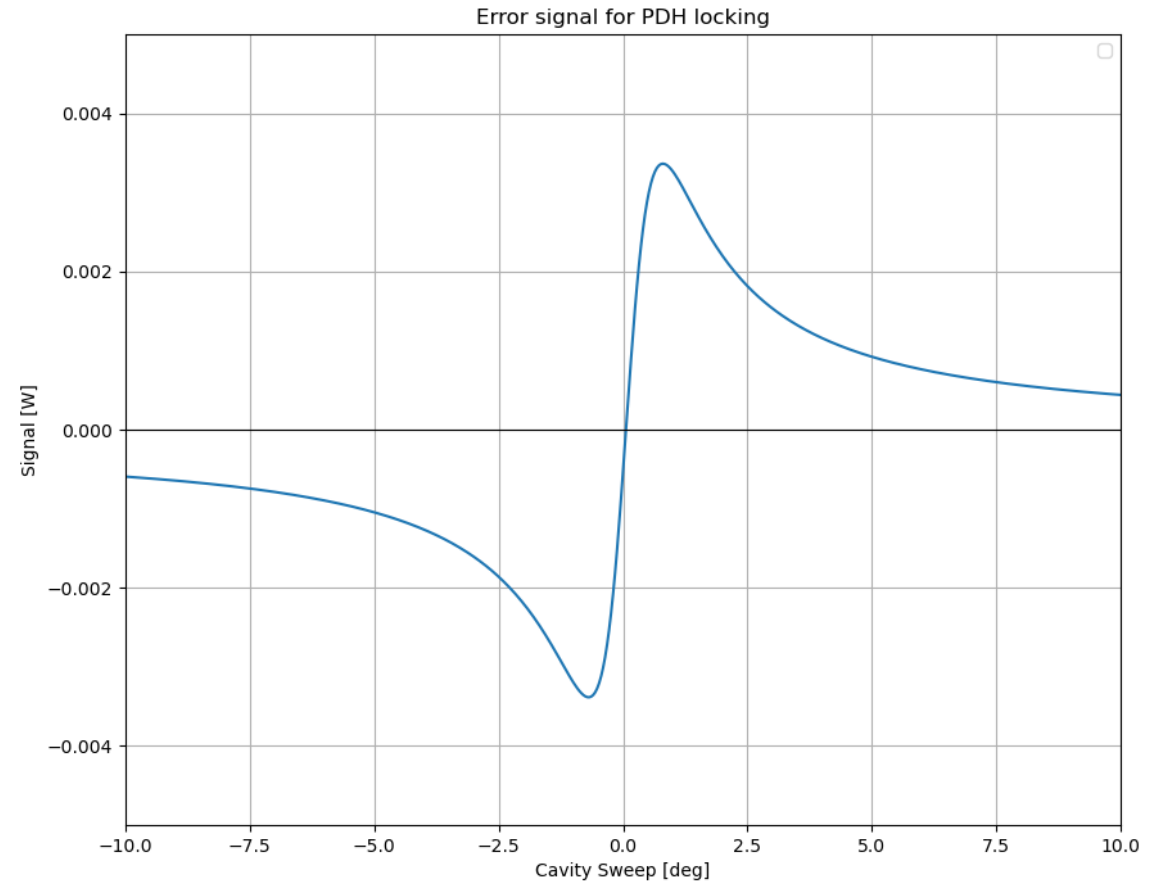
(b) Power leaks from HG_{00} to 2nd order modes



Potential risks

From geometric defects to control-loop degradation

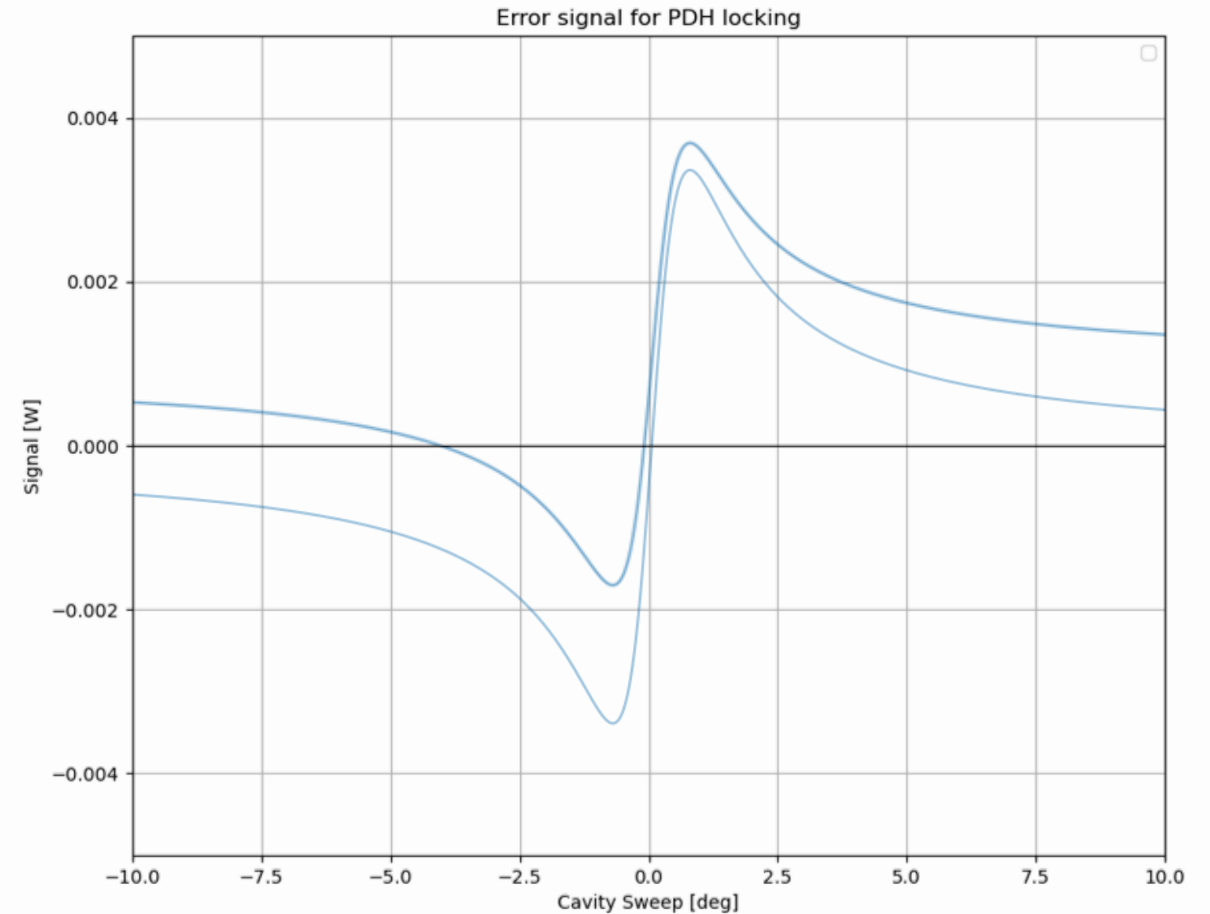
- Nominal AOI design: within the tolerances
- Longitudinal error signals
- Shot noise
- Alignment signals and angular control
- Cross coupling of dofs
- Real world: effects from mirror RoC defects and thermal effects
- Resulting controllability unstudied



