LIGO-G2101095

Optimizing Gravitational-Wave Detector Design for Squeezed Light

Jonathan Richardson
Caltech and LIGO Laboratory

May 18, 2021

Caltech Interferometer Optimization Team

Applying statistical and machine-learning techniques toward GW detector design

Jon Richardson

Swadha Pandey
Undergraduate,
IIT Kanpur

Incoming PhD student,
MIT physics

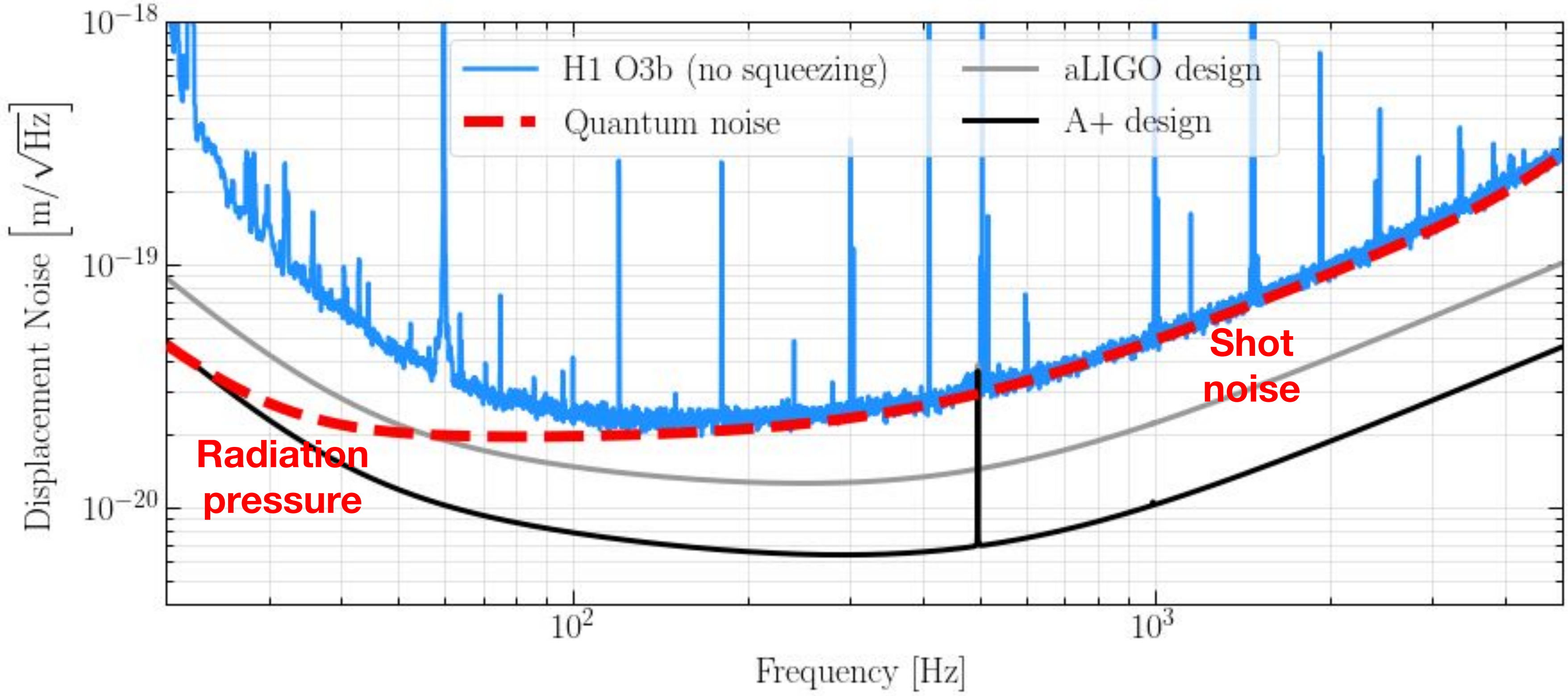
Edita Bytyqi
Undergraduate,
Columbia University

Incoming PhD student,
MIT physics

Tega Edo

Rana X Adhikari

Extending the LIGO frontier



Extending the LIGO frontier

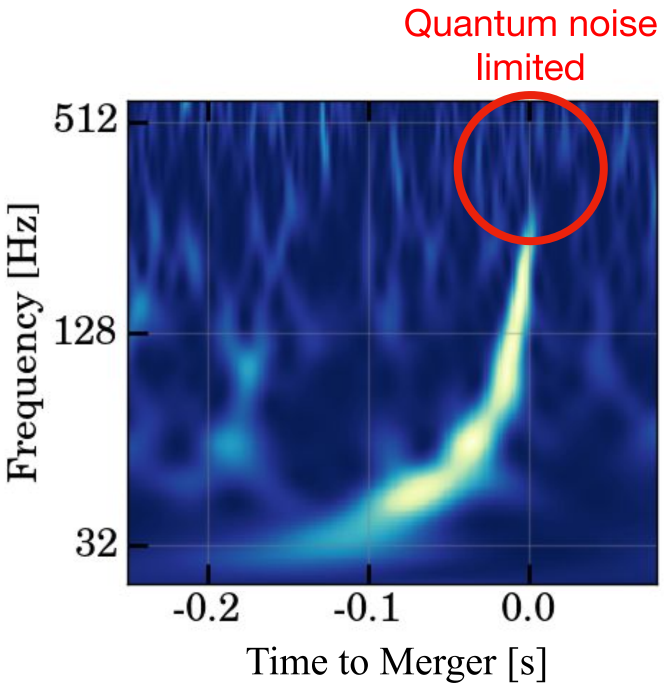
LIGO detectors shot noise limited above 200 Hz

Great scientific potential from improved high-frequency sensitivity:

- Testing physics near the black hole horizon
- Probing dense nuclear matter
- Independently constraining cosmic expansion

Two means of reducing shot noise:

