Cosmic Explorer Optical Design Status

Paul Fulda
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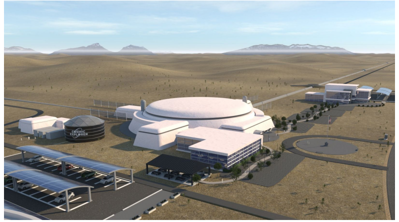
Jon Richardson
University of California, Riverside

On behalf of the CE Optical Design Team



CE Symposium – April 23, 2024

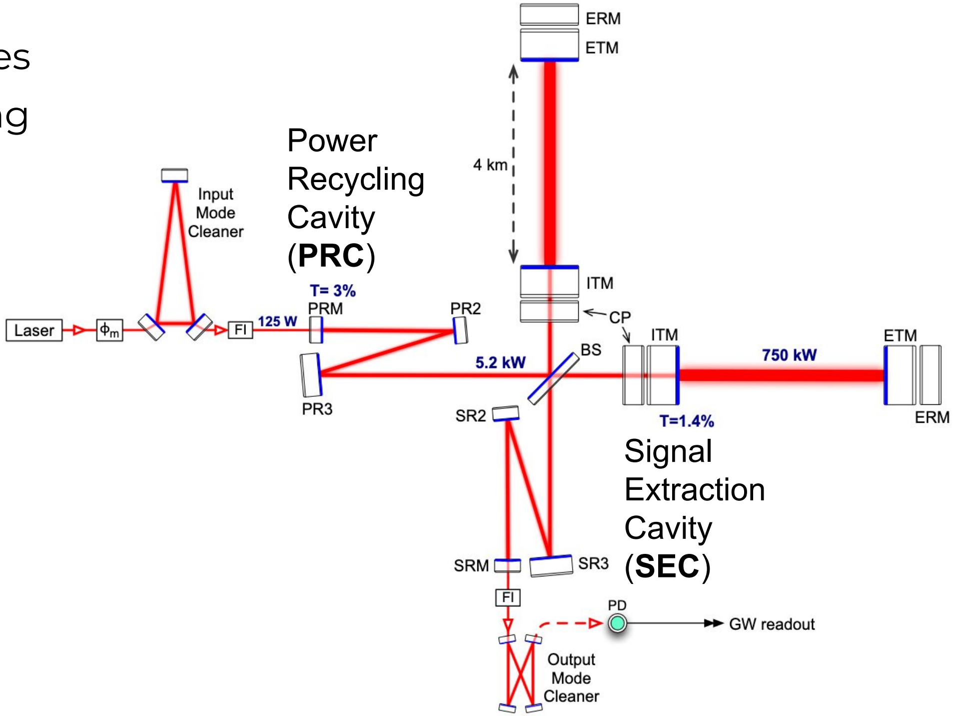
CE-G2400031

Upgrade Path for Fused-Silica Interferometers

LIGO O4 configuration:

- **~350 kW** laser power in the arm cavities
- **~ 5 dB** frequency-dependent squeezing

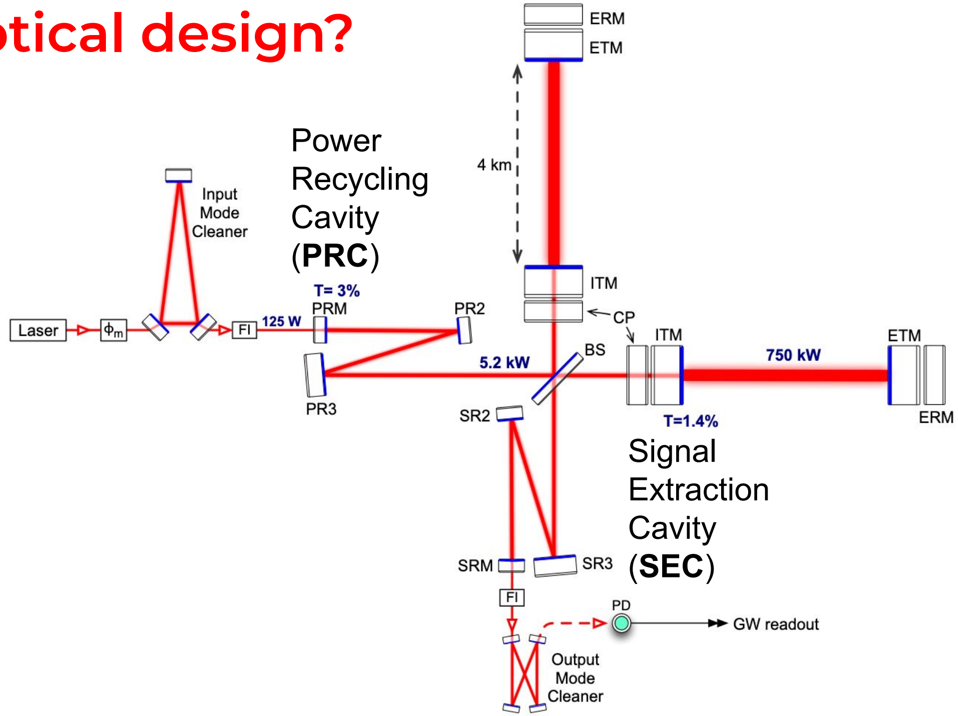
Quantity	A+ (O5)	A$^{\#}$ (O6)
Arm length (km)	4	4
Wavelength (nm)	1064	1064
Mirror mass (kg)	40	**100**
Mirror diameter (cm)	34	**46**
Arm power (MW)	0.8	**1.5**
Squeezing (dB)	6	**10**



Upgrade Path for Fused-Silica Interferometers

Why not just scale up LIGO optical design?

Quantity	A+ (O5)	A# (O6)	CE
Arm length (km)	4	4 →	**40**
Wavelength (nm)	1064	1064	1064
Mirror mass (kg)	40 →	**100** →	**320**
Mirror diameter (cm)	34 →	**46** →	**70**
Arm power (MW)	0.8	**1.5**	**1.5**
Squeezing (dB)	6	**10**	**10**



Cosmic Explorer: Why Not Just Scale up LIGO Design?

1) Unique challenges arise from a 10x longer arm length (CE-G2300033)

- Minimum beam size for 40 km arms is ~12 cm. For < 1 ppm clipping loss on ITMs, require **~70 cm ITMs**. Beamsplitter should be **√2 bigger*** (at 45° AOI). *1 m diameter unfeasible?*
  - ➥ Consider alternate layouts with a **different beamsplitter location**
- SEC resonance **approaches detection band** with 40 km or 20 km arms ($f_s \propto 1/\sqrt{L_s}$)
  - ➥ SEC length must be kept to **< 200 m** (40 km arms) or **< 90 m** (20 km arms)
- FSR of 40 km arms is 3.75 kHz. With same arm finesse, **DARM pole is 10x lower** ($f_p \propto 1/L_a$)
  - ➥ Need **10x higher SEC finesse** to recover same bandwidth

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  - ➥ Need **10x higher SEC finesse** to recover same bandwidth
- With a 10x lower arm cavity FSR, **nearly all higher-order mode (HOM) resonances will lie in the observation band**
  - ➥ **Precision mode-matching** is critical to suppress noise couplings, squeezing loss, and squeezing angle mis-rotation around the frequencies of these resonances

Impact of SEC Mode-Mismatch

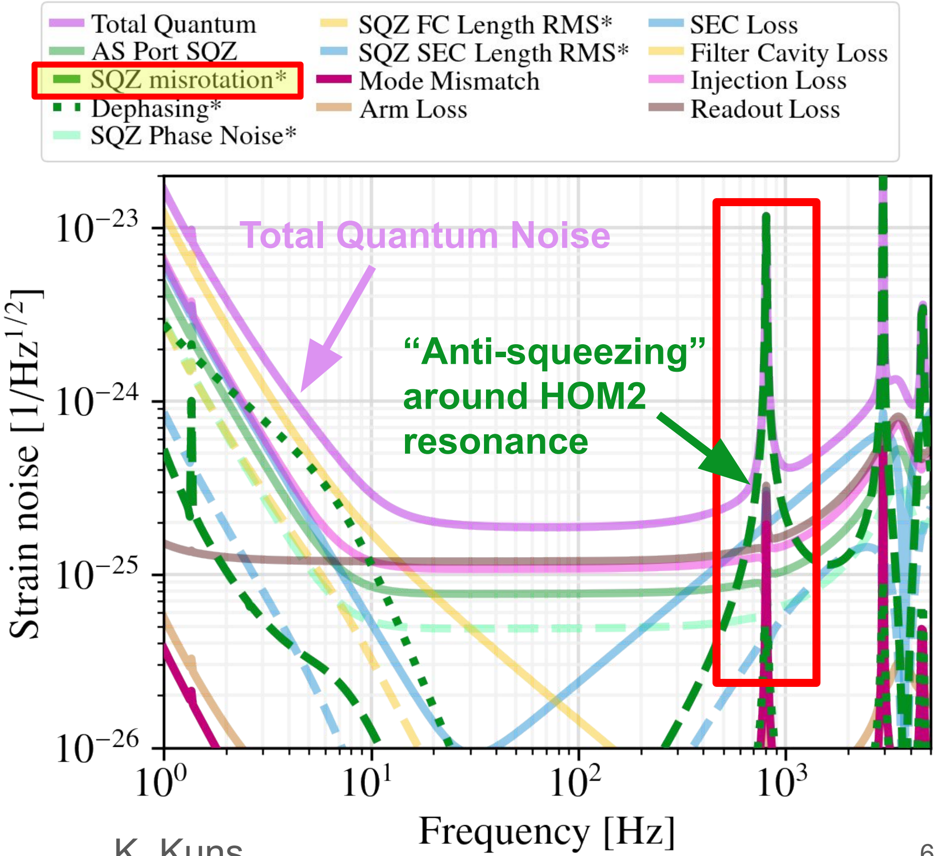
In-band HOM resonances lead to a **coherent mode-scattering** effect:

TEM00 → LG10 → TEM00*

*having accumulated a *different* phase relative to the unscattered TEM00 field (see McCuller *et al.* 2021)

Results in an **effective rotation of the squeezing angle** relative to the interferometer's readout quadrature ("anti-squeezing") at frequencies near HOM resonances