Potential risks

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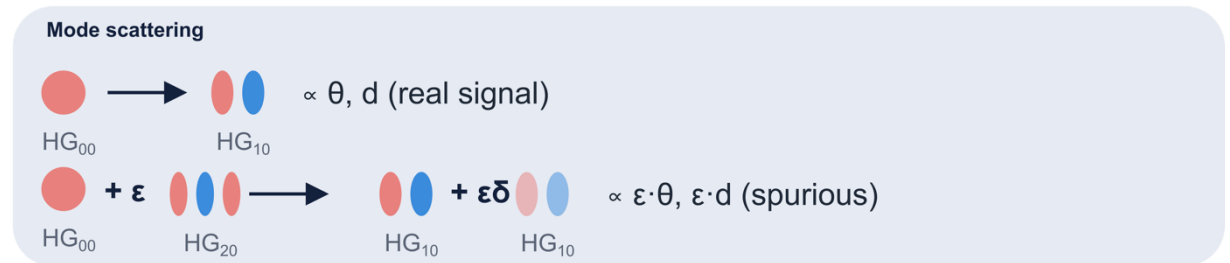
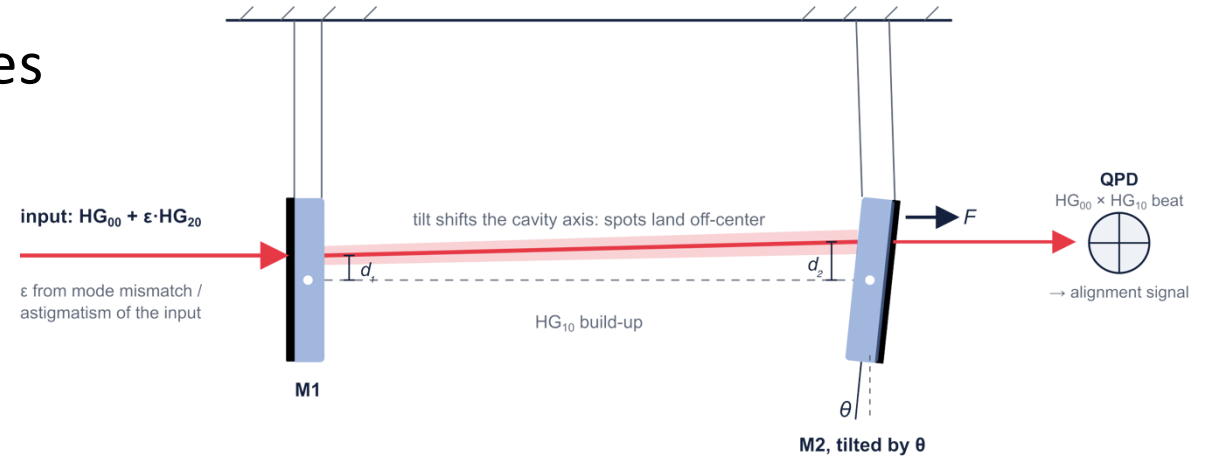
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Our work frame

A Finesse-based pipeline, with astigmatism as the first testbed

Parameter space

- Aol
- Radii of curvature
- Longitudinal compensation
- Beam decentering
- Residual displacement
- Misalignment
- Defects

Optical response

- Frequency response of every sensor to every degree of freedom
- Full sensing scheme and cross-couplings.

Closed-loop model

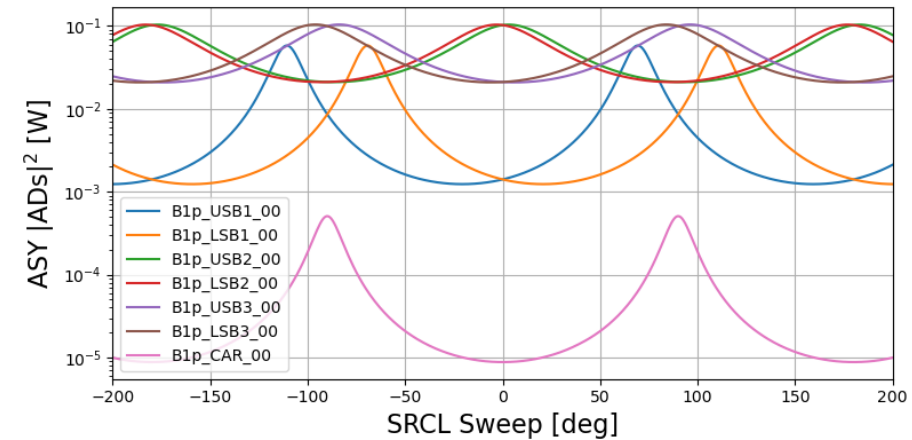
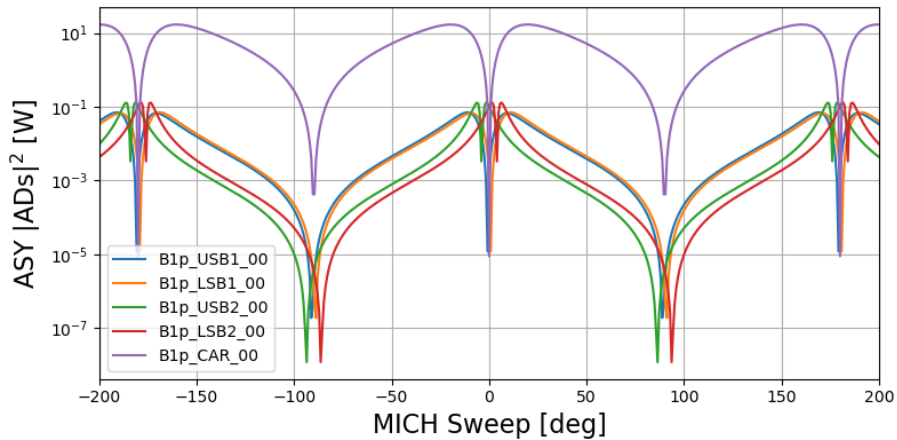
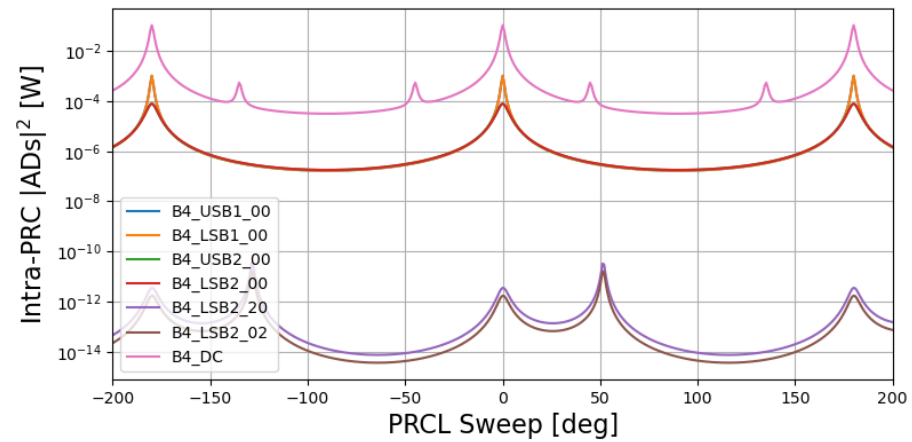
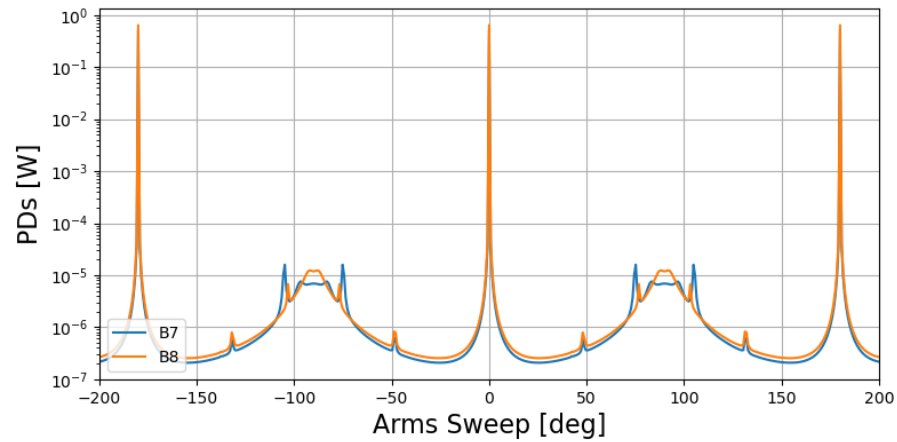
- Suspensions
- Control filters
- Optimise filters
- Characterise open-loop phase margins