1. More power on the beamsplitter
2. Squeezed light



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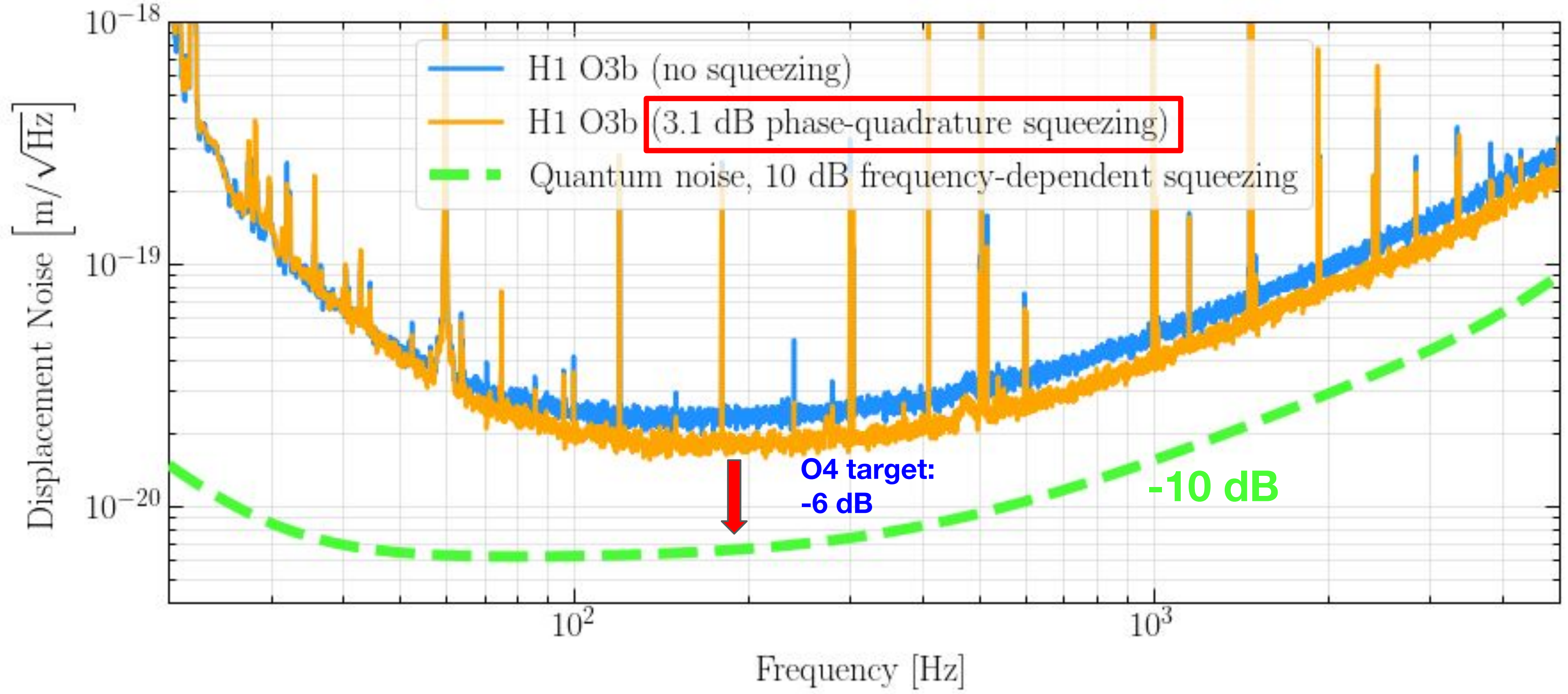


Frequency-dependent squeezing in O4

LIGO Livingston on April 30

300 m filter cavity to be installed at both sites

- Site prep underway; vacuum tube installation in Fall 2021
- Expected to enter commissioning by early Spring 2022

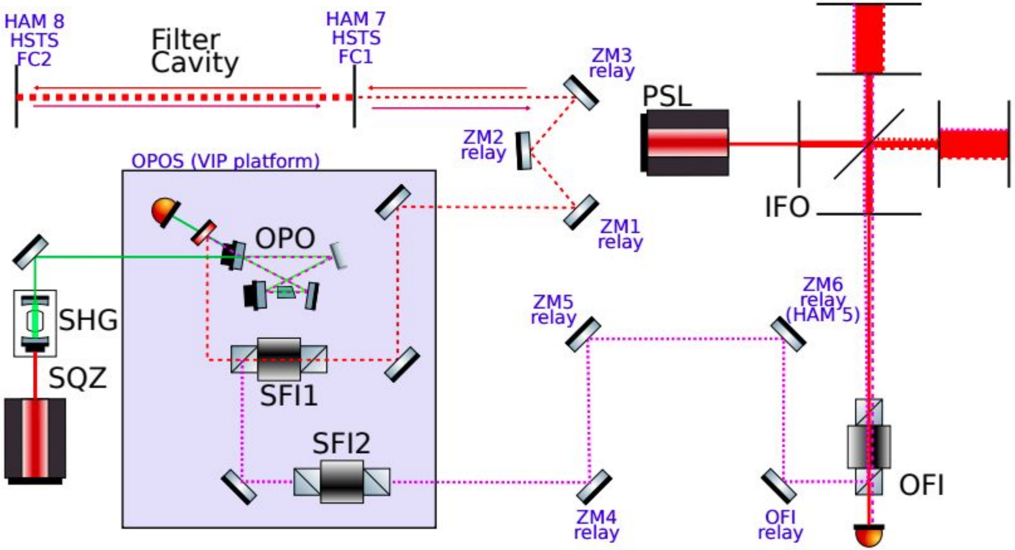


Figure from McCuller, Biscans, & Barsotti (2020) [LIGO-T1900649]

Achieving maximum squeezing in LIGO and beyond

In a real interferometer, random optical errors will always be present

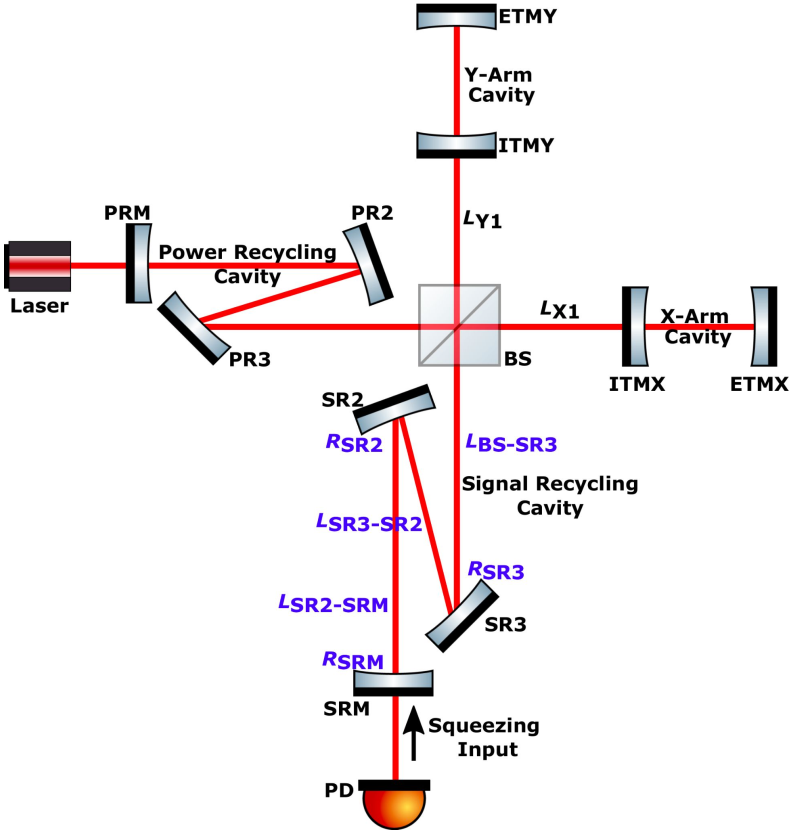
- Optical fabrication limits:
    - Radius of curvature to ±0.1%
    - Higher-order defects (e.g., point absorbers)
- Hand-placement of optics:
    - Relative positioning to ±3 mm