Example Quantum Noise Budget
with 1% SEC mode-mismatch to arms



K. Kuns

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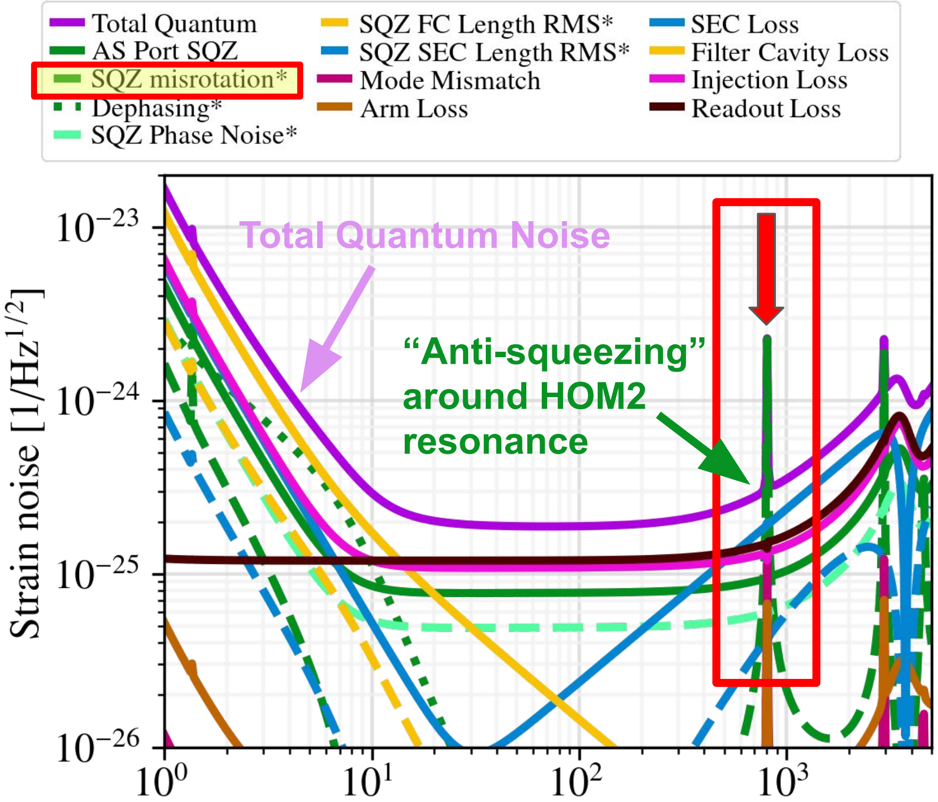
Example Quantum Noise Budget with 0.1% SEC mode-mismatch to arms



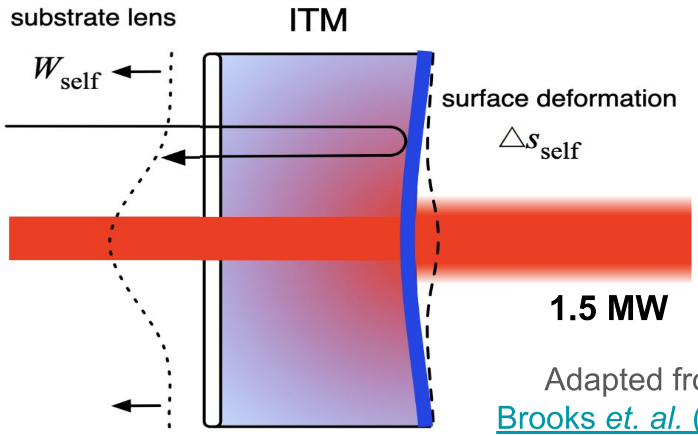
K. Kuns

Cosmic Explorer: Why Not Just Scale up LIGO Design?

2) Thermal distortions are a <u>much</u> stronger design driver (LIGO-G2300624)

CE's quantum noise target assumes:

- **1.5 MW** of circulating arm power
  4x higher than aLIGO O4
- **10 dB** of frequency-dependent squeezing
  - Requiring **< 500 ppm** SEC loss
    10x lower than LIGO A+



Adapted from Brooks *et. al.* (2016)

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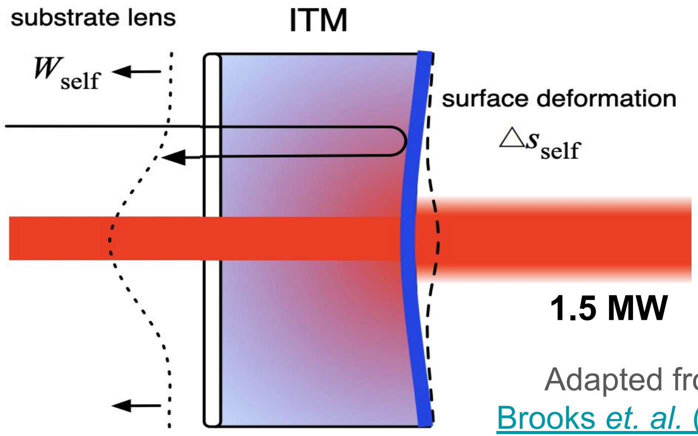


Adapted from Brooks *et. al.* (2016)

Overcoming thermal distortions requires:

- Pick-off port locations to **directly sense mode-matching** between cavities
- Cavity **Gouy phases** chosen to minimize impact on squeezing (avoid HOM co-resonances)
- **Higher-precision wavefront control**, beyond radius of curvature correction

Does 500 ppm SEC Loss Preclude 45° Beamsplitter AOI?

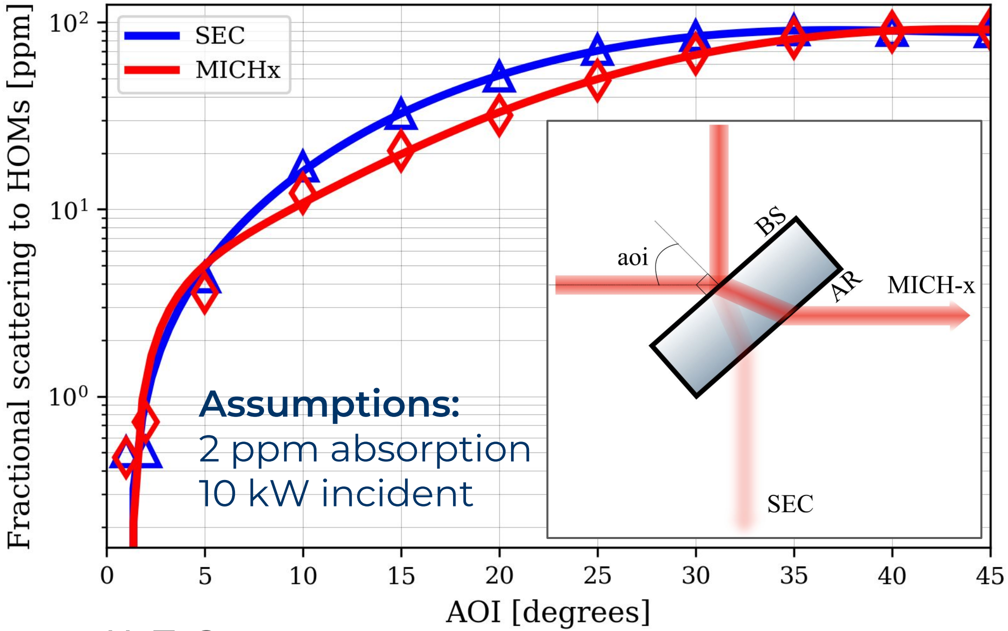
With ~10 kW in the PRC, **thermal lensing in the beamsplitter** substrate is a significant effect

- Uncompensated HOM scattering loss could consume the majority of the SEC loss budget
- But limited capability to thermally compensate at 45° AOI

Lower AOI on the beamsplitter:

- Improves the effectiveness of thermal compensation 100x
- Reduces the beamsplitter size requirement by a factor of √2

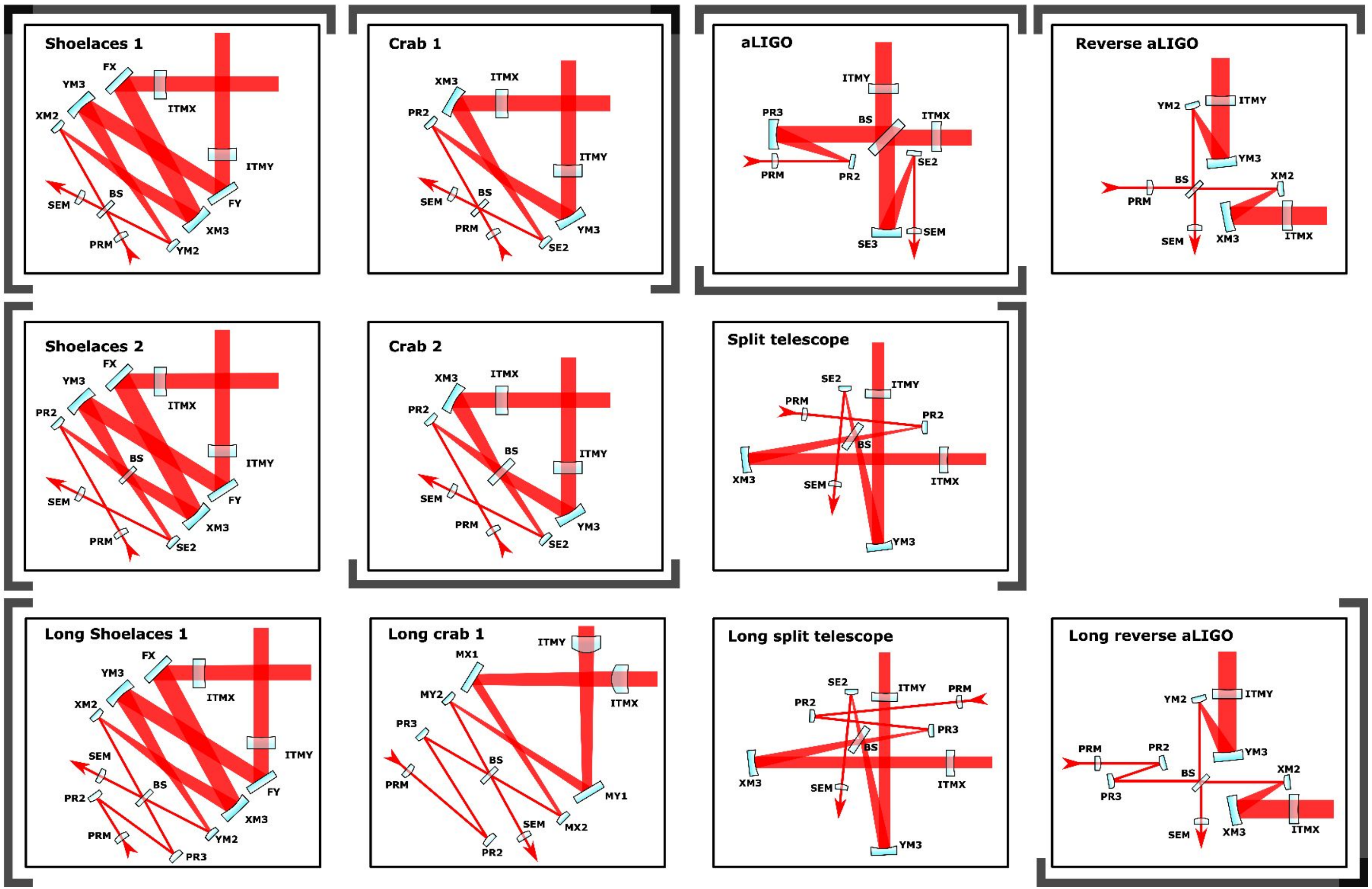
Single-Pass Beamsplitter HOM Scattering
with optimal thermal compensation