Integration

- High power
- Thermal effects
- Full IFO scale

Results to-date

Checking the working points with nominal AOIs

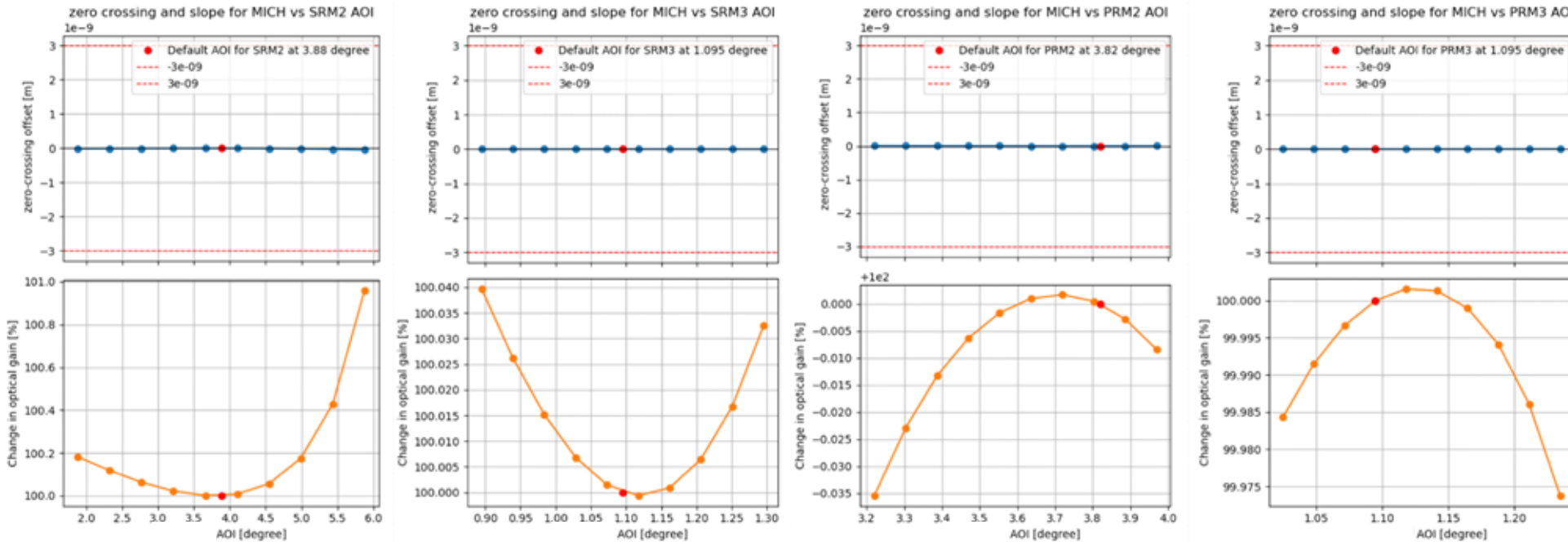
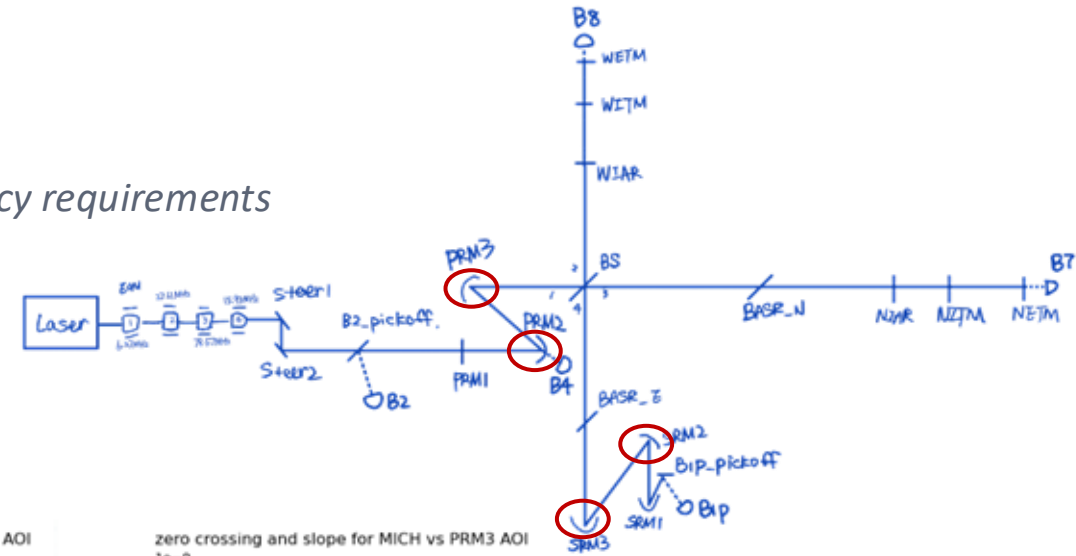


Results to-date

Tuning AOIs of each recycling mirror to cross check with the longitudinal accuracy requirements