Poses a major challenge for 1% intercavity mode-matching, for 10+ dB of squeezing

We explore extent to which cavity design can be made maximally *insensitive* to common optical errors, to achieve **optimal squeezing performance**

- Applied to case of LIGO A+ signal recycling cavity (SRC)

Signal recycling cavity (SRC) optimization



Six SRC parameters:

- Radii of curvature: R_{SR3}, R_{SR2}, R_{SRM}
- Distances: $L_{BS\text{-}SR3}$, $L_{SR3\text{-}SR2}$, $L_{SR2\text{-}SRM}$

Two constraints:

- **Fixed total length** to preserve f_2 (45 MHz) sideband resonance
- **100% mode-matching** to arm cavities ($q_{SRC} = q_{ARM}$ at ITM HR surface)

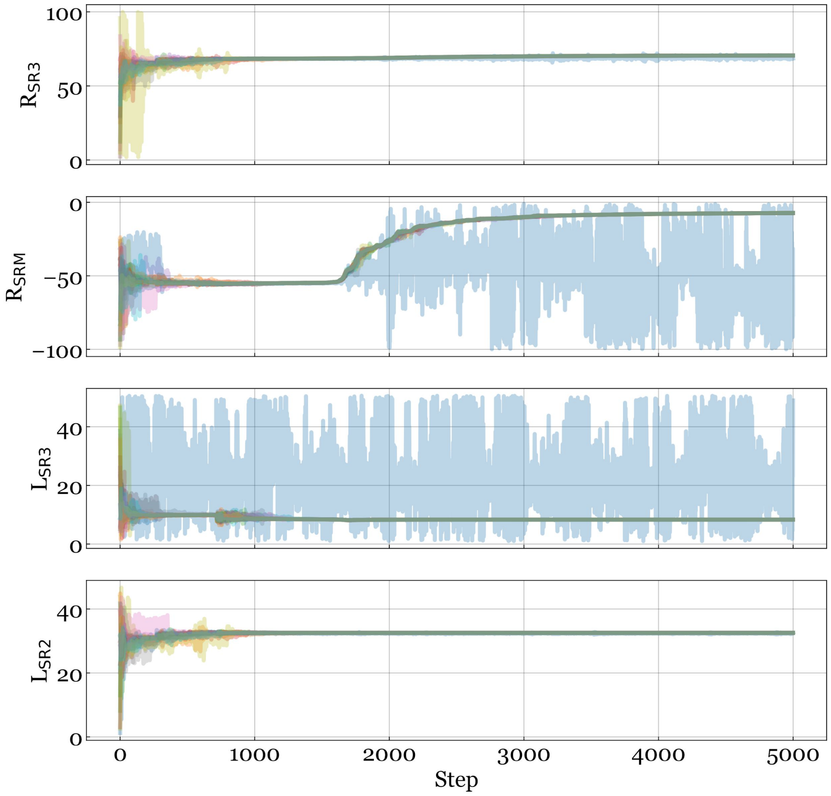
Arm cavity and power recycling cavity modes treated as fixed

Optimization procedure

1. Construct **cost function** penalizing:
   - Partial derivatives of observed squeezing with respect to each SRC parameter
   - Marginally stable cavity
   - Higher-order mode co-resonances
   - Larger beam size at SRM

2. Identify lowest-cost cavity design via **particle swarm optimization**
   - Parallelizable evolutionary search algorithm
   - Iteratively executes a Finesse simulation of LIGO A+ interferometer, while varying SRC

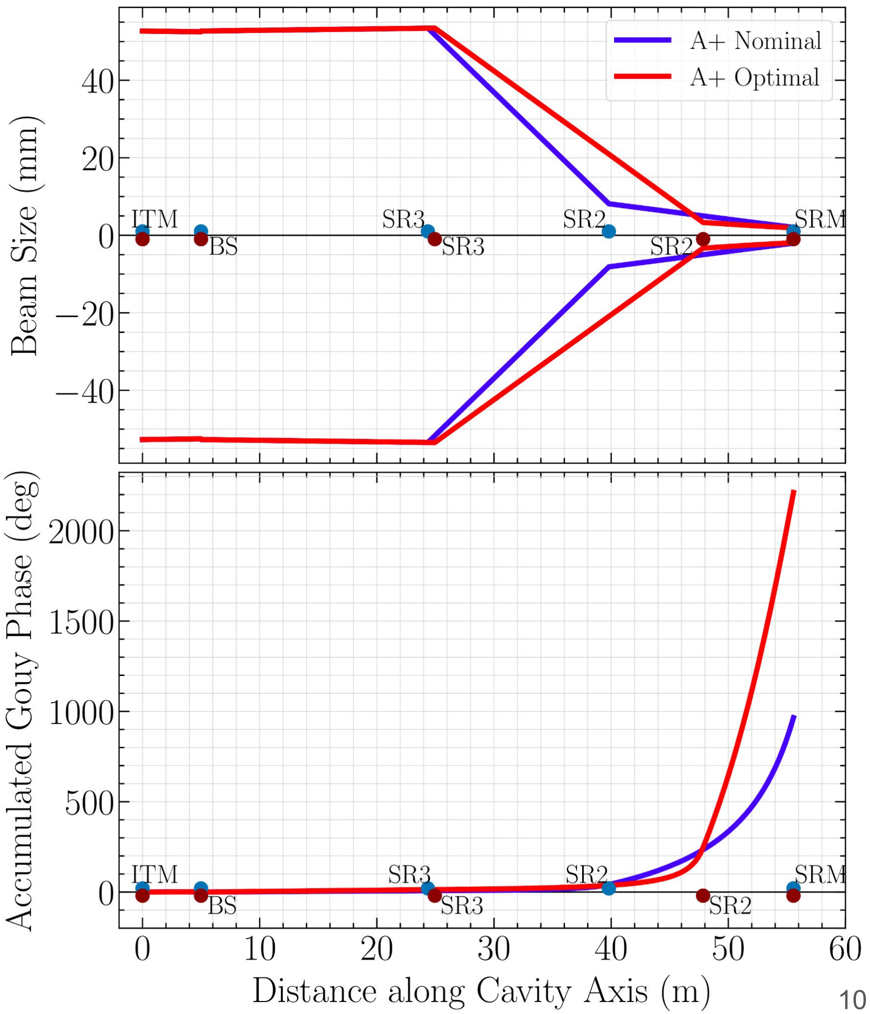
Example of particle trajectories during optimization