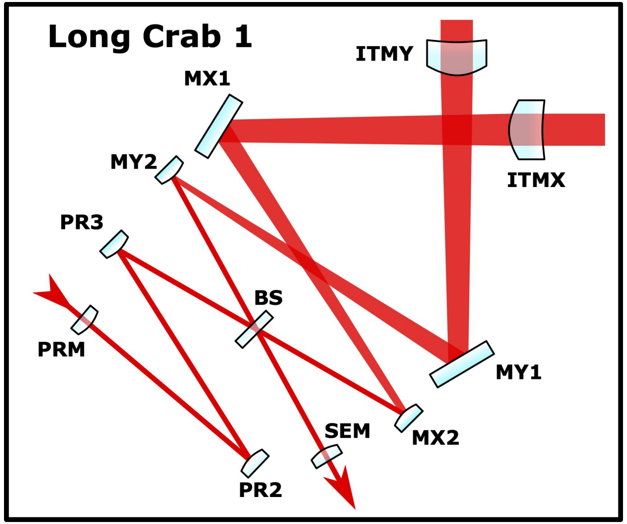
H. T. Cao

Considered Interferometer Topologies

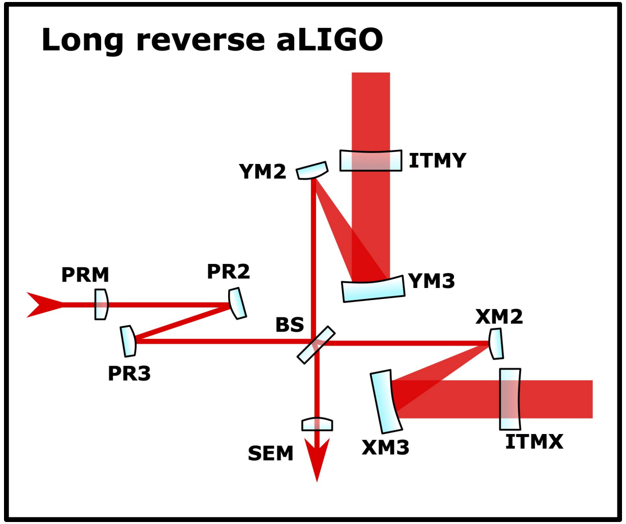
	Low AOI on beamsplitter		45deg AOI on beamsplitter	
	Extra folding mirror required	Needs toroidal M3 mirrors (~22 deg AOI)	No arm specific MSC actuators	Two arm specific MSC actuators
Two arm specific MSC actuators; One SEC/PRC specific MSC actuators; Beam collimated through BS	Shoelaces 1	Crab 1	aLIGO	Reverse aLIGO
One arm specific MSC actuator; Two SEC/PRC specific MSC actuators; Beam expanding through BS	Shoelaces 2	Crab 2	Split telescope	
Additional PRC optics for independent matching to arms	Long Shoelaces 1	Long crab 1	Long split telescope	Long reverse aLIGO



Favored CE Interferometer Topologies

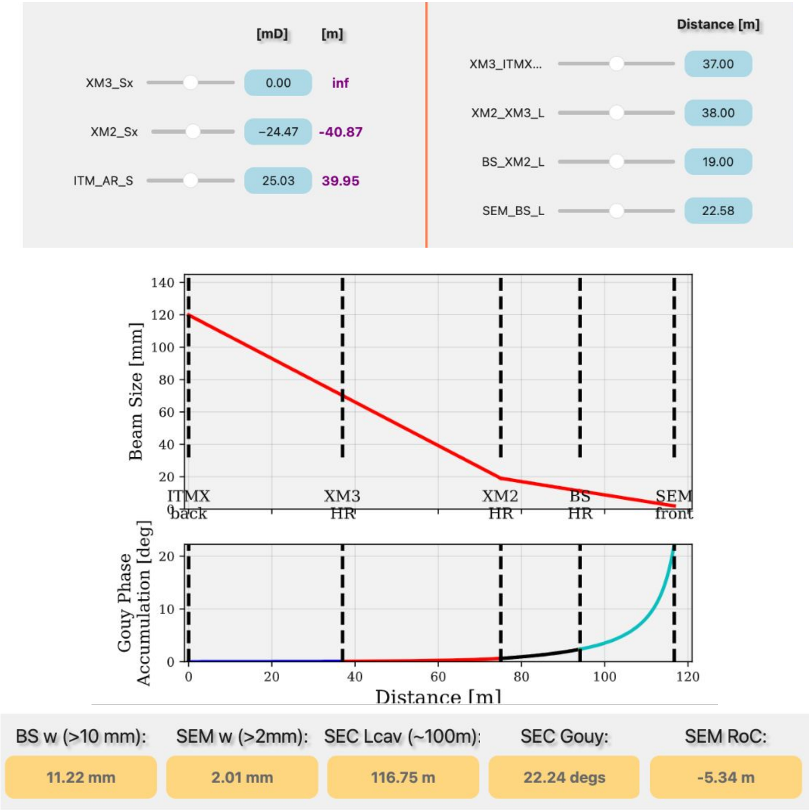


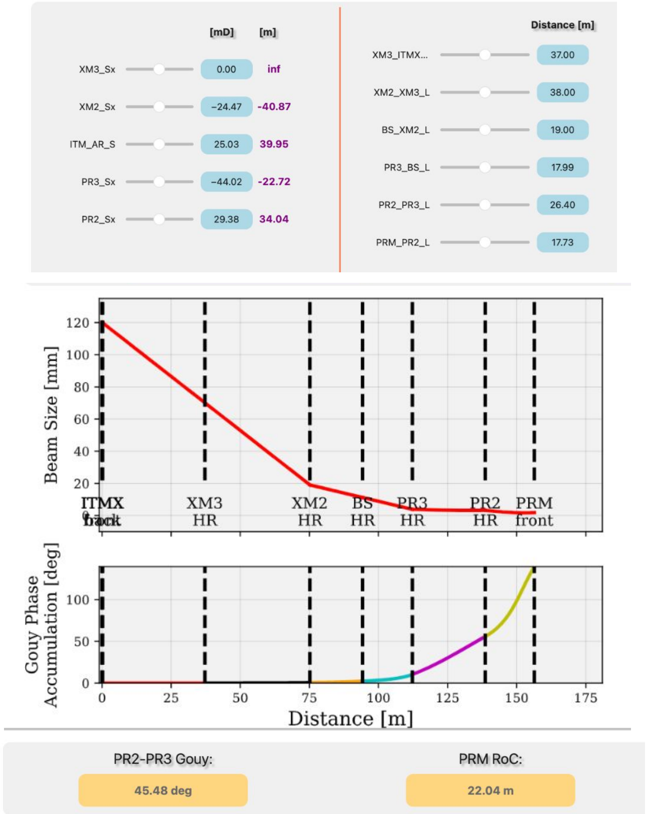
- ~1° beamsplitter AOI
- Static lens polished onto ITM AR surface



- 45° beamsplitter AOI
- Will benefit from static ITM lens.
- A lower-risk option, *if* beamsplitter thermal lensing is manageable

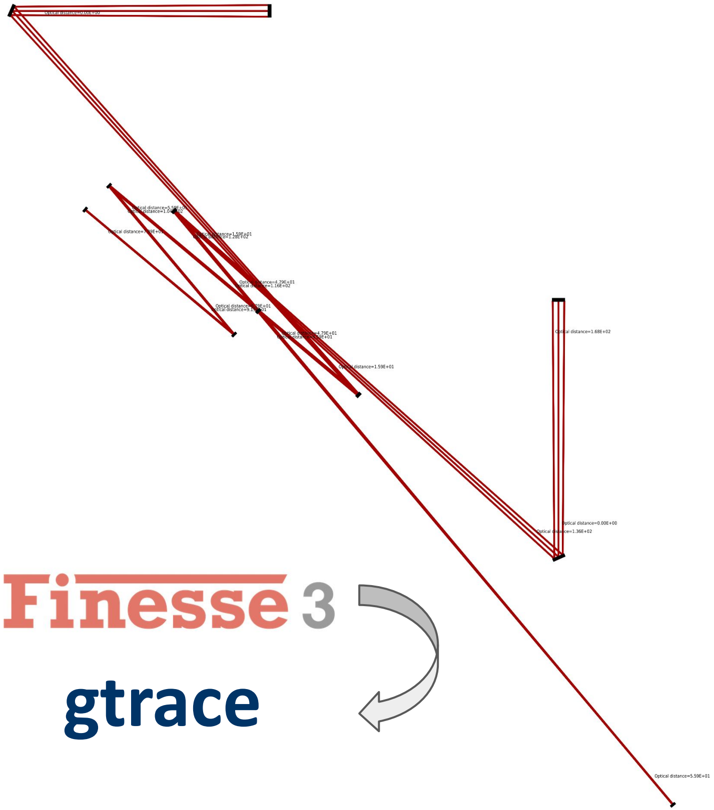
PRC and SEC design progress: eigenmodes





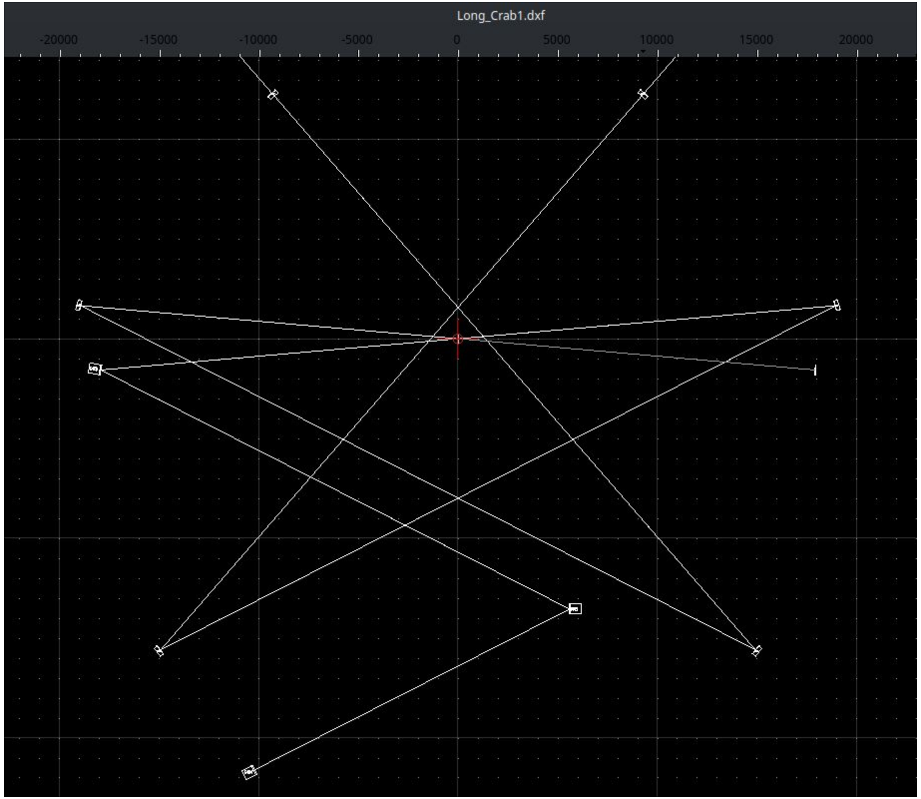
Work on this topic by Sagar Gupta, Liu Tao, Matt Todd, Kevin Kuns, ++