PRCL	MICH	SRCL
$5 \times 10^{-11} \text{ m}$	$3 \times 10^{-9} \text{ m}$	$6 \times 10^{-9} \text{ m}$

[1,2]

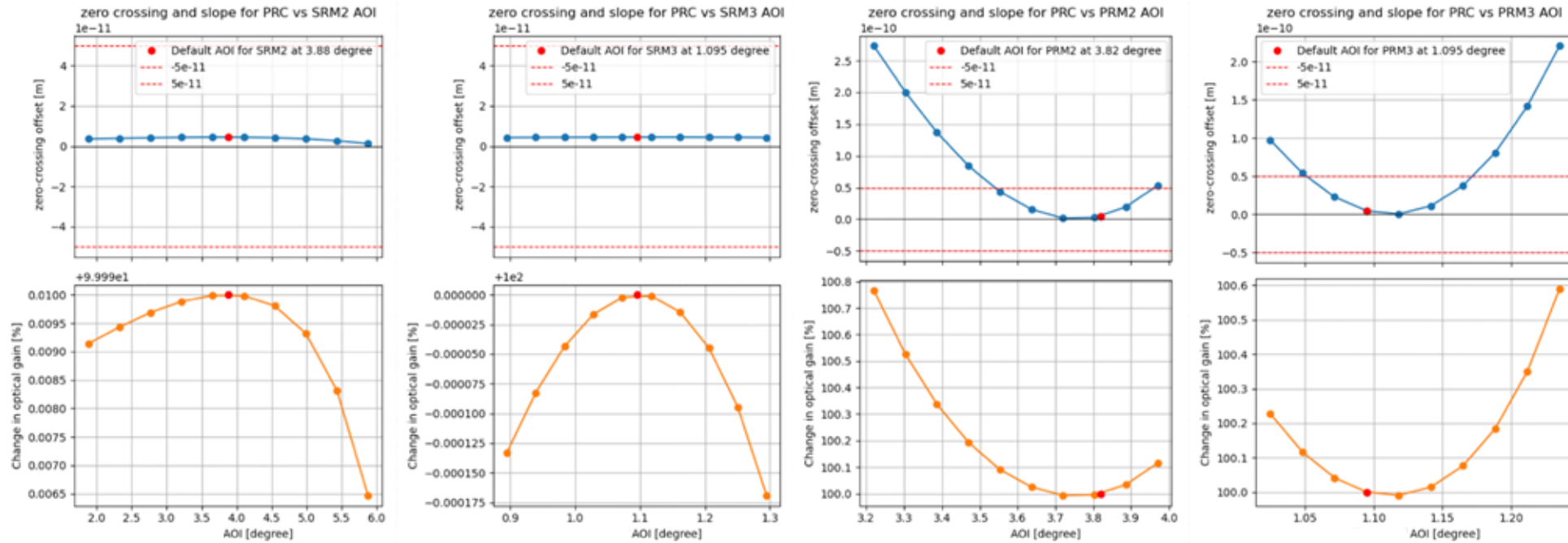
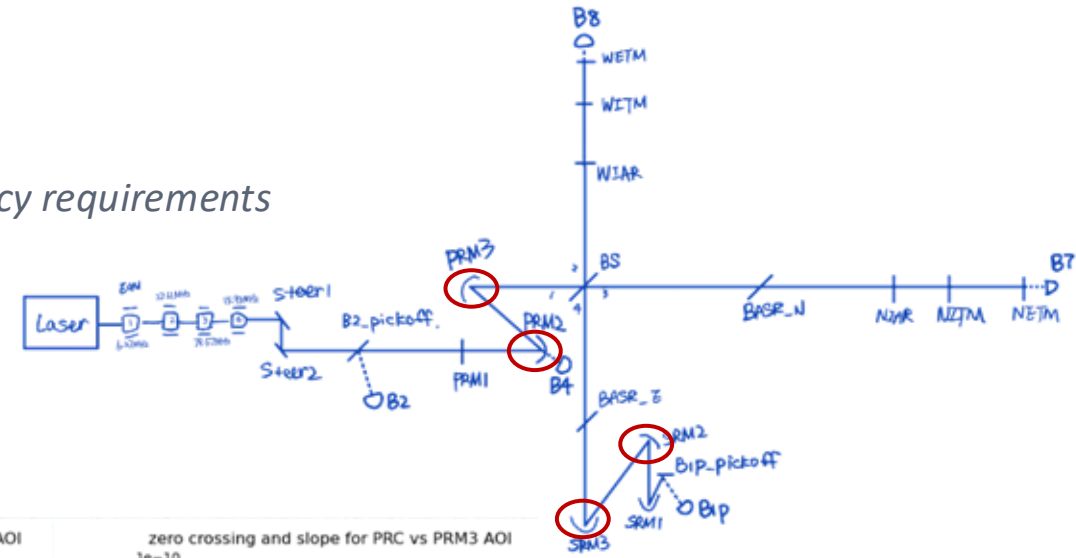