Optimal SRC design

Nominal versus optimal SRC parameters:

Parameter	A+ Nominal	A+ Optimal
SR3 radius of curvature	35.97 m	48.13 m
SR2 radius of curvature	-6.41 m	-3.34 m
SRM radius of curvature	-5.69 m	-36.41 m
Beamsplitter to SR3 length	19.37 m	19.96 m
SR3 to SR2 length	15.44 m	22.89 m
SR2 to SRM length	15.76 m	7.71 m

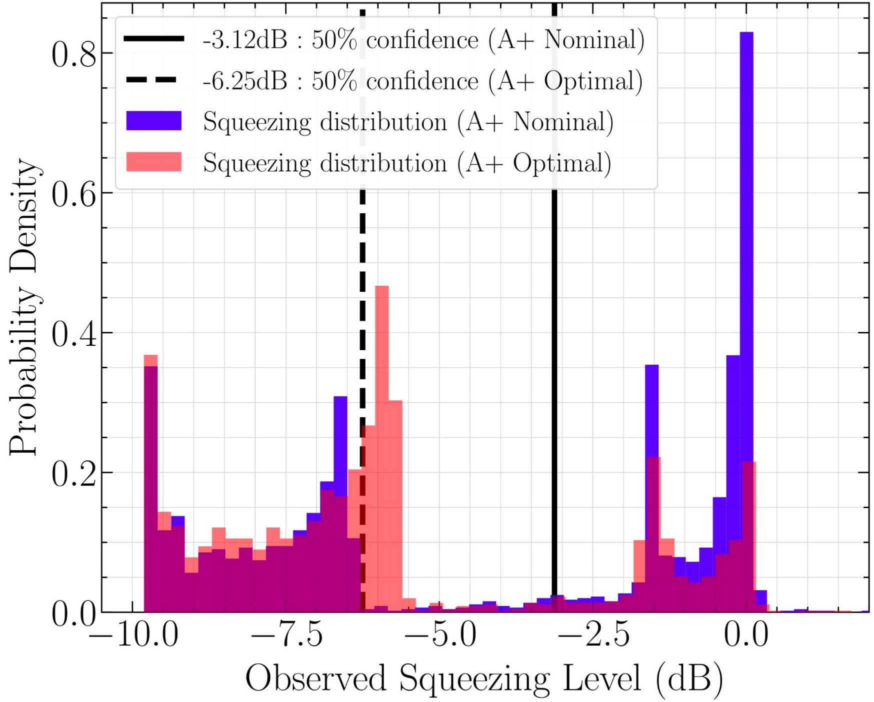


Squeezing performance improvement

Relative squeezing improvement estimated via Monte Carlo method:

1. Start with nominal design under test
2. Add realistic random errors to each SRC parameter
3. Compute observed squeezing
4. Iterate for 2,000 trials

Ratio of median shot noise reduction factors: **1.43**



*Here, the squeezing level only has *relative* meaning (not exactly A+ parameters; excludes readout loss)

Achieving maximum power in LIGO

Point absorbers currently limit LIGO's power-handling capability

- Present on half the LIGO test masses
- Induce increasingly higher arm losses with higher power

Objective:

Reduce **loss susceptibility** of arm cavities to point absorbers by eliminating higher-order mode (HOM) co-resonances

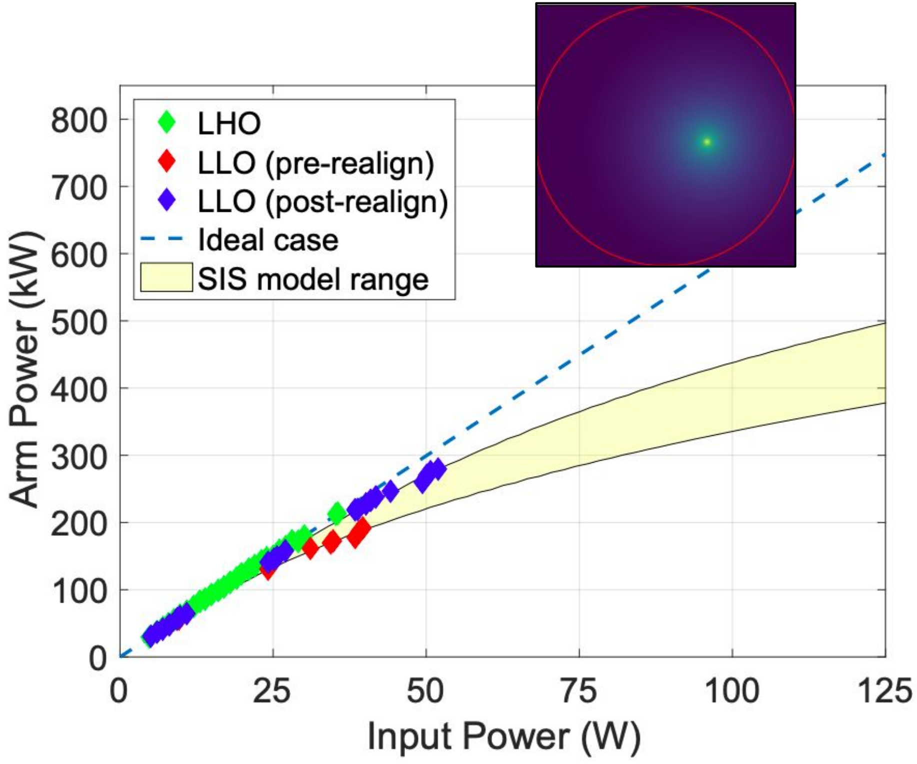
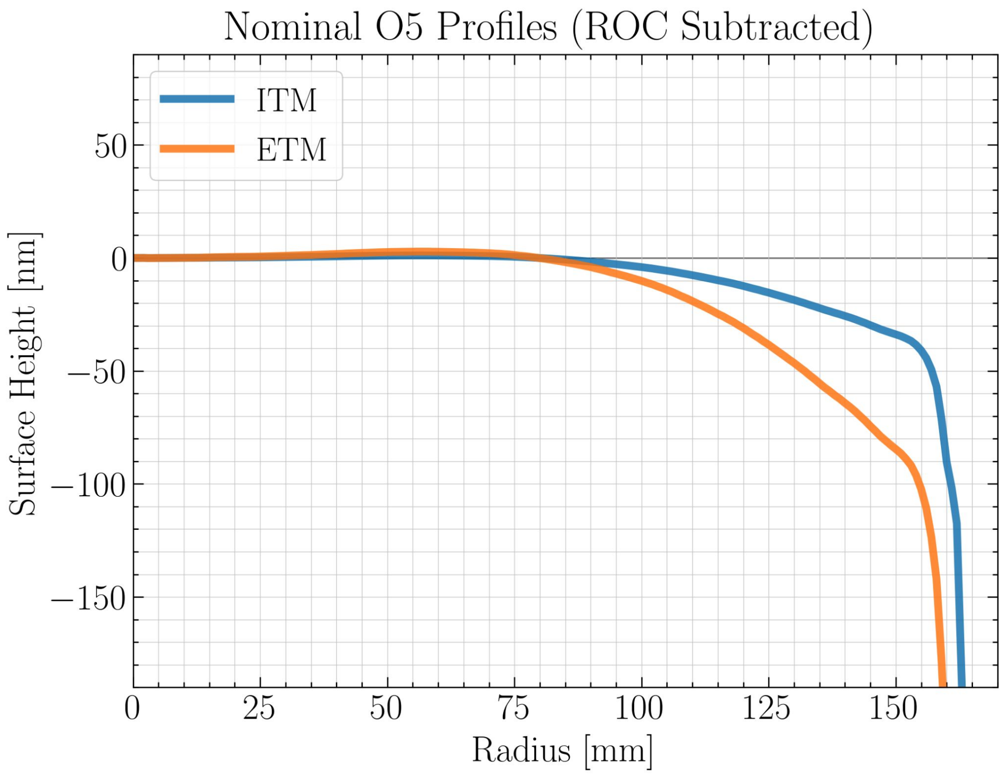


