AEI 10m Prototype

Leibniz Universität Hannover

Length sensing and optical design aspects

for the AEI 10m sub-SQL Interferometer

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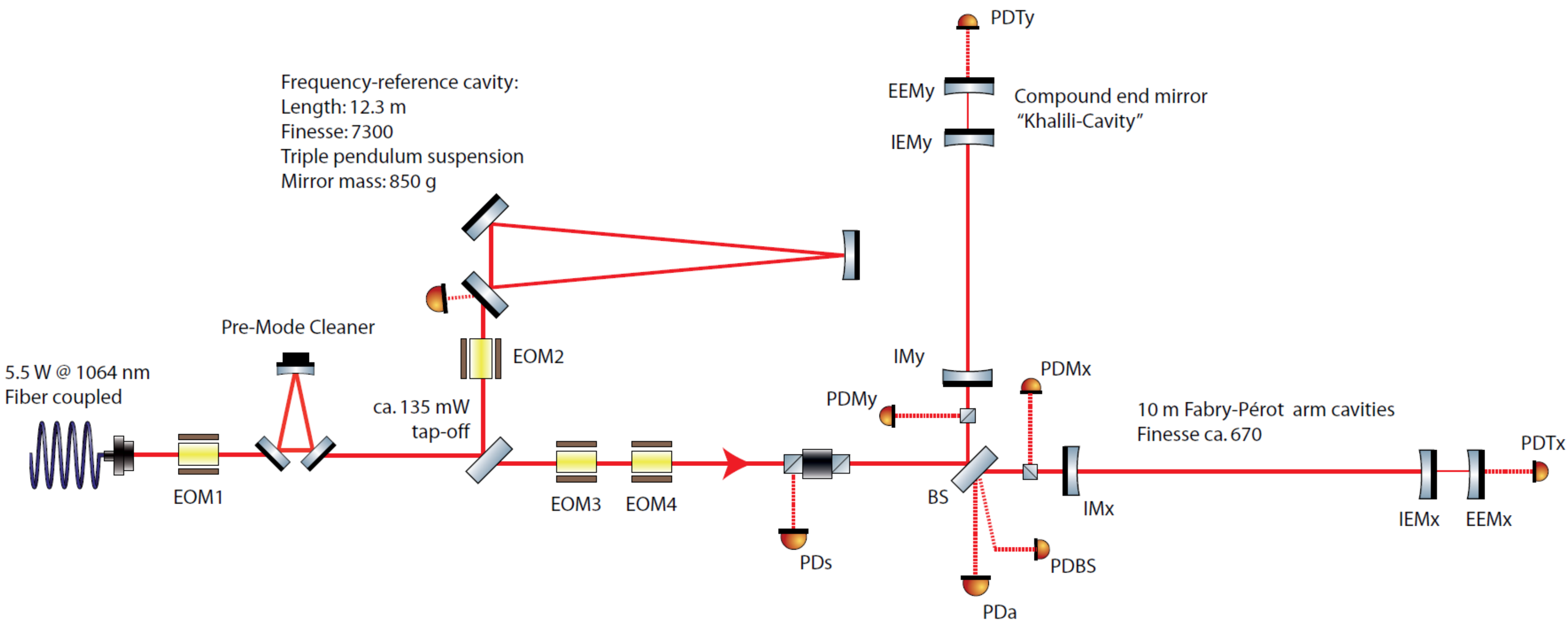
May 2011 – GEO Simulation and ISC meeting

Outline

Today‘s topics:

- A brief introduction
- Design of the SubSQL IFO 5DOF length sensing system
- Cavity stability of the coupled cavity IFO arms