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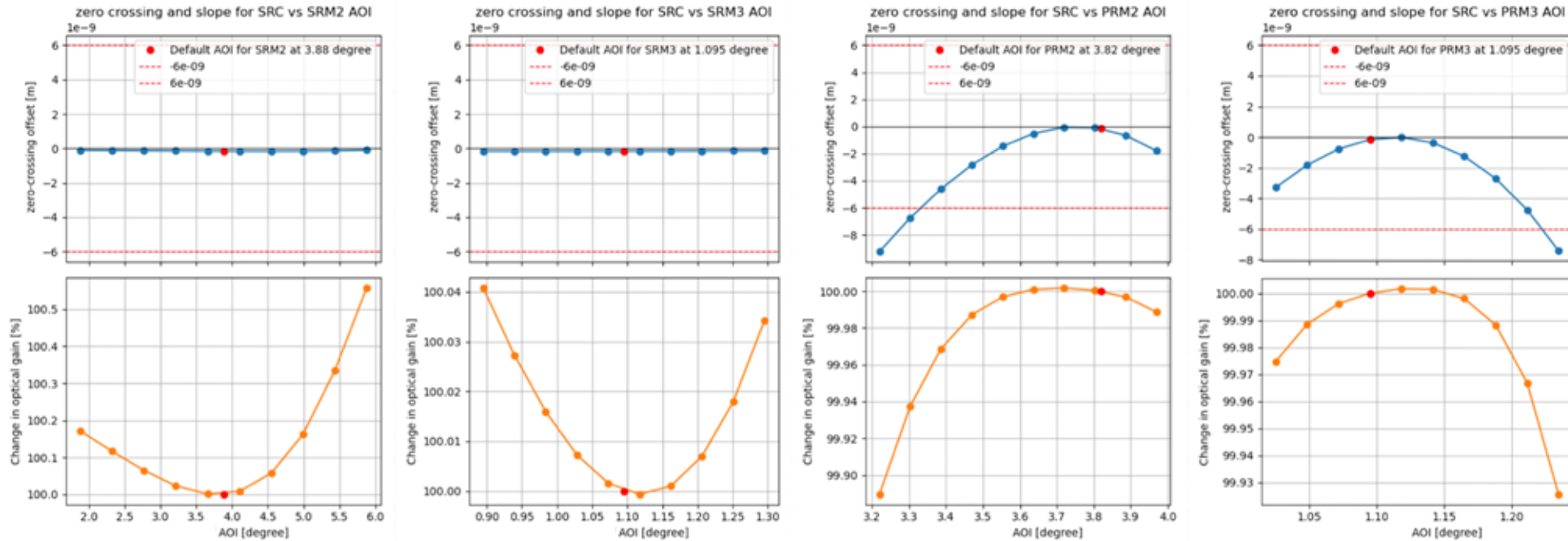
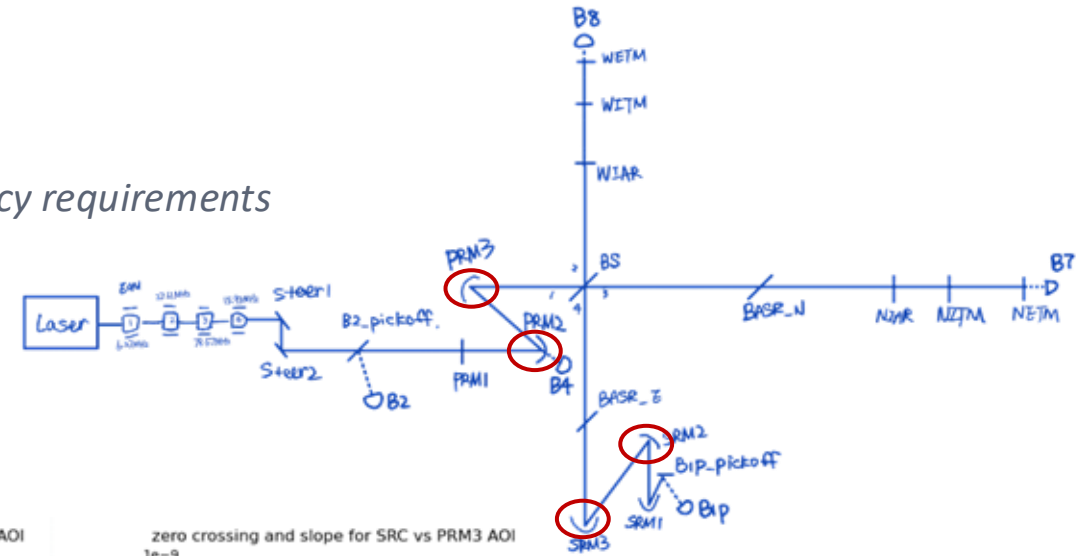


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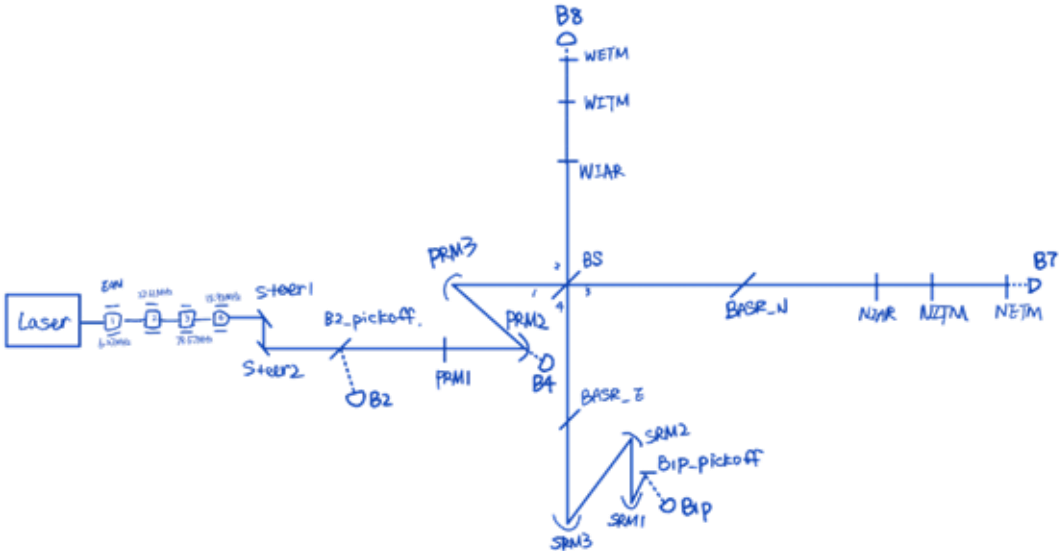


Results to-date

Tuning ROCs of each recycling mirror to cross check with the tolerances

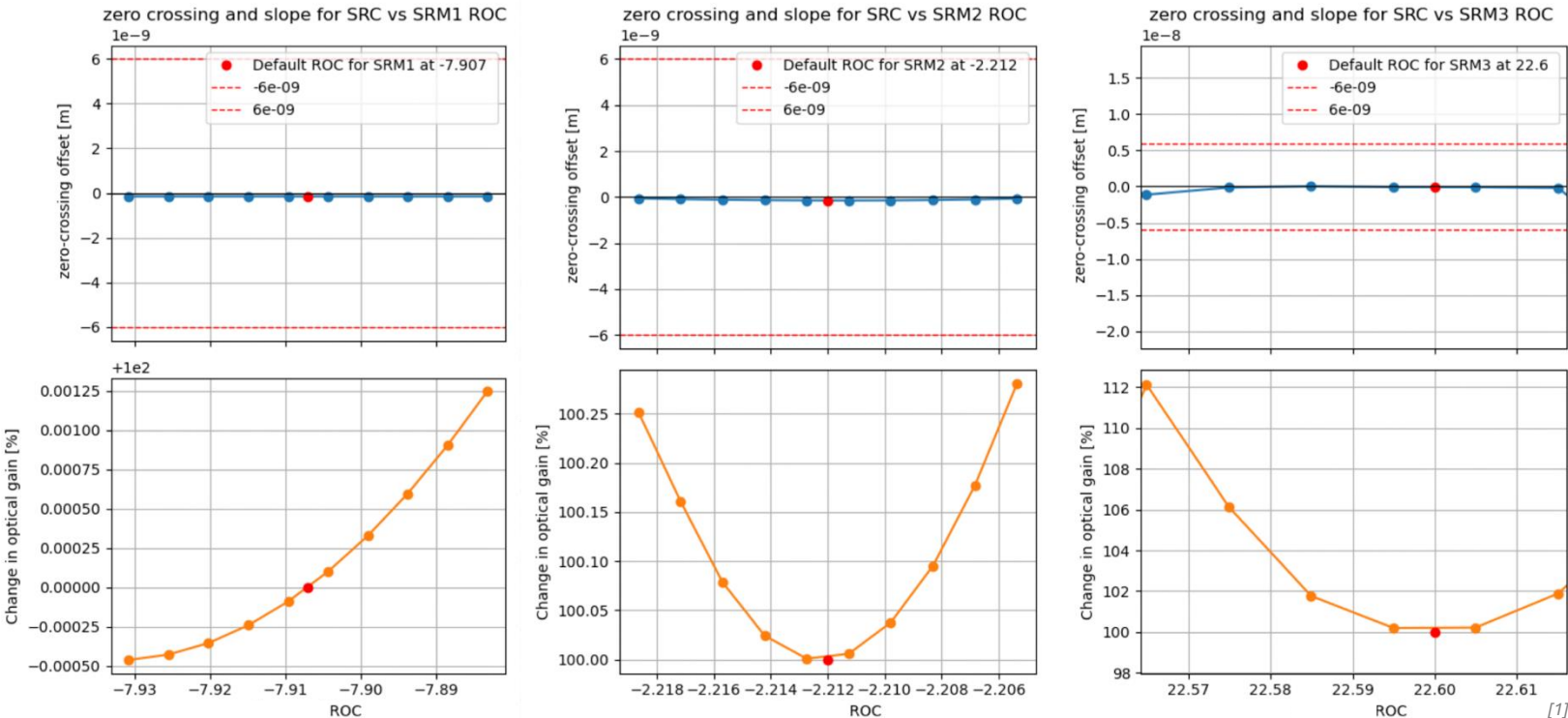
[1,2]