Figure from Brooks et al. 2021 [LIGO-P1900287]

Expected coating nonuniformity in O5



Expected profiles:

Measured O4 ETM coating plume profile (LIGO-T2000643) *times* thickness correction factor for Ti:Ge

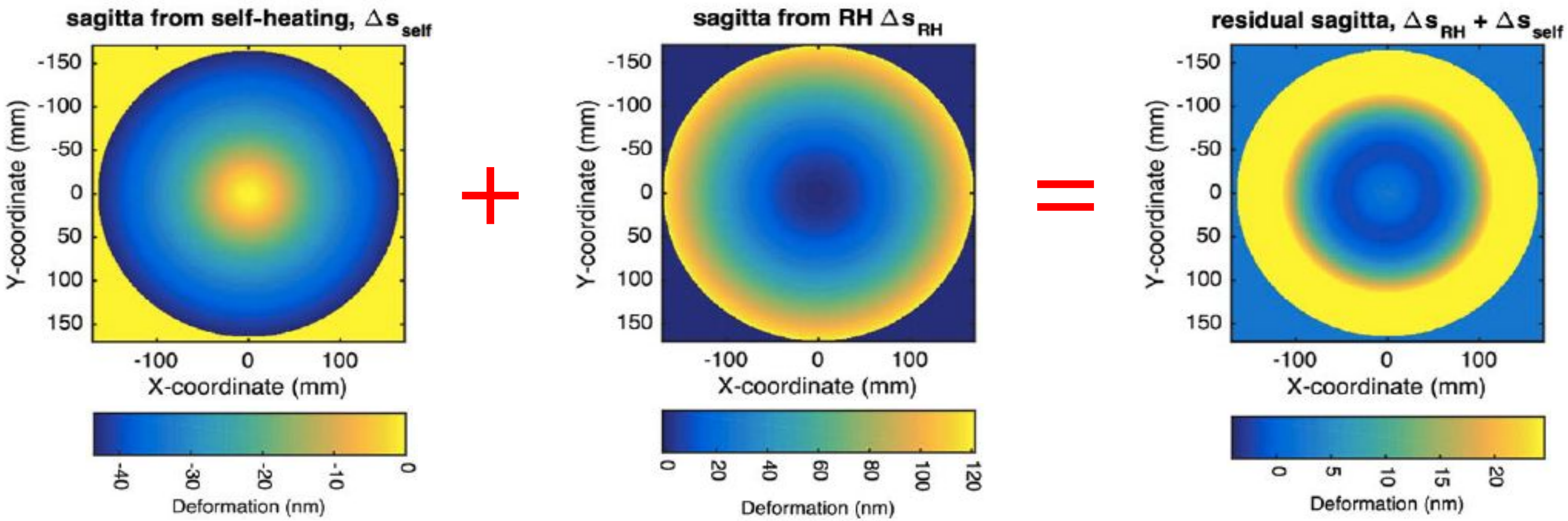
O5 ETM = O4 ETM × 1.5

O5 ITM = O4 ETM × 0.6

Edge roll-off produces **static shift** of HOM resonance frequencies

Residual thermal deformation

Ring heater (RH) compensation of 375 mW of absorbed power



Figures from Brooks *et al.* 2016 [LIGO-P1600169]

Residual thermal deformation

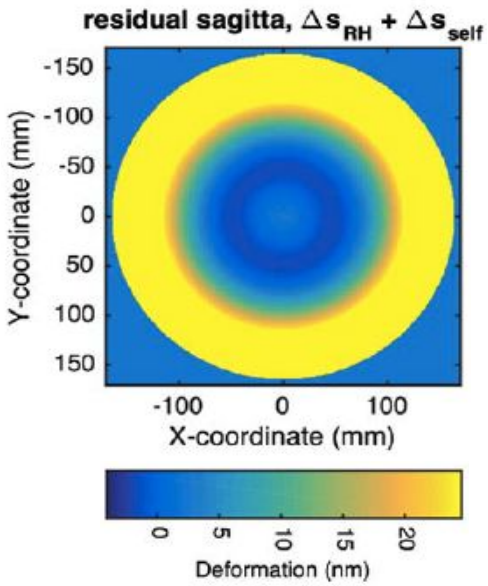
Ring heater (RH) compensation of 375 mW of absorbed power