PRC and SEC design progress: geometric layout



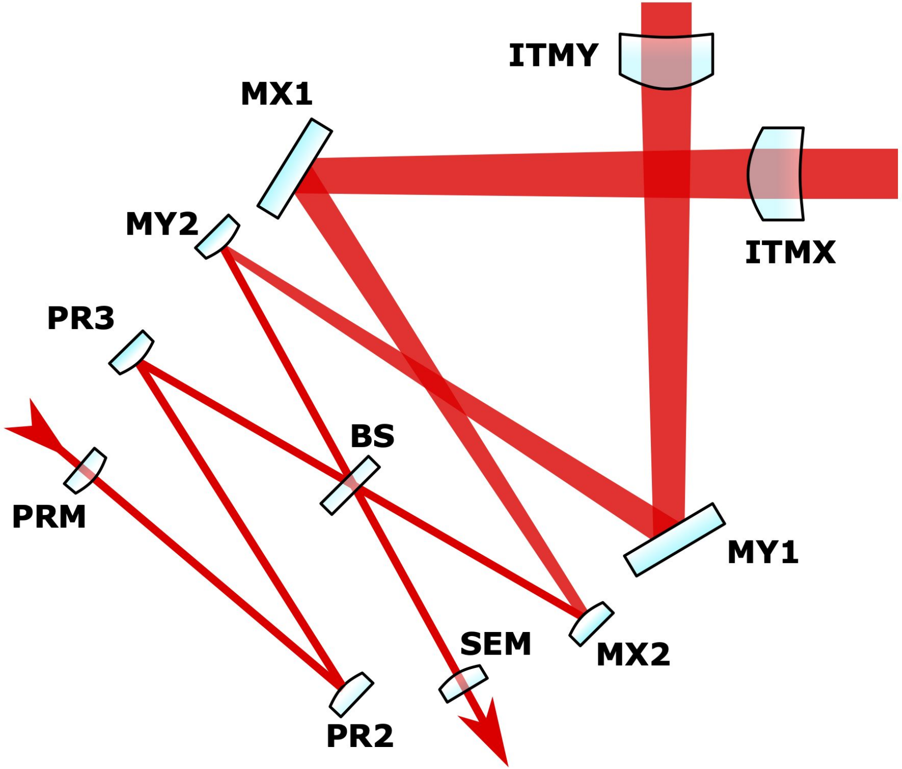
Finesse 3

gtrace



Work on this topic by Matt Todd and Pooyan Goodarzi

Concept for Next-Generation Thermal Compensation



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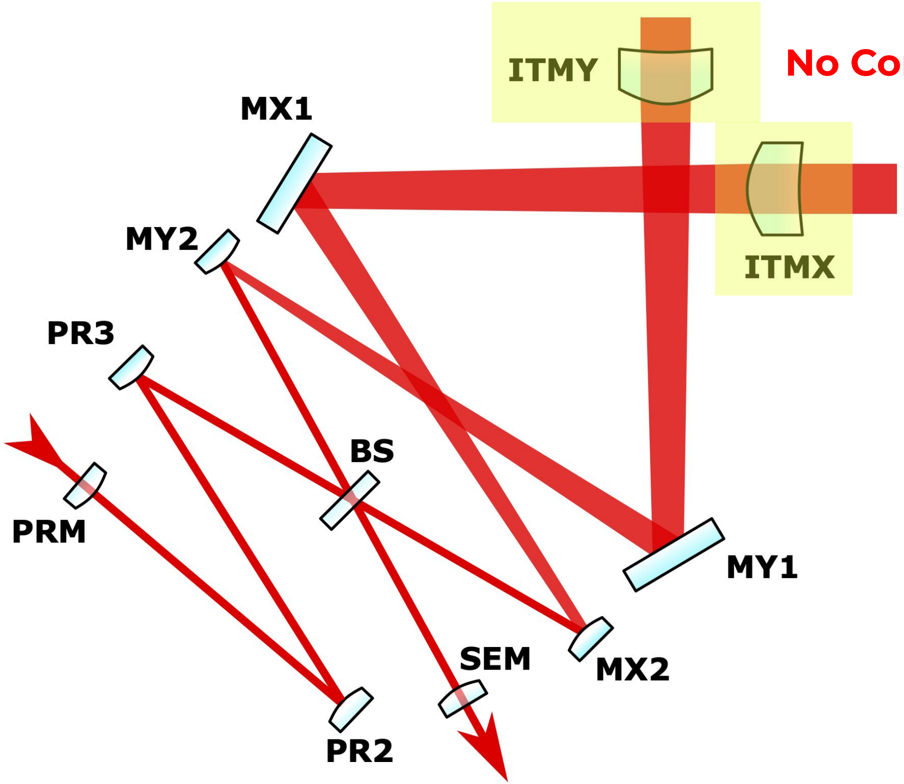
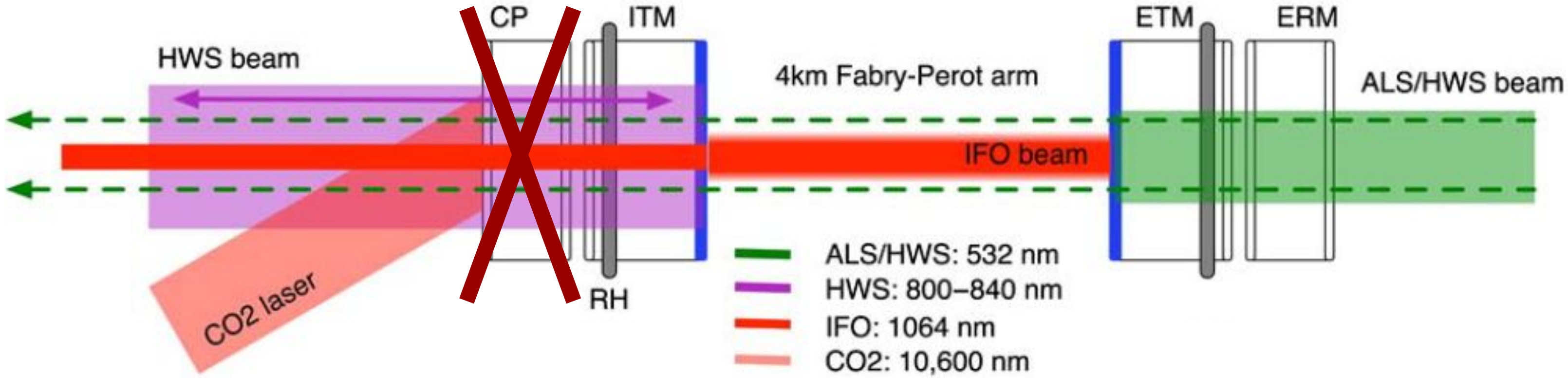


No Compensation Plates

500 ppm SEC Loss Precludes Compensation Plates

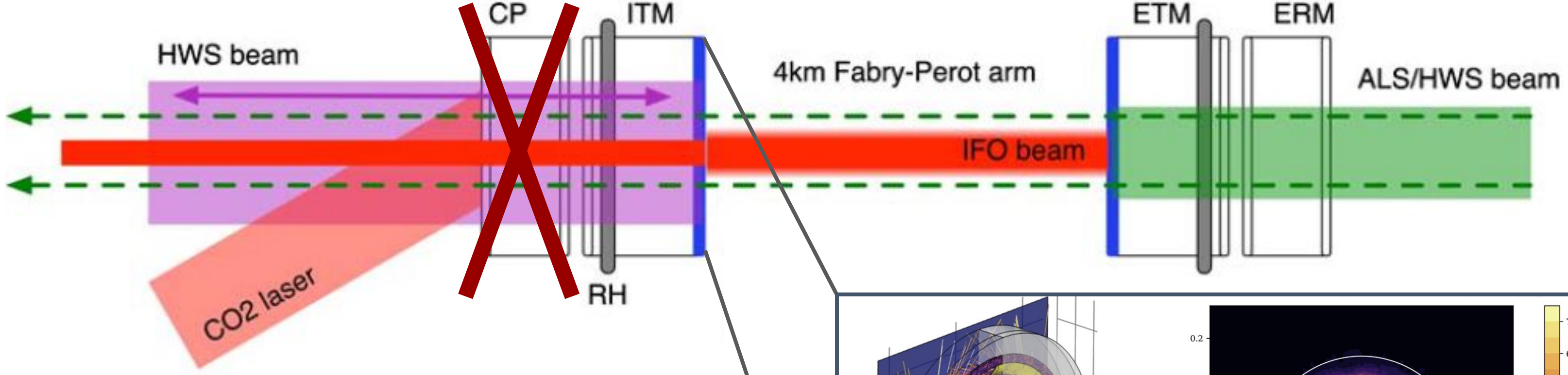
Based on aLIGO AR coatings, expect high-angle scattering loss of **up to 200 ppm** (roundtrip) per compensation plate (CP)



Brooks *et. al.* (2016)

500 ppm SEC Loss Precludes Compensation Plates

Requires a *qualitatively* new approach to wavefront control, with actuation on **fine spatial scales** (2-5 cm) and **low displacement noise** (RIN < $10^{-9}/\sqrt{Hz}$)

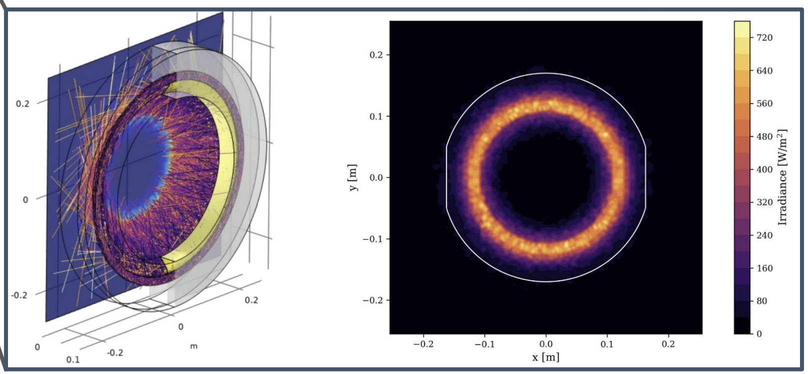


R&D effort underway to develop a CP alternative:

ITM front-surface correction

(used in conjunction with RH)