Mirror	SRM1	SRM2	SRM3
RoC tolerance	$\pm 0.3\%$	$\pm 0.3\%$	$\pm 0.2\%$



Changing Rcx only

SRM1	$\pm 0.3\%$
SRM2	$\pm 0.3\%$
SRM3	$(-0.155\%, 0.007\%)$



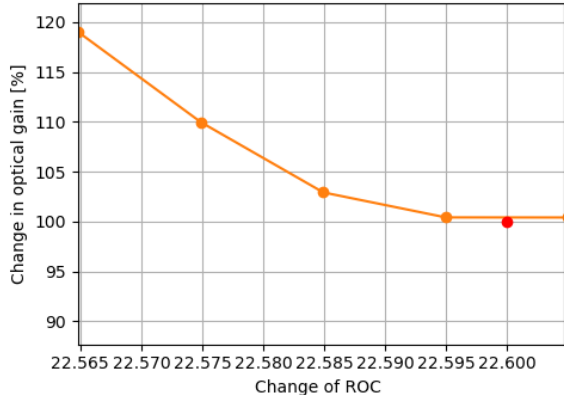
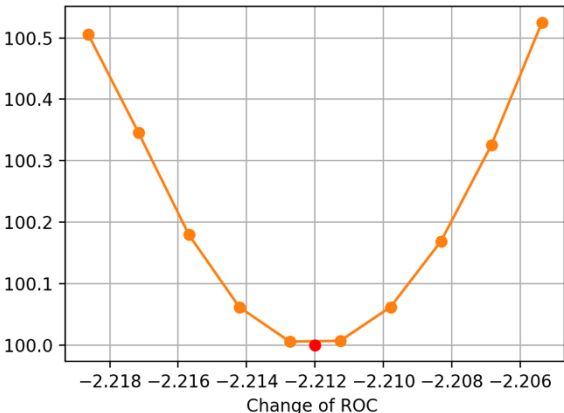
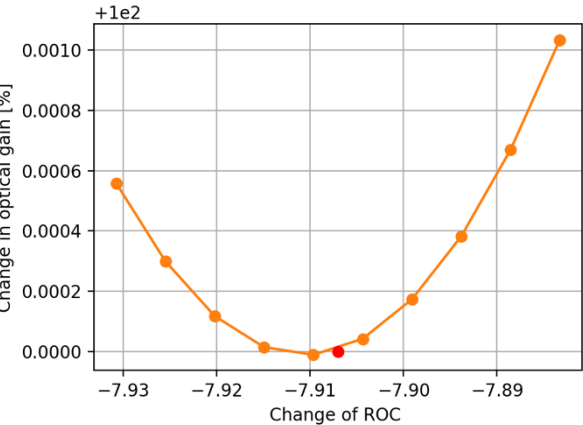
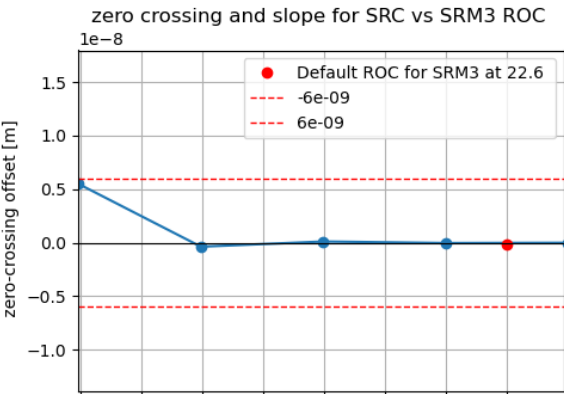
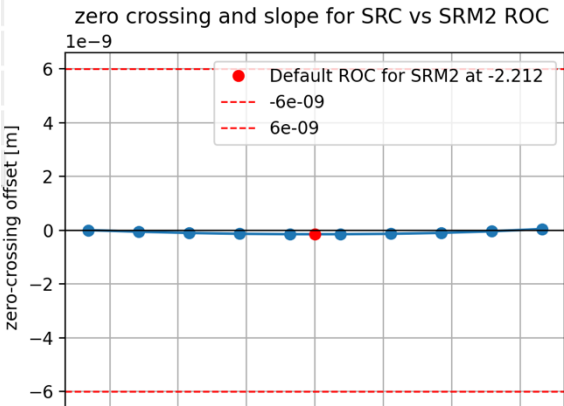
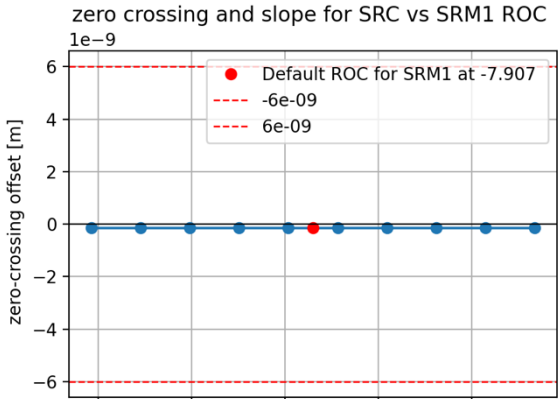
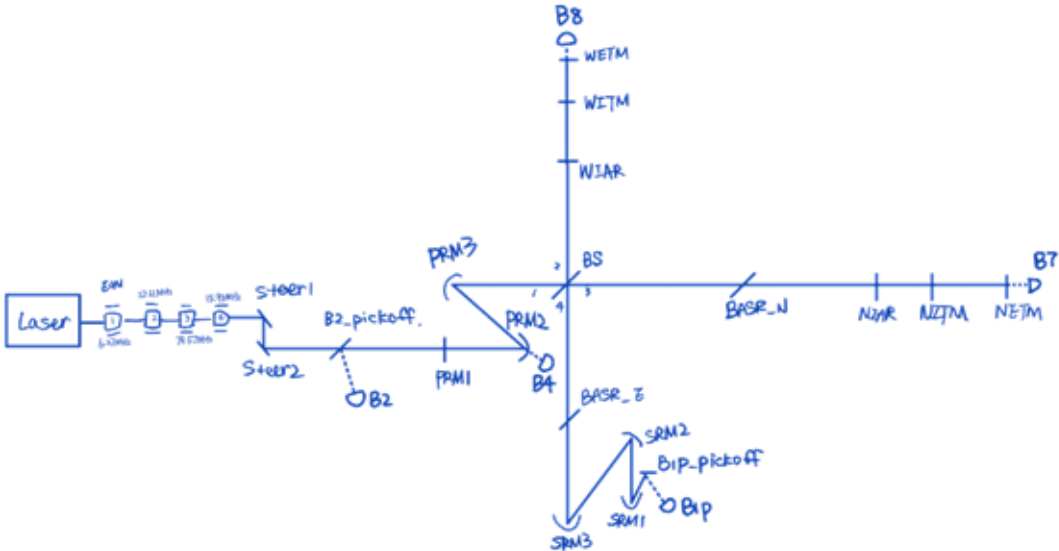
[1] M. Valentini, "The longitudinal control for the Advanced Virgo Plus gravitational wave detector", VIR-0064A-23
[2] M. Boldrini et al. "Total accuracy requirement offset refinement in the longitudinal directions", VIR-0644A-25