Excellent correction in central 160 mm

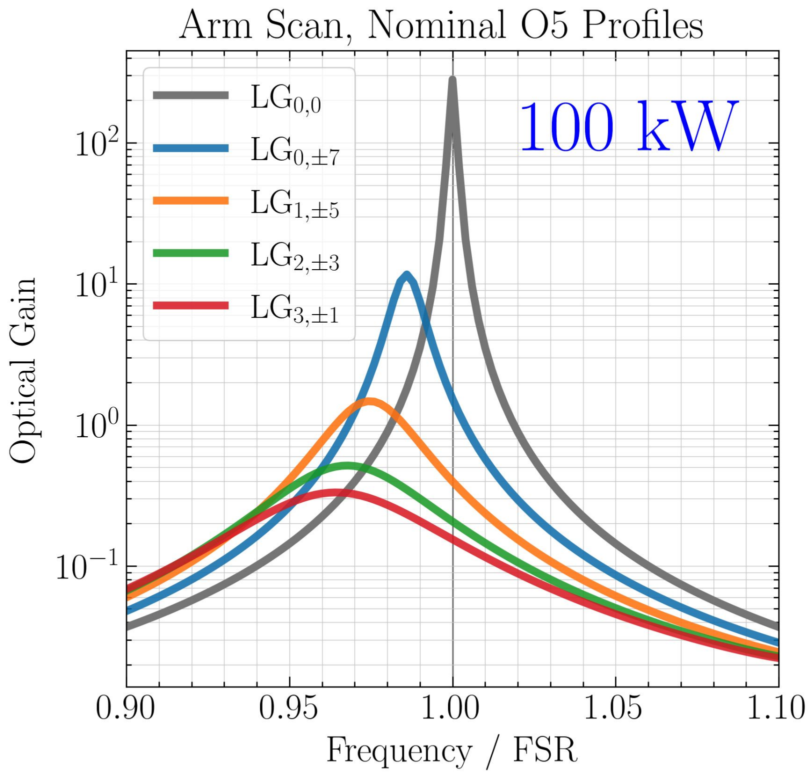
“Overcorrection” at outer radii

- Net surface *rises* towards edge

Produces **power-dependent shift** of HOM resonance frequencies



Implication for LIGO A+ arm cavities



Analytically, expect HOM scattering losses to be **resonantly amplified** by optical gain factor

- Vajente (2014) [link]
- Brooks *et al.* (2020) [LIGO-P1900287]

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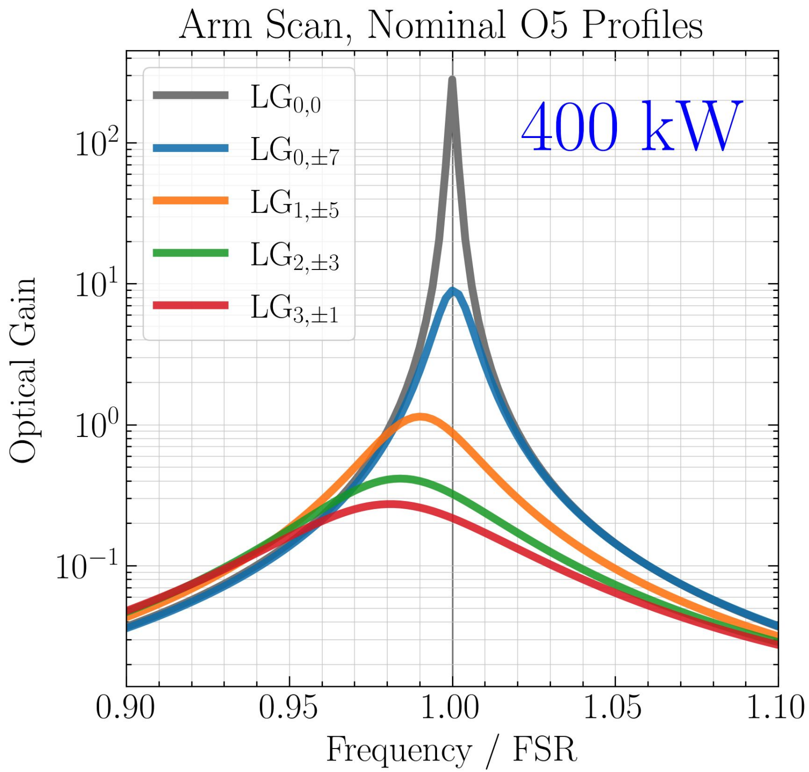

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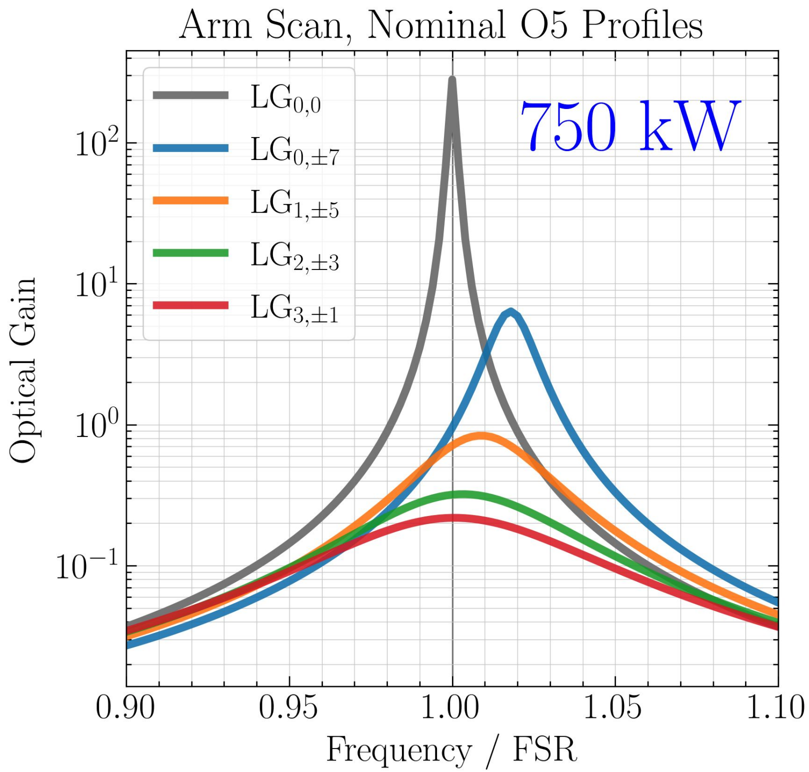