CE-G2300032, LIGO-G2400546



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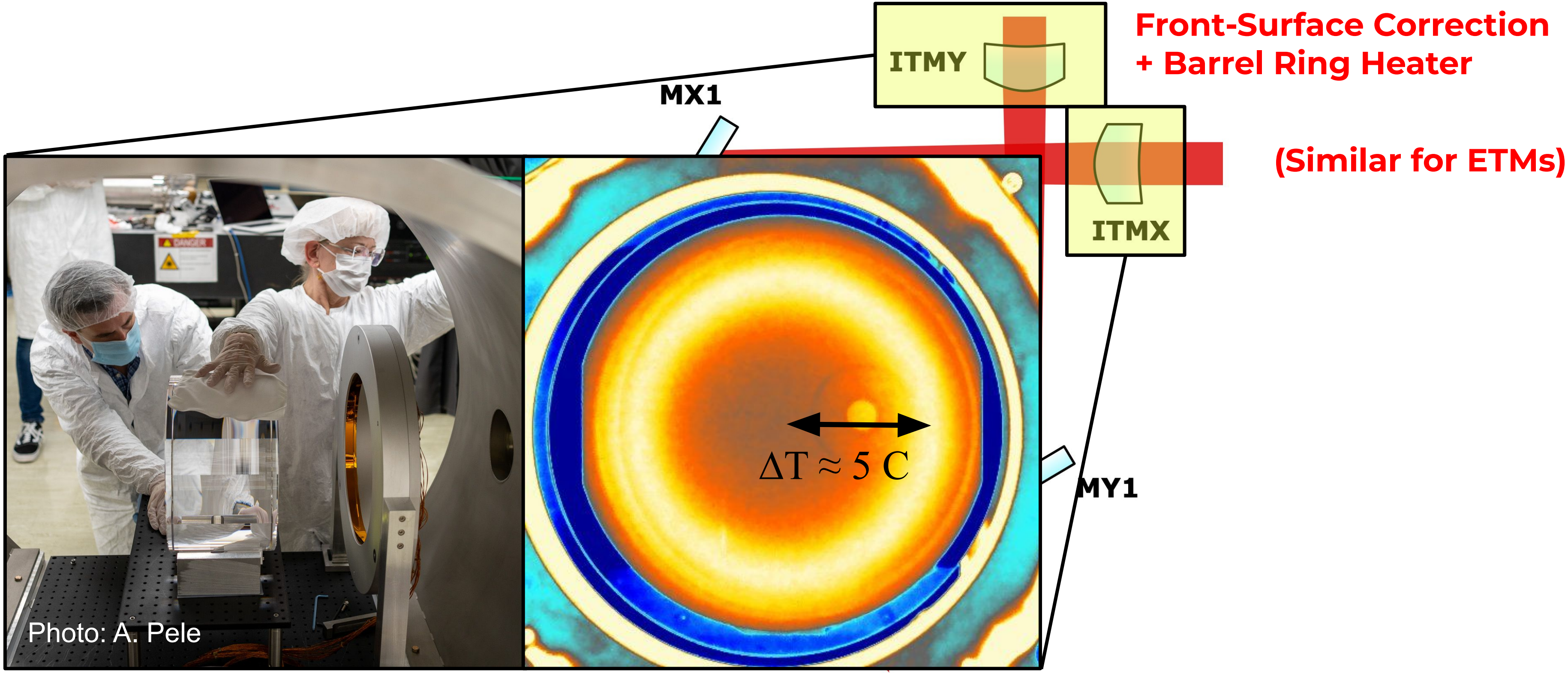


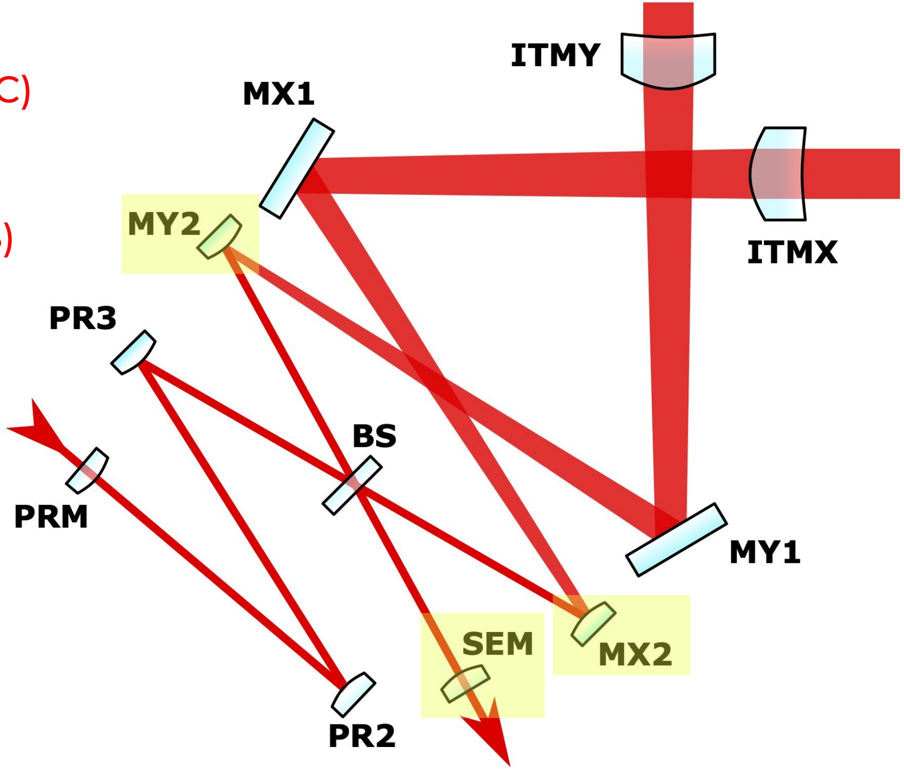
Prototype test at LIGO Lab-Caltech

Measured temperature profile

Concept for Next-Generation Thermal Compensation

SEC Mode-Matching

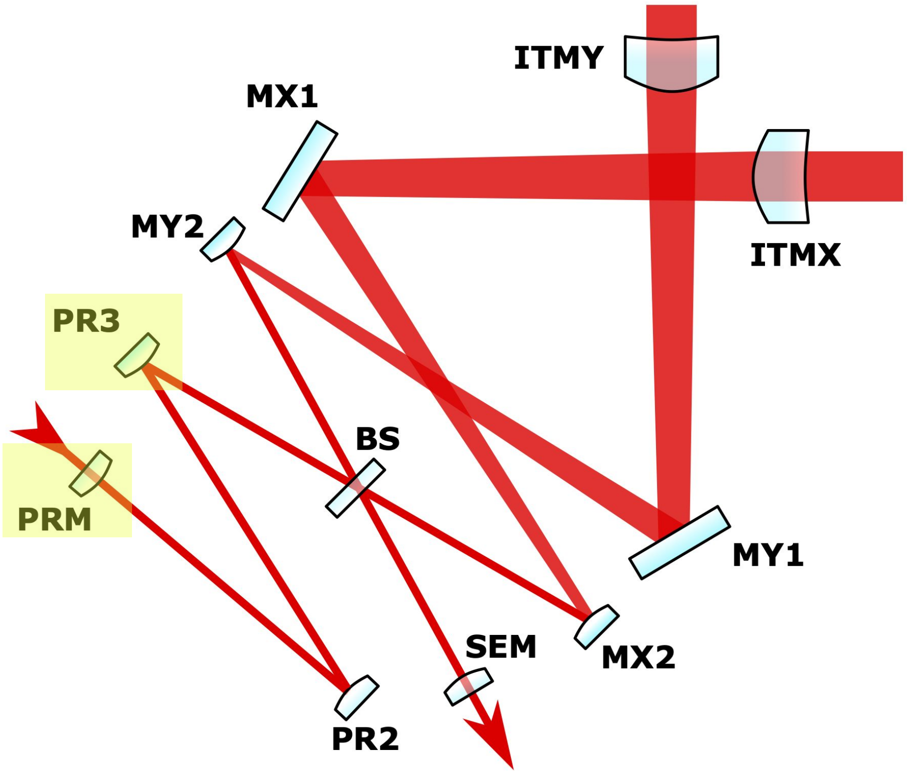
- Three low-order (RoC) actuation points
- Existing technology (ring heater, T-SAMS)
- > 20° Gouy phase separation between MX/Y2 and SEM



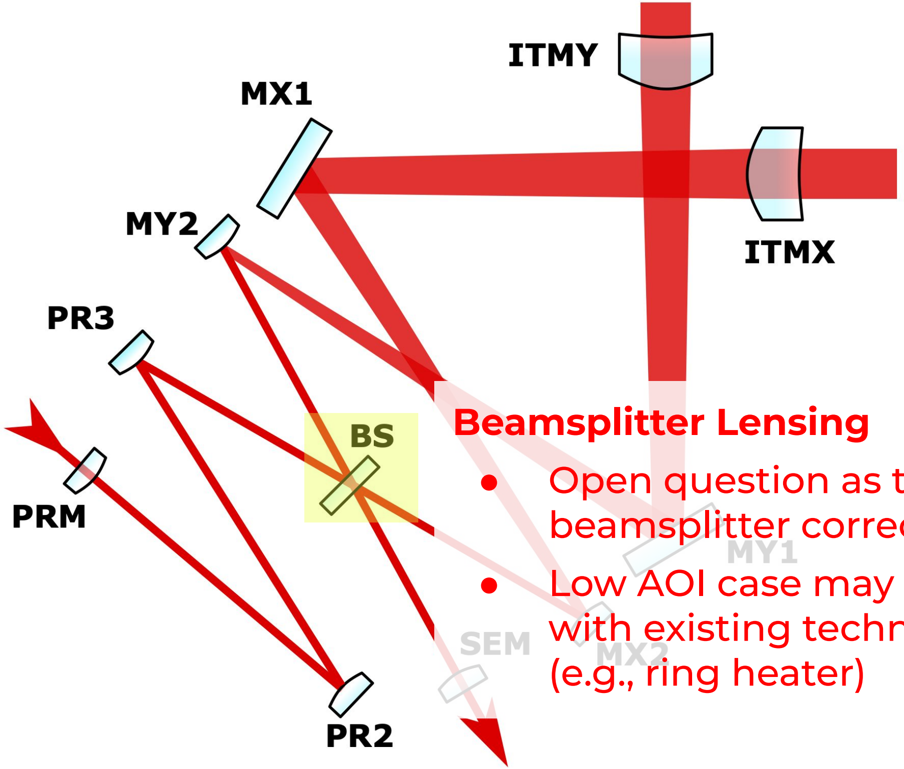
Concept for Next-Generation Thermal Compensation

PRC Mode-Matching

- Two additional low-order (RoC) actuation points
- Less stringent loss requirement allows for additional optics in PRC path
- **Independent control of SEC and PRC mode-matching**
- > 20° Gouy phase separation between PR3 and PRM



Concept for Next-Generation Thermal Compensation



Beamsplitter Lensing

- Open question as to whether active beamsplitter correction is required
- Low AOI case may be correctable with existing technology (e.g., ring heater)

Summary of Technical Challenges

- The many corner layouts studied for CE have been reduced to two contenders, the "Long Reverse aLIGO" and "Long Crab." **Are there any obvious showstoppers for either of these?**
- One challenge with 40 km arms is that an FSR of 3.75 kHz means every HOM resonance is in-band. **What does this mean for quantum noise performance and laser noise coupling with imperfect mode matching?**
- An additional 40 km arm challenge is sensing CARM, as the arm bandwidth is too low to do what aLIGO currently does. **Are there any alternatives?**
- So far, parametric instabilities have been regarded as a secondary concern, to be addressed later in the design process. **Is this prioritization appropriate?**
- **Which of these risks/topics, or others not listed, are crucial to study now for placing requirements on the infrastructure/facility design?**

Extra Slides

Reference: Basic CE Design Parameters

Quantity	CE
Arm length (km)	40
Wavelength (nm)	1064
Mirror mass (kg)	320
Mirror diameter (cm)	70
Arm power (MW)	1.5
Power on BS (kW)	10
Arm Finesse	450
SRM T (%)	2
Squeezing (dB)	10