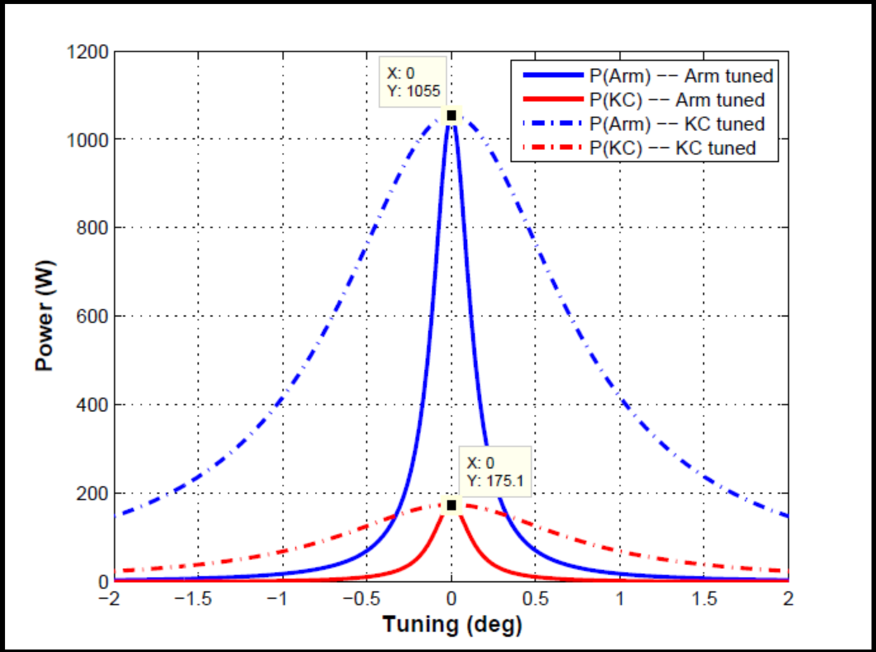
SubSQL Interferometer topology



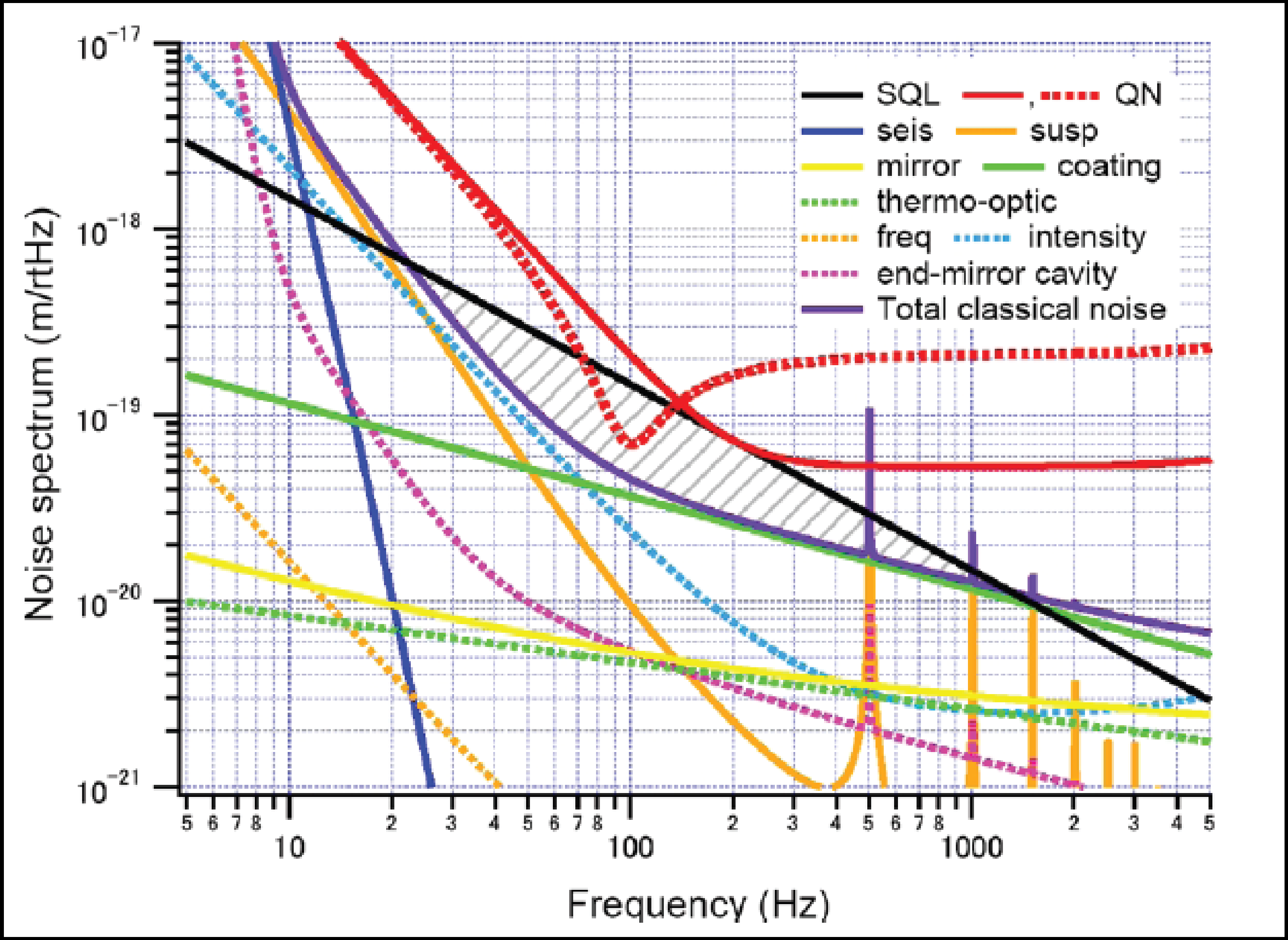
CTN reduction: Khalili Cavities

Replace end mirror with over coupled **compound cavity**

- Small number of coating layers on IEM, highly reflecting EEM
- Cavity held on anti-resonance to act as a reflector