Results to-date

Tuning ROCs of each recycling mirror to cross check with the tolerances

[1,2]

Mirror	SRM1	SRM2	SRM3
RoC tolerance	$\pm 0.3\%$	$\pm 0.3\%$	$\pm 0.2\%$



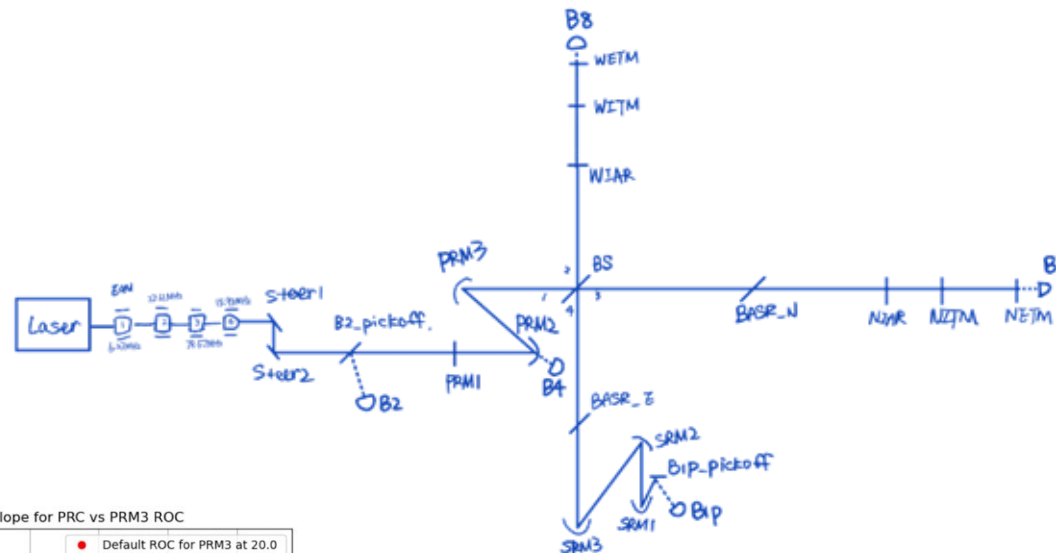
Changing RoC

SRM1	$\pm 0.3\%$
SRM2	$\pm 0.3\%$
SRM3	$(-0.154\%, 0.002\%)$

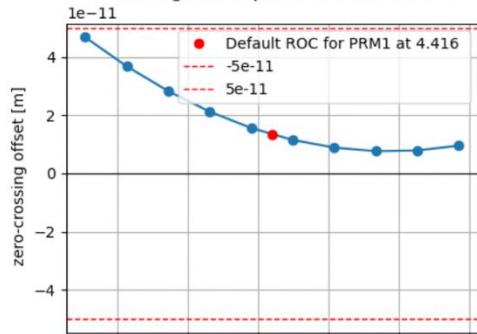
Results to-date

Tuning ROCs of each recycling mirror to cross check with the tolerances [1,2]

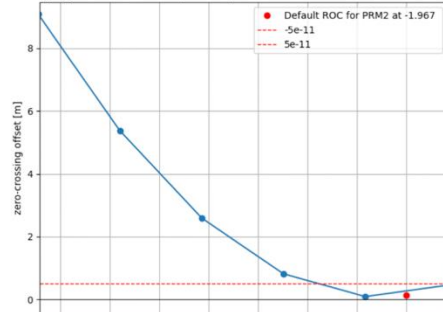
Mirror	PRM1	PRM2	PRM3
RoC tolerance	$\pm 0.3\%$	$\pm 0.3\%$	$\pm 0.2\%$



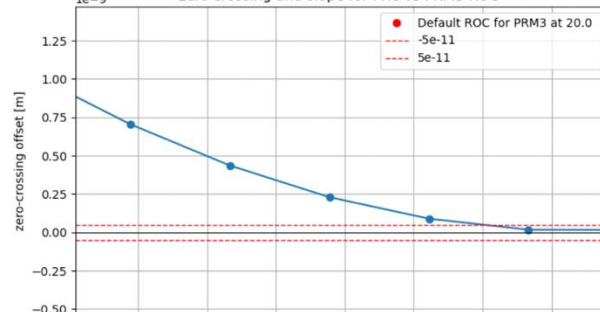
zero crossing and slope for PRC vs PRM1 ROC



zero crossing and slope for PRC vs PRM2 ROC

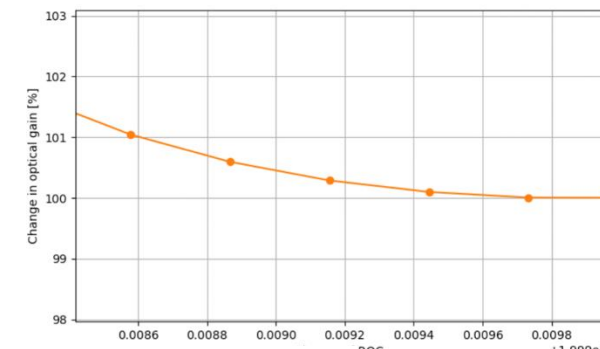
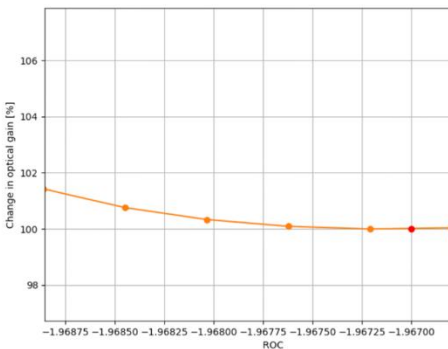


zero crossing and slope for PRC vs PRM3 ROC



Changing Rcx only

PRM1	$\pm 0.3\%$
PRM2	(-0.09% , 0.01%) for stability (-0.03%, 0.00025%) for tol
PRM3	(-0.0085%,0.0015%) for stability (-0.002%,0.00085%) for tol