Quantity	CE
PRM T (%)	3
SEC loss (ppm)	500
Roundtrip loss (ppm)	40
Arm pole (Hz)	4.2
CARM pole (Hz)	0.02
DARM pole (Hz)	825
SEC length (m)	80-200
FC length (km)	4
Beam size on TM (cm)	12

Beamsplitter in a strongly converging telescope: concerns

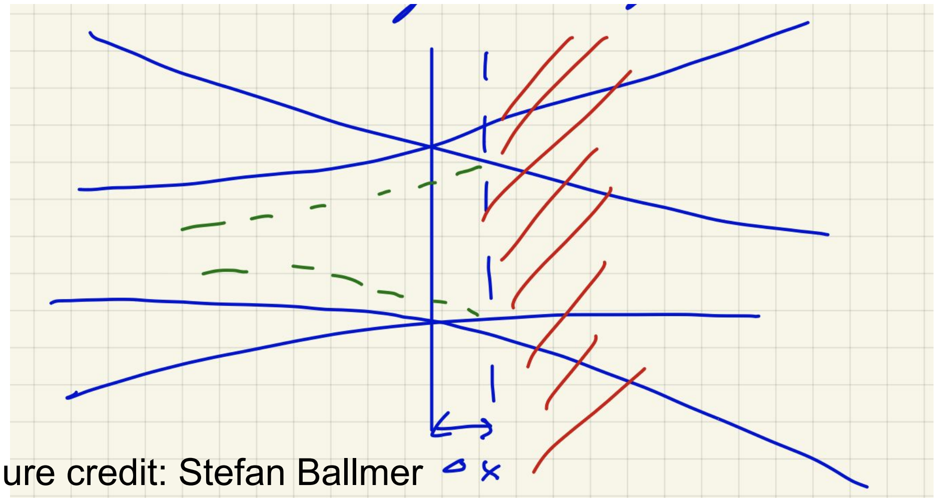


Figure credit: Stefan Ballmer

- Especially at 45deg AOI, coating reflectivity will vary across the beam spot.
- Linear dependence of reflectivity on AOI actually just has a mode matching effect.
- Combines with the more obvious mode matching effect (see sketch).

In words, what matters is directly the Rayleigh length of the beam passing through the BS. For example, if we assume a BS placement tolerance of 5mm, and a maximum acceptable loss of 25ppm, the minimum acceptable Rayleigh length is

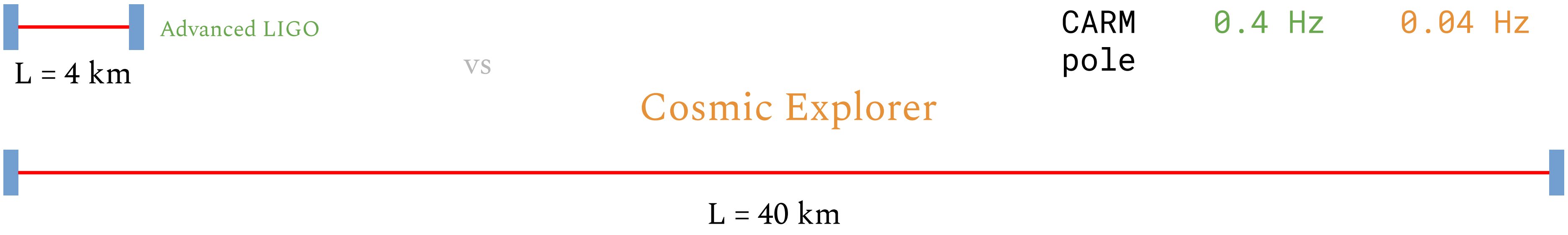
$$z_{R,min} = \frac{5\text{mm}}{\sqrt{25 \cdot 10^{-6}}} = 1\text{m} \quad (12)$$

Matthew Todd and Stefan Ballmer: CE-T2300014

CARM Feedback Main problem

For Cosmic Explorer, the arms will be 40 km long.
The free-spectral range of LIGO is 38 kHz.
The free-spectral range of Cosmic Explorer is 3.8 kHz.

	Advanced LIGO	Cosmic Explorer
Arm Length	4 km	40 km
FSR	38 kHz	3.8 kHz
CARM pole	0.4 Hz	0.04 Hz



Problem: LIGO's current frequency stabilization bandwidth is around 30 kHz. However, the controller cannot extend beyond the FSR due to the overcoupled arm cavity phase dynamics.
Additionally, the extremely low linewidth (0.04 Hz) makes the CE shot noise limit insufficient at 500 Hz.

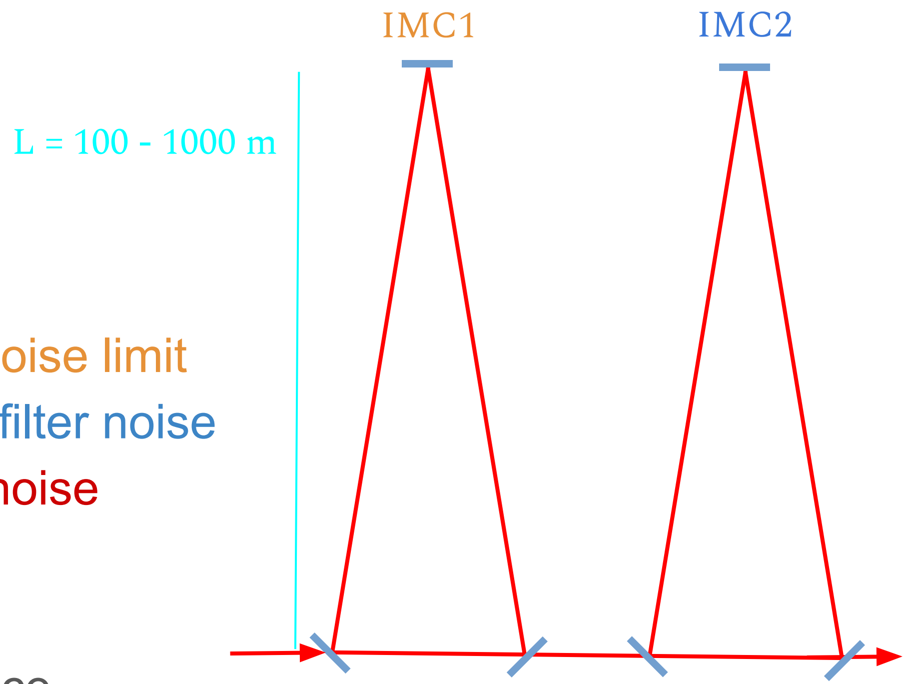
Solution: do not rely on CARM for HF feedback

Do not rely on the interferometer
for frequency noise suppression

Instead, use two long input mode cleaners

First IMC is high-bandwidth to reach shot noise limit
Second IMC is low-bandwidth to passively filter noise
Main interferometer will also strongly filter noise

Advantages:
1) Long cavity is a better frequency reference
2) No feedback from IFO required

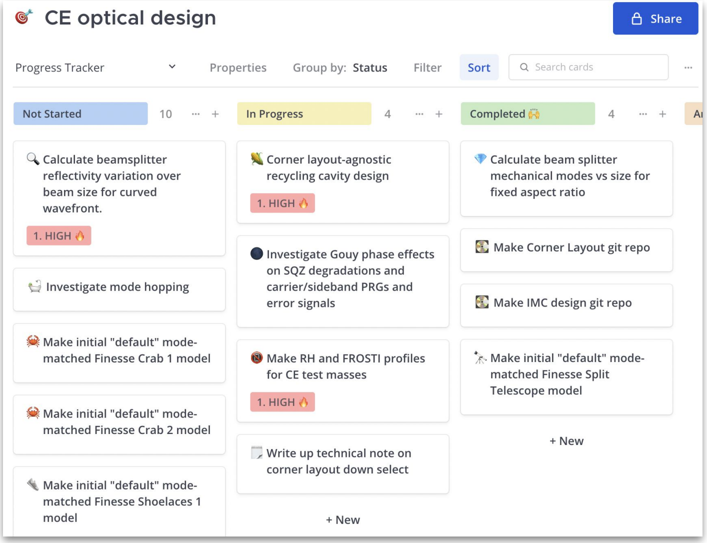


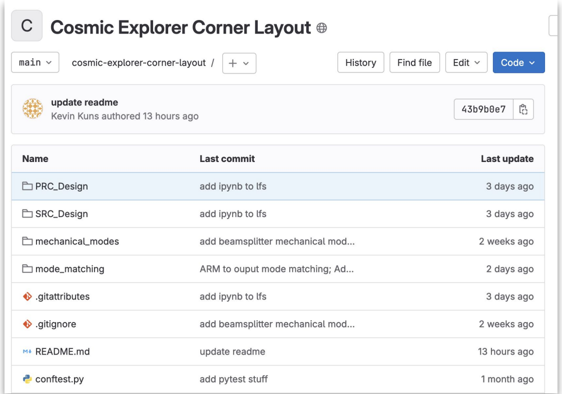
Simulation tools for CE optical design

- Finesse 3
  - For noise couplings, quantum noise calc., closed loop controls.
- pyGWINC
  - Noise budgets, science metrics.
- SIS
  - High-order scattering, stray light modeling.
- GTrace, Zemax, …
  - Geometrical layouts, ghost beams.
- FEA tools
  - COMSOL, ANSYS
  - FEniCSx (open-source)
- Time domain optical modeling software.
  - Lock acquisition, glitch response, …
- …others we should be aware of?
- …physics that is needed but not covered by these?

Optical design team organization

- CE mailing list: optdes@cosmixeplorer.org
- Weekly Zoom calls, Monday 4pm EST. Alternating:
    - Week A “formal” call, with progress updates.
        - Agenda, notes and recordings stored on CE DCC here under different document versions.
    - Week B “informal” workshop-style call.
        - Students encouraged to bring modeling questions etc.
- Mattermost Channel used for discussion among project members.
- Mattermost Board used for coordination of tasks.
- Gitlab instance used for optical design modeling repositories.





Optical design NSF award

Design work split into 4 work packages:

- Core optical design
- Interferometer sensing and control.
- Laser stabilization and lock acquisition.
- Readout and quantum enhancement.