- Rear mirror thermal noise contribution effectively suppressed by cavity, less noise coupling from EEM
- Reduction of EEM coating thermal noise approximately by a factor of two to three



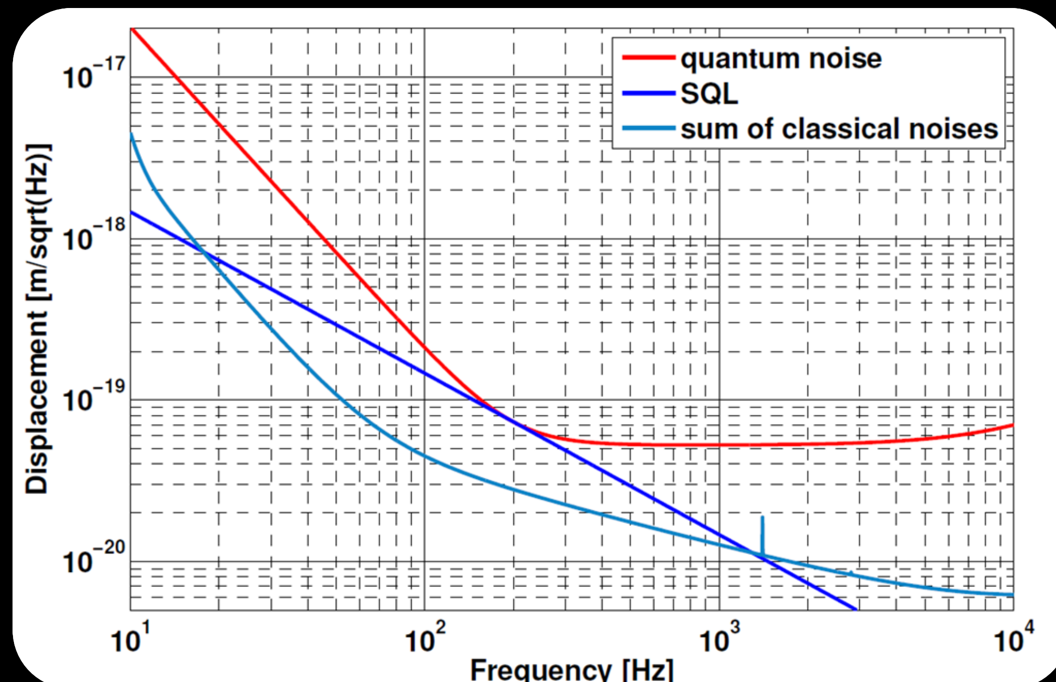
Design sensitivity



Longitudinal control requirements

Primary requirement for LSC sub-system: **compatibility with the sensitivity goal**