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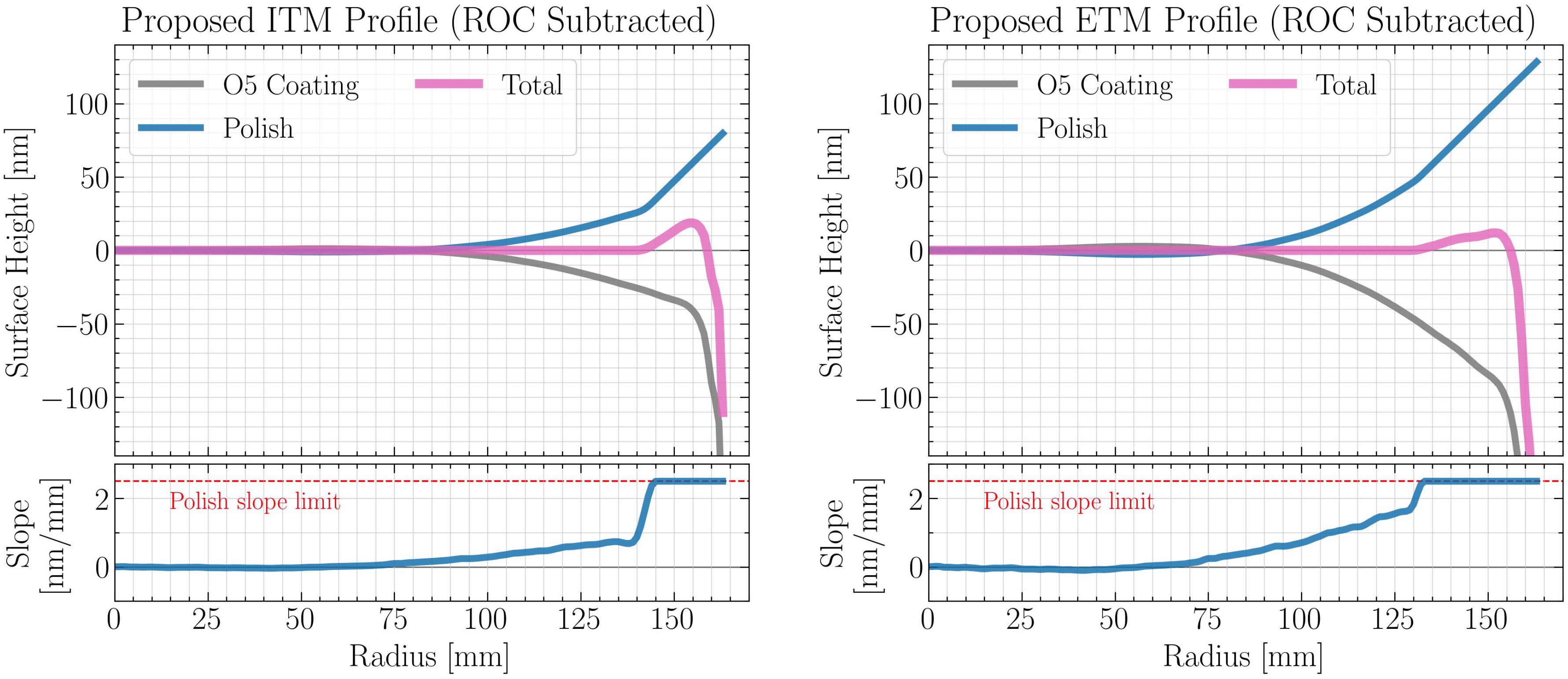
Mitigation with custom polishing figure



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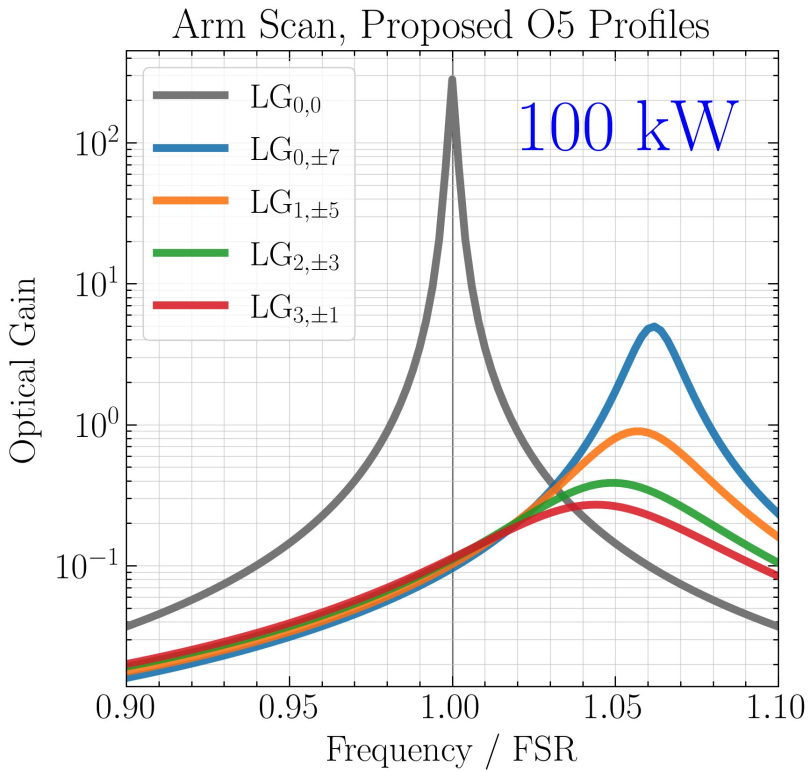

Strategy:

Shift “cold” locations of Mode 7 resonances to higher frequency

Then, any degree of heating **strictly reduces** the optical gains

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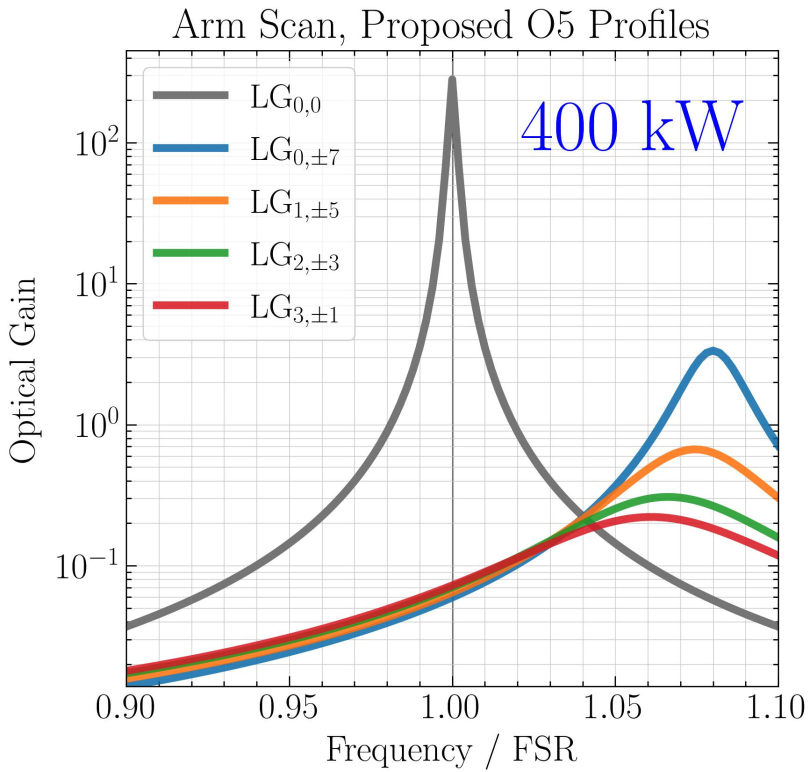