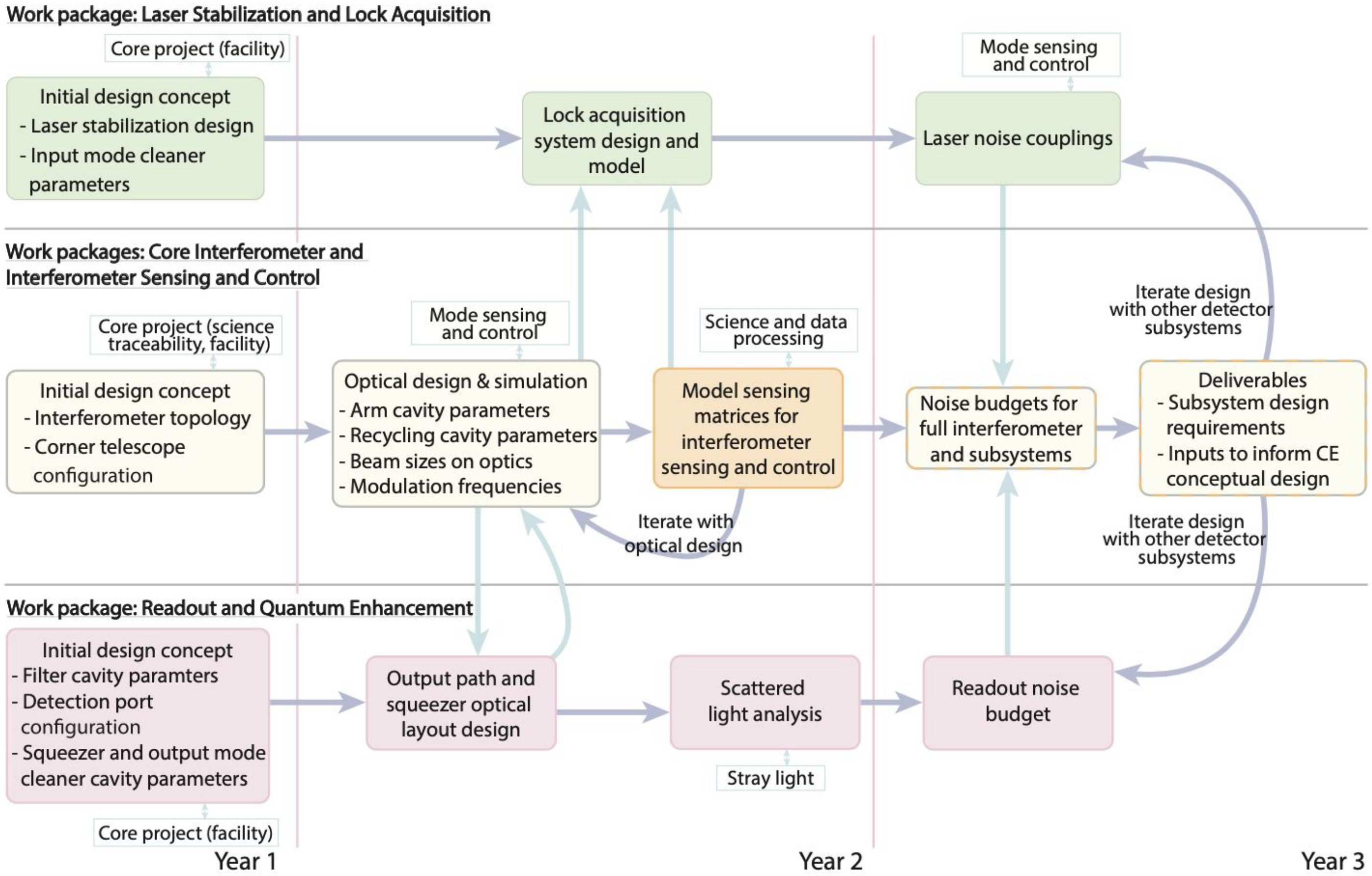
Key project deliverables:

- Conceptual design of CE interferometers, performance consistent with science targets.
- Subsystem requirements specifications.
- Interferometer noise budget (beyond fundamental noises).
- Reference simulation models for CE IFOs.

Work package	Resources (FTE)	Deliverables	Milestones
Core Interferometer	UF Faculty (PF) *1 wk + acad.* UF Faculty (DBT) *1 wk + acad.* SU Faculty (SB) *1 wk + acad.* MIT Scientist (KK) *12.5%* MIT Scientist (LB) *acad.* UF Postdoc *30%* UF Engineer (JG) 4% Y2, 8% Y3	• Initial design of the interferometer topology and corner telescope parameters. • Code base and parameter files for full interferometer optical simulations. • Noise budget for the full interferometer. • Design requirements document for related subsystems interfacing with the optical design. • Draft CAD layout of major optical components within notional vacuum enclosures.	**Y1**. Initial design of the overall interferometer topology and corner station telescopes complete. **Y2**. Design for arm cavity parameters, recycling cavity parameters, beam sizes on optics. **Y3**. Noise budgets for full interferometer and key subsystems complete.
Interferometer Sensing and Control	UF Faculty (PF) *1 wk + acad.* MIT Scientist (KK) *12.5%* MIT Scientist (LB) *acad.* UF Postdoc *30%* SU postdoc *30%*	• Initial design of sensors and actuators for length and angular control. • Definition of the phase modulation sidebands. • Model files and parameters for sensing matrices. • Model files and parameters of cross-couplings between ISC components. • Requirements document for design of ISC scheme and interfacing subsystems.	**Y1**. Establish sensing ports and interfaces, and develop initial controls models. **Y2**. Commission interferometer control and noise simulations, converge with core interferometer design on key sensing and actuation parameters. **Y3**. Model cross-couplings and compile noise budget.
Laser Stabilization and Lock Acquisition	SU Faculty (CC) *2 wks + acad.* SU Faculty (GM) *1 wk + acad.* SU Postdoc *30%*	• Initial design for laser stabilization system. • Initial design of input mode cleaner including length and cavity geometry. • Simulation files and model parameters for realistic laser noise and coupling to GW readout. • Lock acquisition system and procedure for CE interferometers.	**Y1**. Initial design concept of frequency noise suppression system complete. **Y2**. Initial design of lock acquisition system and procedure. **Y3**. Model of laser noise couplings.
Readout and Quantum Enhancement	CIT Faculty (LM) *2 wks + acad.* SU Faculty (GM) *1 wk + acad.* CIT Postdoc *25%*	• Output path design document including optical parameters for output telescope, output mode cleaner cavity, and output Faraday isolator(s) • Squeezer and filter cavity optical design. • Backscatter and controls noise modeling code base.	**Y1**. Initial design of output cavities, telescopes, readout scheme. **Y2**. Modeling of potential squeezer degradations, design sensing and control scheme for output path. **Y3**. Noise analysis of gravitational-wave readout.

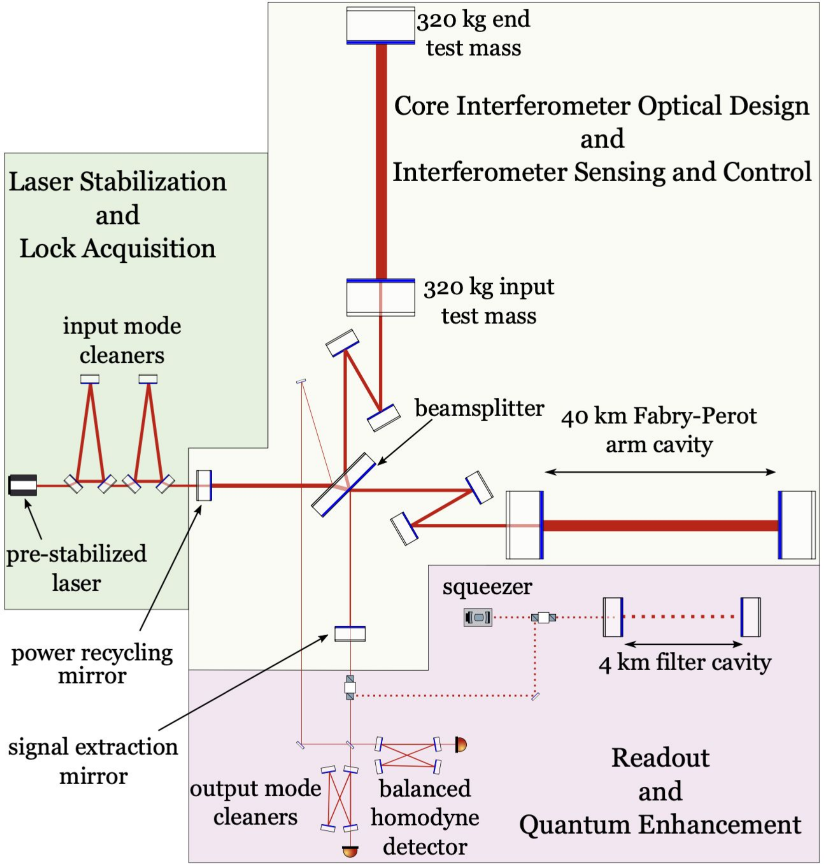
Optical design work flowchart

% Georgia Mansell



We are here

CE optical design basics



Interferometers are *frequency-dependent squeezing-enhanced dual-recycled Fabry-Perot Michelson interferometers* (like A+) .

40km and 20km arm lengths.

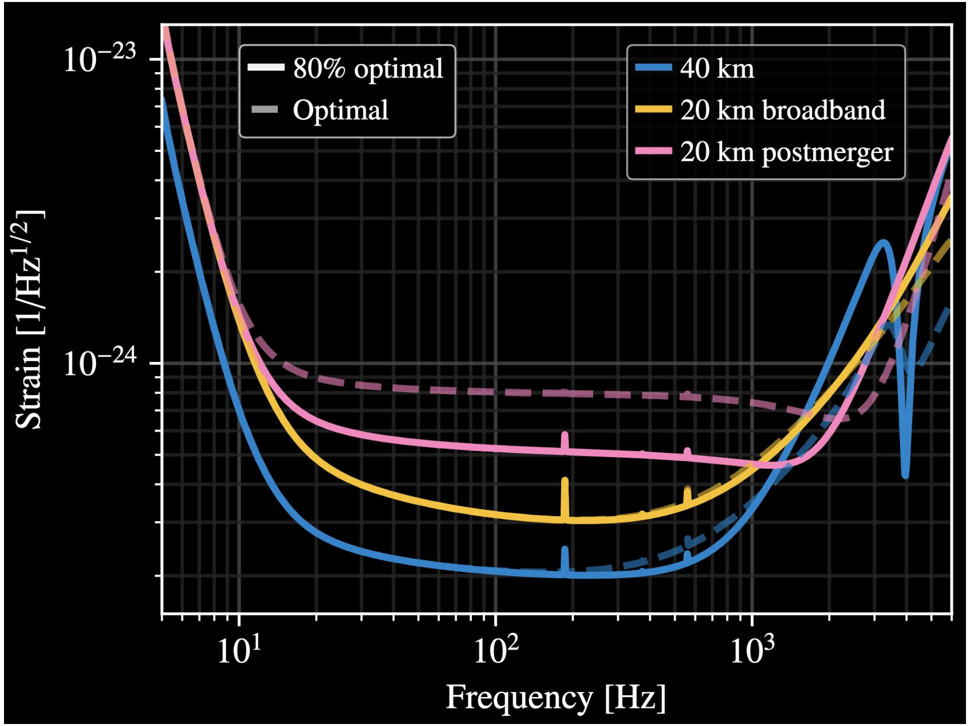
- Longer arms (at same finesse) means lower FSR (and cavity pole).
- SEC finesse must be higher to retain broadband response.
- Beam radius on TMs ~12cm.

1.5 MW circulating arm power.

Stable recycling cavities.

Balanced homodyne readout.

SEC length effect on sensitivity to post-merger signals



In CE the SEC resonance falls within the detection band (unlike aLIGO), especially for long SEC.
This can reduce sensitivity around 2kHz, where BNS post-merger signal lives.
80% reduction from optimal post-merger sensitivity when:

- L_{SEC} 20m → 200m (CE 40km)
- L_{SEC} 25m → 90m (CE 20km post-merger tuned).

For reference, aLIGO L_{SRC} ~55m.
Optical design challenge is to keep SEC short within other constraints (e.g. beam size reduction from arms to output).