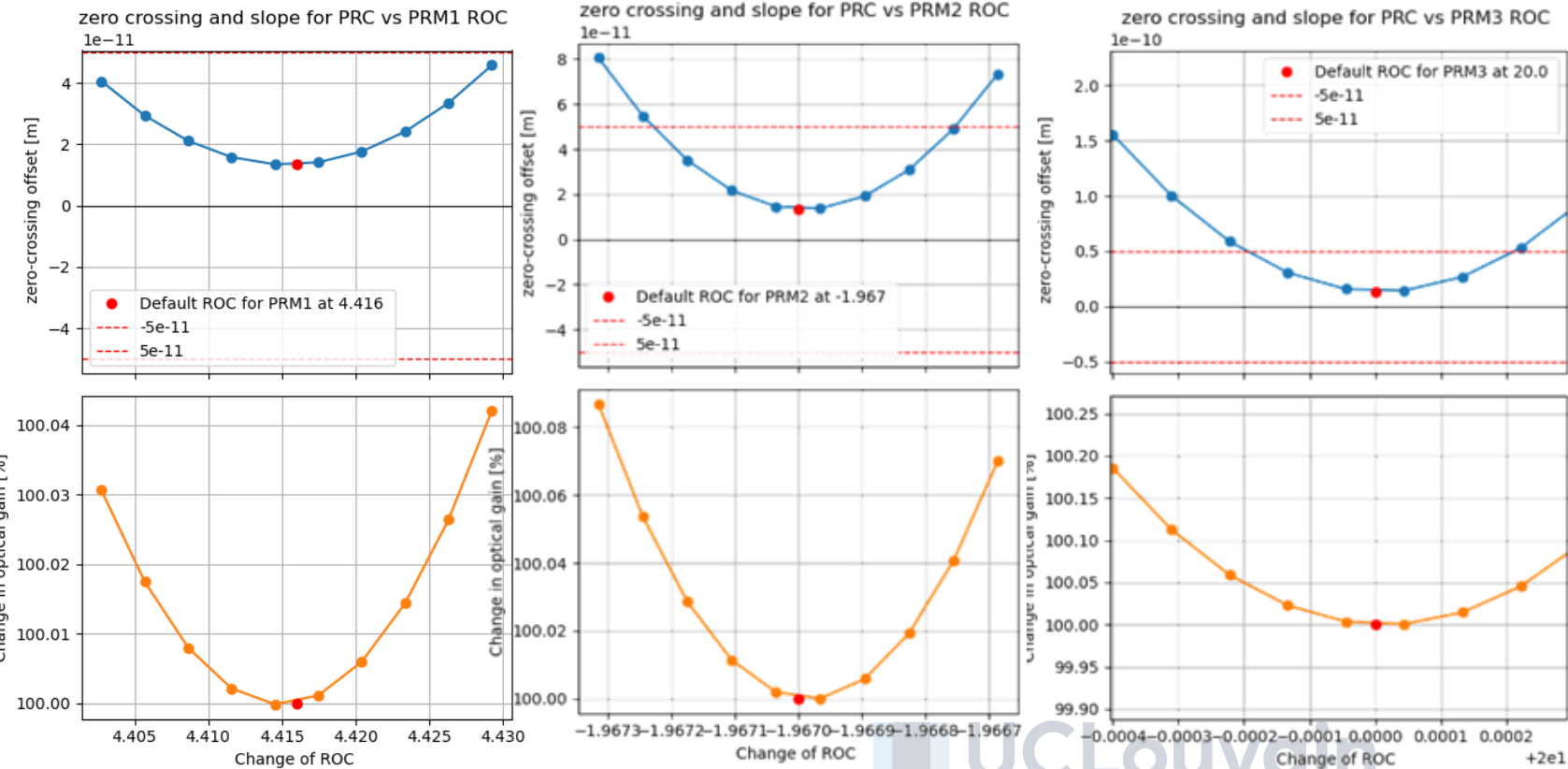
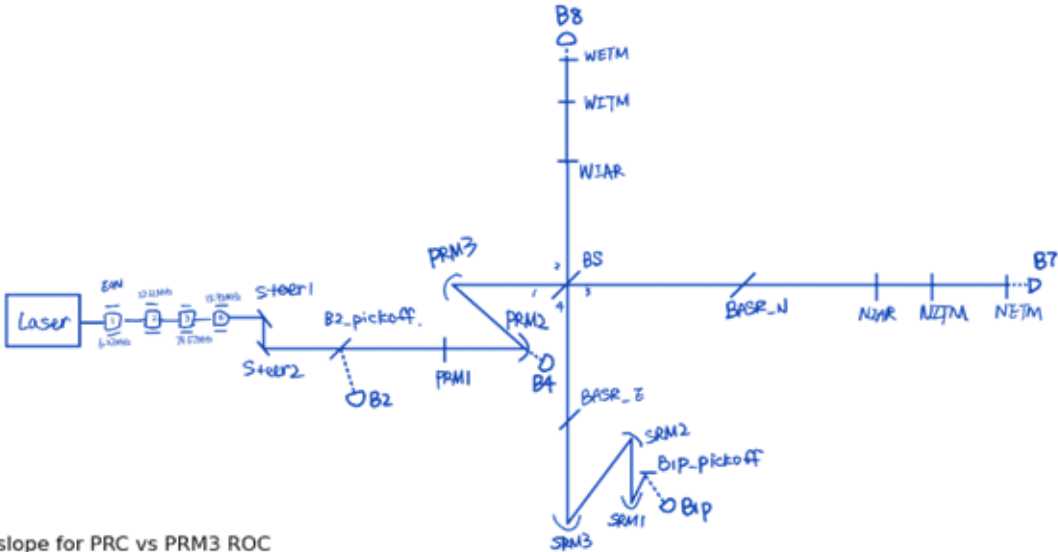


Results to-date

Tuning ROCs of each recycling mirror to cross check with the tolerances

Mirror	PRM1	PRM2	PRM3
RoC tolerance	$\pm 0.3\%$	$\pm 0.3\%$	$\pm 0.2\%$

[1,2]



Changing RoC

PRM1	$\pm 0.3\%$
PRM2	± 0.012 for tol
PRM3	± 0.001 for tol

[1] M. Valentini, "The longitudinal control for the Advanced Virgo Plus gravitational wave detector", VIR-0064A-23

[2] M. Boldrini et al. "Total accuracy requirement offset refinement in the longitudinal directions", VIR-0644A-25

Next Steps

- Longitudinal compensation