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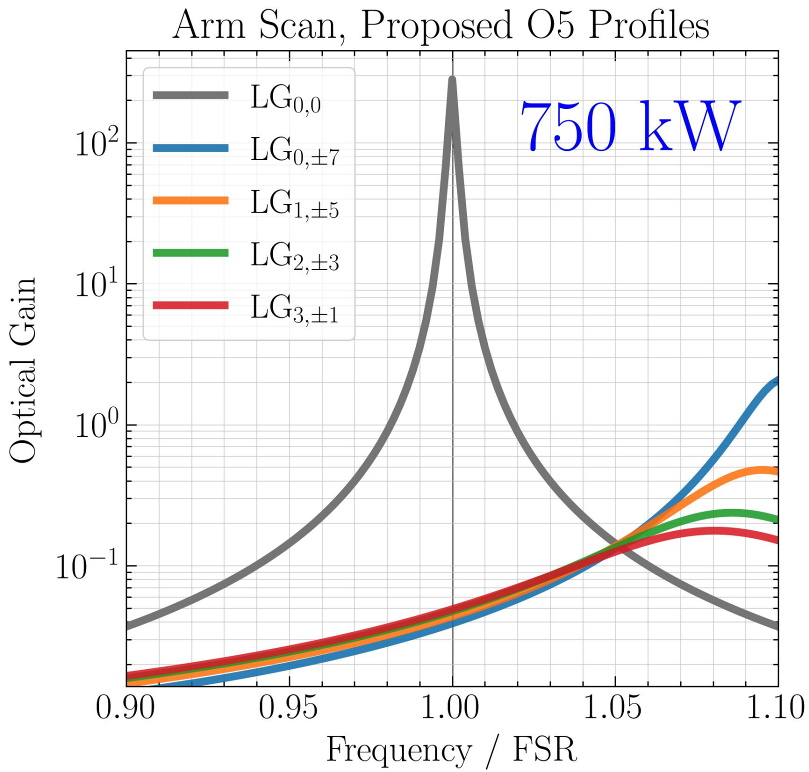

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Arm cavity loss reduction

Monte Carlo SIS model including:

Coating absorption at aLIGO level (0.3 ppm)

Optimal ring heater correction

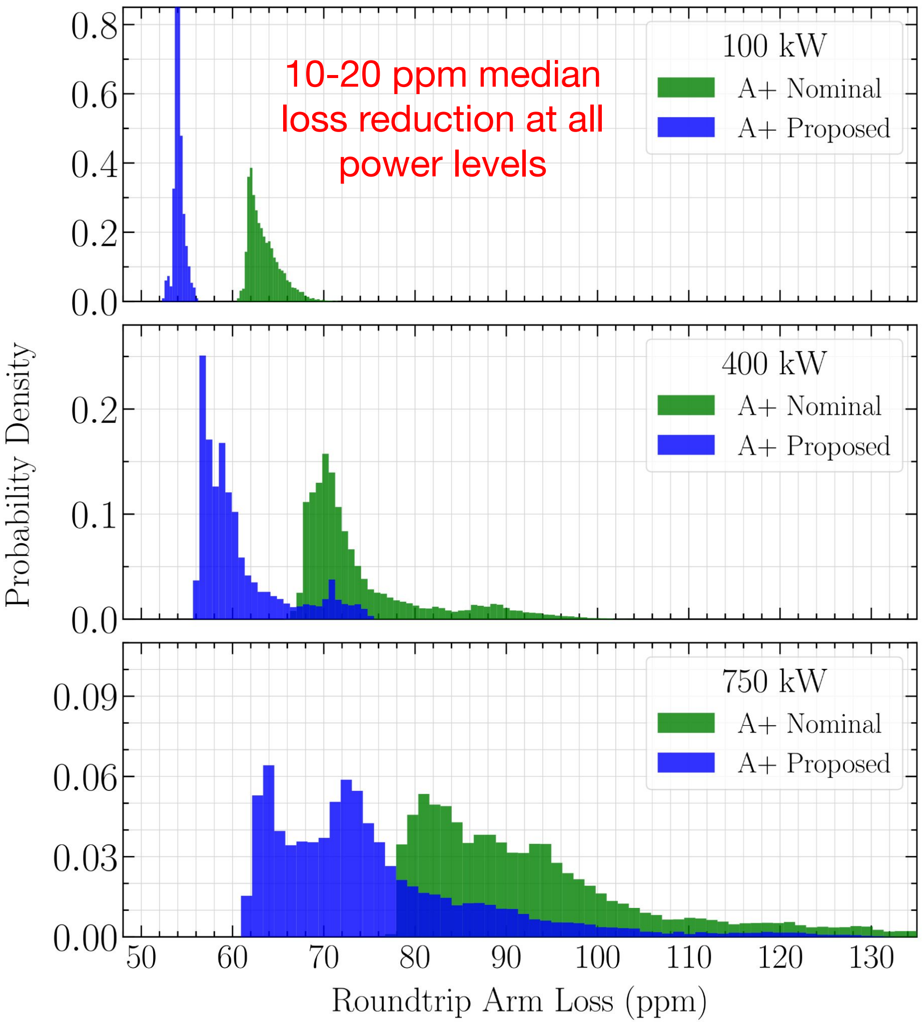
1 randomly-positioned point absorber/test mass

- Uniformly distributed within central 150 mm
- Absorptivity fixed to aLIGO level
(20 mW @ 250 kW, when centered)

Random surface roughness (= aLIGO PSD)

Random beam miscenterings

- Gaussian-distributed (μ=0 mm, σ=5 mm)



Conclusions

We have presented a two-part design study of the LIGO A+ interferometer

1. **Signal recycling cavity:**
   Optimization for maximum squeezing robustness to curvature and length errors
2. **Arm cavities:**
   Reduction of point absorber scattering loss through nonspherical test mass figures

First results look very promising

- Large performance improvements appear to be possible
- Achievable without major infrastructural changes
- Minimal impact to current length and angular control systems

Gives A+ the best chance of reaching design power, with maximal squeezing