Kevin Kuns: CE-G2300033

SEC length effect on sensitivity to post-merger signals

20km

Configuration	$\mathcal{F}_a$	L_s [m]	T_s [%]	$\rho_{pm}^{(max)}$	$\rho_{pm}^{(90)}$	$\rho_{pm}^{(50)}$	BNS range [Mpc]
Optimal PM	450	24	0.45	12.0	10.7	8.1	1700
90 % optimal PM	450	63	0.64	10.7	9.1	6.4	1800
80 % optimal PM	450	89	1.13	10.7	8.0	5.8	2100
Compact binary	450	89	4.00	10.6	7.0	5.4	2600
Optimal PM	800	20	0.28	9.3	8.3	6.3	1700
90 % optimal PM	800	42	0.58	9.4	7.2	5.4	2000
80 % optimal PM	800	64	0.98	9.5	6.5	4.8	2300
Compact binary	800	64	2.30	9.7	6.1	4.7	2600

40km

$\mathcal{F}_a$	L_s [m]	T_s [%]	$\rho_{pm}^{(max)}$	$\rho_{pm}^{(90)}$	$\rho_{pm}^{(50)}$	BNS range [Mpc]
450	20	2.00	13.7	7.9	6.2	3700
450	100	2.00	13.1	6.2	5.0	3700
450	200	2.00	12.4	4.8	3.7	3700
450	400	2.00	11.5	3.6	2.5	3700
800	20	1.10	12.4	6.8	5.3	3600
800	100	1.10	11.6	4.8	3.7	3600
800	200	1.10	10.9	3.7	2.5	3600
800	400	1.10	10.2	3.4	1.7	3600

Kevin Kuns: CE-G2300033

SEC length effect on sensitivity to post-merger signals

20km

Configuration	$\mathcal{F}_a$	L_s [m]	T_s [%]	$\rho_{pm}^{(max)}$	$\rho_{pm}^{(90)}$	$\rho_{pm}^{(50)}$	BNS range [Mpc]
Optimal PM	450	24	0.45	12.0	10.7	8.1	1700
90 % optimal PM	450	63	0.64	10.7	9.1	6.4	1800
80 % optimal PM	450	89	1.13	10.7	8.0	5.8	2100
Compact binary	450	89	4.00	10.6	7.0	5.4	2600
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80 % optimal PM	800	64	0.98	9.5	6.5	4.8	2300
Compact binary	800	64	2.30	9.7	6.1	4.7	2600

Question to consider:

Maintaining the post-merger sensitivity places what seems to be a challenging constraint on SEC length for the 20km IFO.

Might we need to review a science case trade on this item?

Kevin Kuns: CE-G2300033

Laser wavelength: accommodating 2μm

CE baseline design is for 1064 nm.

Potential upgrades include a Voyager-like configuration in the future.

- Cryogenic silicon test masses.
- Laser wavelength required to change to ~2 μm.

Challenge is to avoid ***facility*** constraints that will make this "difficult".

Examples:

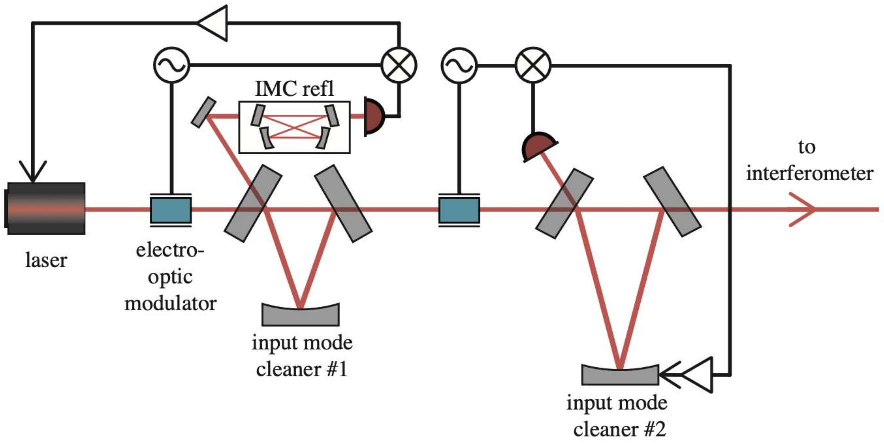
- Baseline beam size for 2 μm over 40 km is 16.5 cm
- Would want higher arm finesse (~3x) to take advantage of better thermal handling (which would also remove benefit of 20 km post-merger tuning) Section 8.4 of the horizon study.

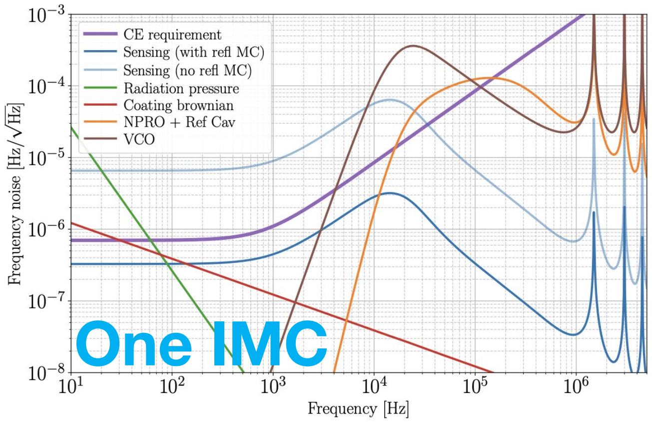
Question: *To what degree do we need to keep these things in mind as we proceed with the 1064nm design?*

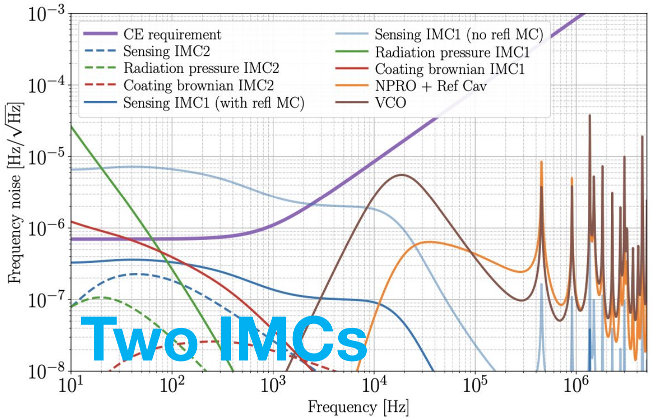
Frequency noise mitigation

Low arm FSR precludes using arms as in-band frequency reference (UGF too low).
Alternative scheme uses a long (100m+) input mode cleaner as frequency reference.
Second mode cleaner may be needed for passive filtering (also IMC refl. Mode cleaner).

Matthew Todd and Peter Zhou
Syracuse University

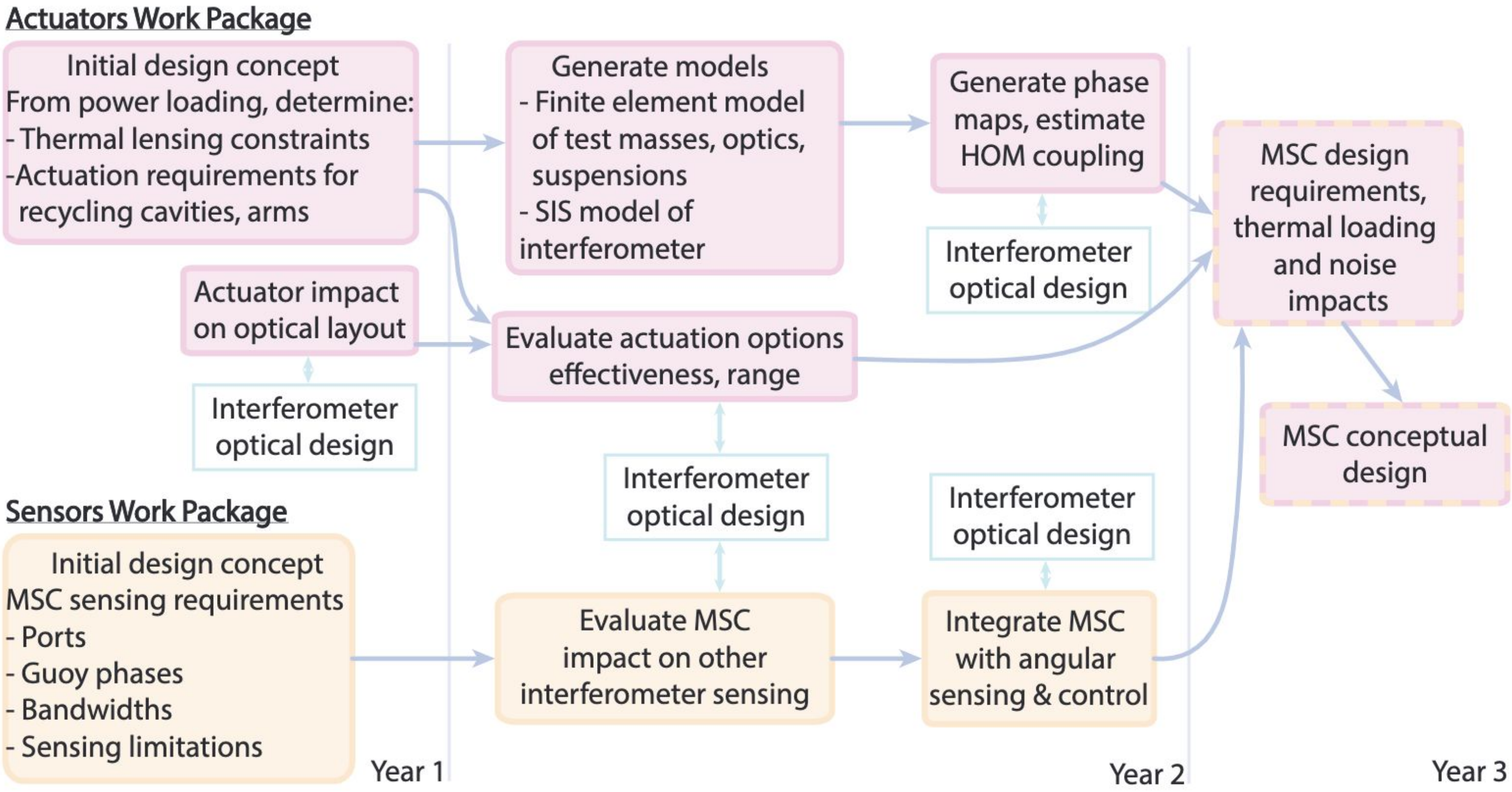






Craig Cahillane, Georgia Mansell, Daniel Sigg,
Opt. Express 29, 42144-42161

Mode Sensing and Control Project Summary



We are here

Summary of MSC Challenges

- **MSC will drive optical topology of entire interferometer**
  - E.g., Beamsplitter AOI
- CE's quantum noise target (1.5 MW / 10 dB SQZ) requires:
  - <1% mode-mismatch between interferometer cavities
  - <500 ppm loss in Signal Extraction Cavity (SEC)
- **Requires a new generation of wavefront actuators**
  - Apply more accurate wavefront correction to test masses under extreme thermal loading
  - Eliminate the transmissive compensation plates relied on by LIGO
- **Requires closed-loop sensing and control of these actuators**