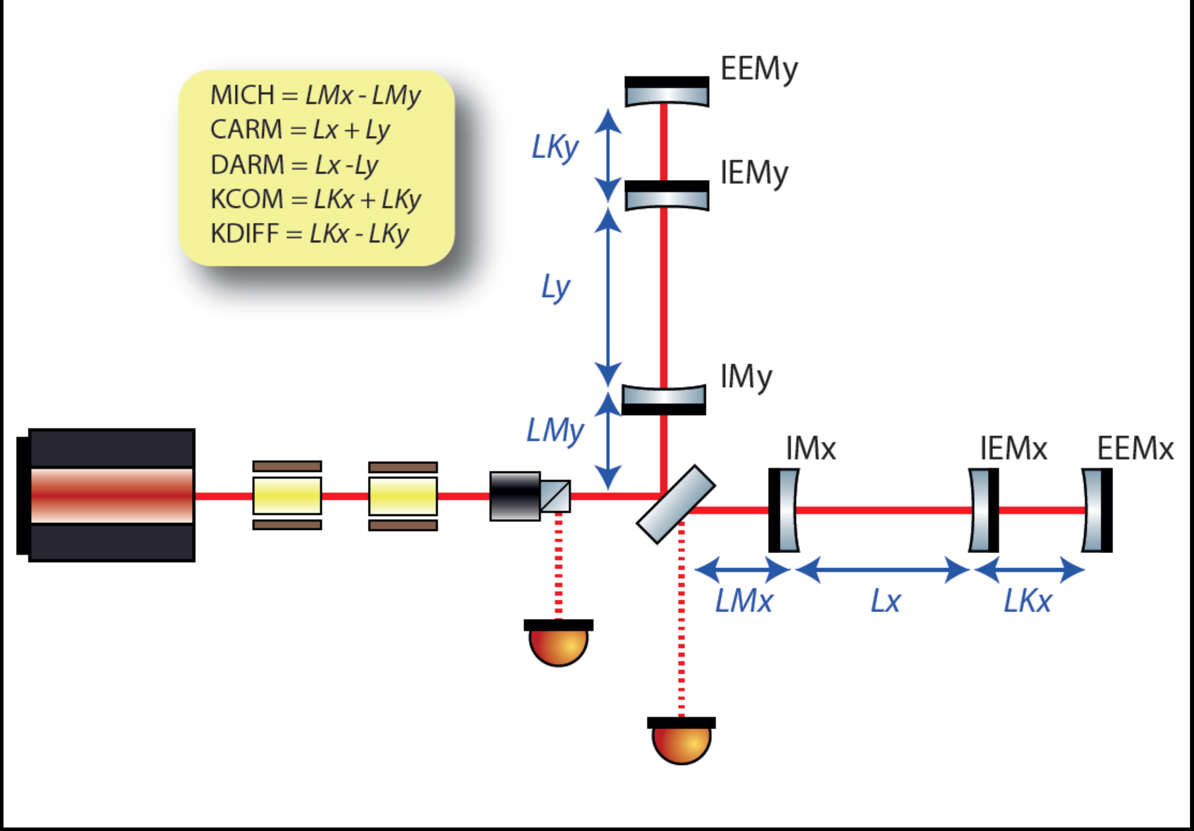
- Suppress DARM fluctuations in order to reach QN limited sensitivity of the diff. arm cavity mode
- Fluctuations of remaining DOF must not impair DARM sensitivity, i.e. noise contributions must be below DARM sensitivity
- Stabilize RMS deviation of each length-DOF to within 1% of its corresponding line width



Longitudinal DOF

Five longitudinal DOF to be stabilized:

- Central MI differential, 2 arm cavities, 2 Khalili cavities
- Coupled cavity systems incorporate coupled error signals, resonance state depends on all mirrors' tunings
- Design goal: obtain decoupled length signals for all five degrees of freedom with least effort possible
- Starting point: traditional frontal PM based control scheme



The formal description

Regarding the IFO as an LTI system:

- Linear relation between displacement and extracted length signals
- Sensing matrix M
  - Elements are DC limits of optical TFs
  - Each column corresponds to one length DOF
  - Each row corresponds to one length signal
- Optically decoupled sensing systems preferred, i.e. looking for fully diagonal M
- “Indirect“ diagonalization by changing sensing system parameters not always trivial, many knobs to turn

Sensing Matrix

$$\boxed{M \cdot \vec{\Delta} = \vec{s}}$$

Signal vector

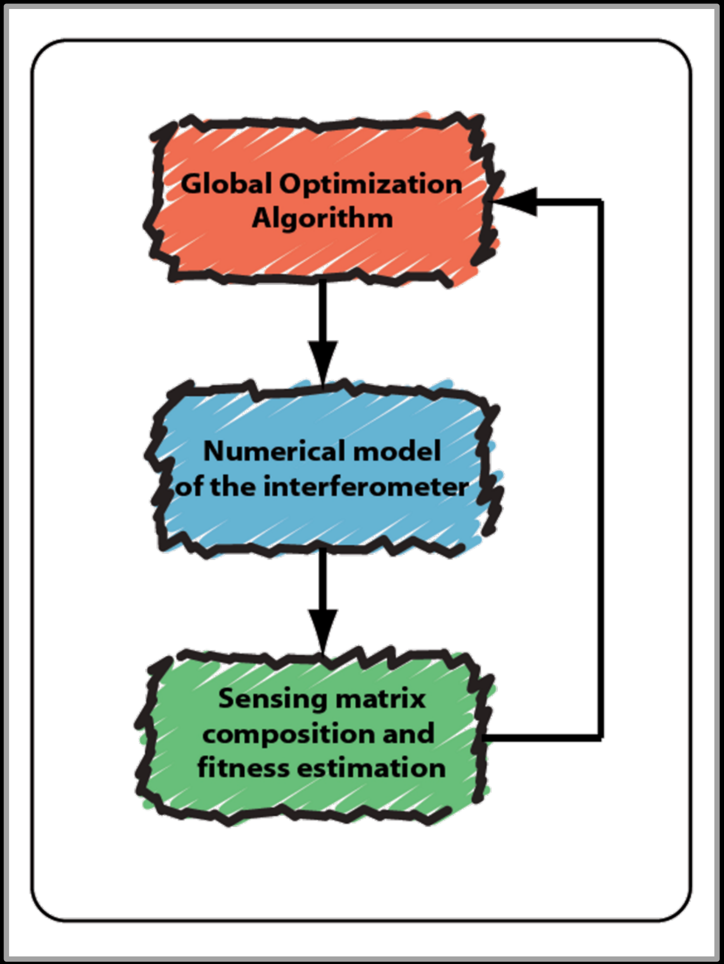
Displacement vector

Columns = length DOF1 – DOF5

$$\begin{pmatrix} \alpha(1) & \alpha(2) & \alpha(3) & \alpha(4) & \alpha(5) \\ \beta(1) & \beta(2) & \beta(3) & \beta(4) & \beta(5) \\ \gamma(1) & \gamma(2) & \gamma(3) & \gamma(4) & \gamma(5) \\ \delta(1) & \delta(2) & \delta(3) & \delta(4) & \delta(5) \\ \varepsilon(1) & \varepsilon(2) & \varepsilon(3) & \varepsilon(4) & \varepsilon(5) \end{pmatrix} = M$$

$$S = \{\alpha, \beta, \gamma, \ldots\}$$

Sensing system optimization



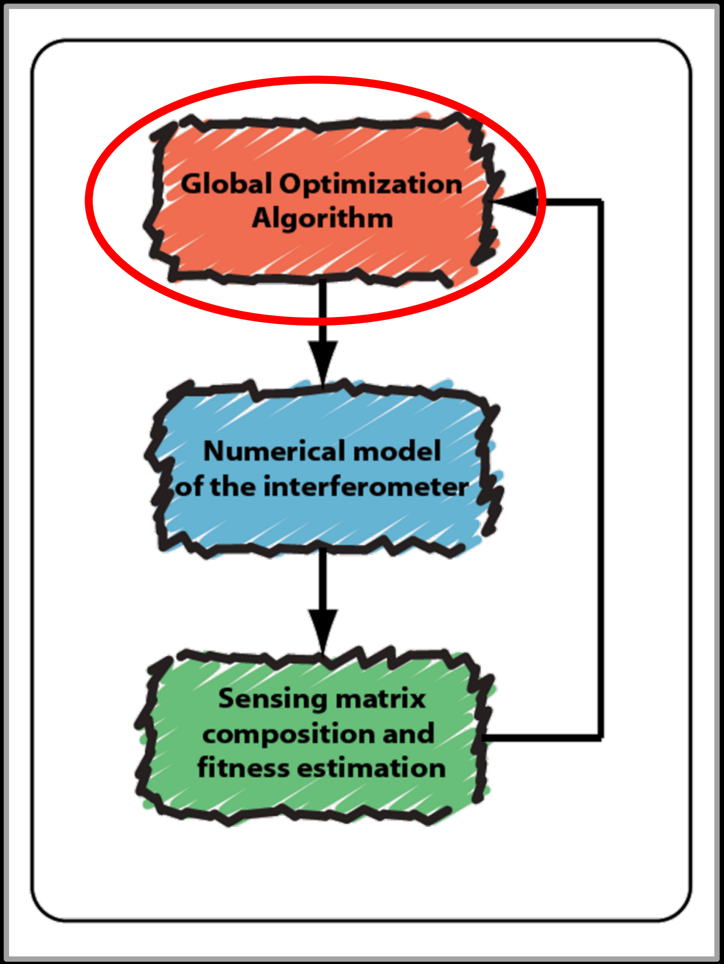
<u>Sensing system design ingredients:</u>

- Numerical IFO model
- Parametrized sensings system: PM frequencies, phases, ...
- Iterative “trial-and-error“ search for sensing system with desired performance

<u>Automating this task:</u>

- Formulation as an optimization problem
- Wrap numerical model up in between an optimization algorithm and a module to evaluate iteration step quality

Sensing system optimization



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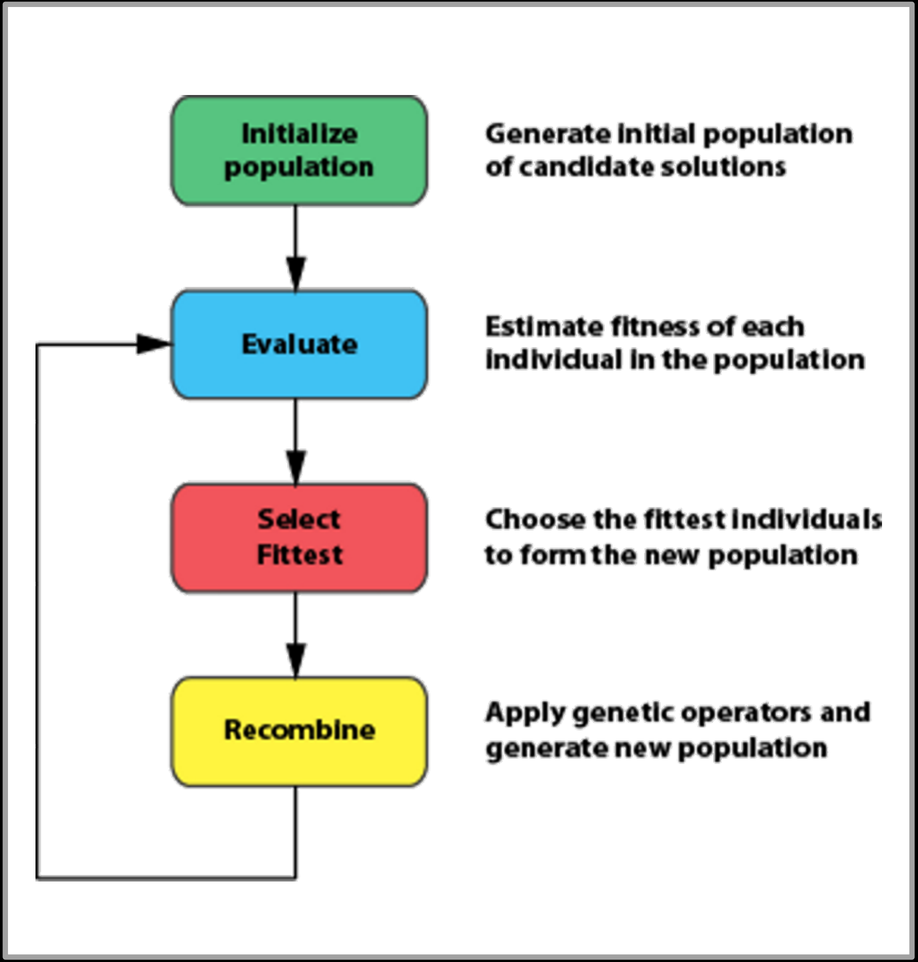
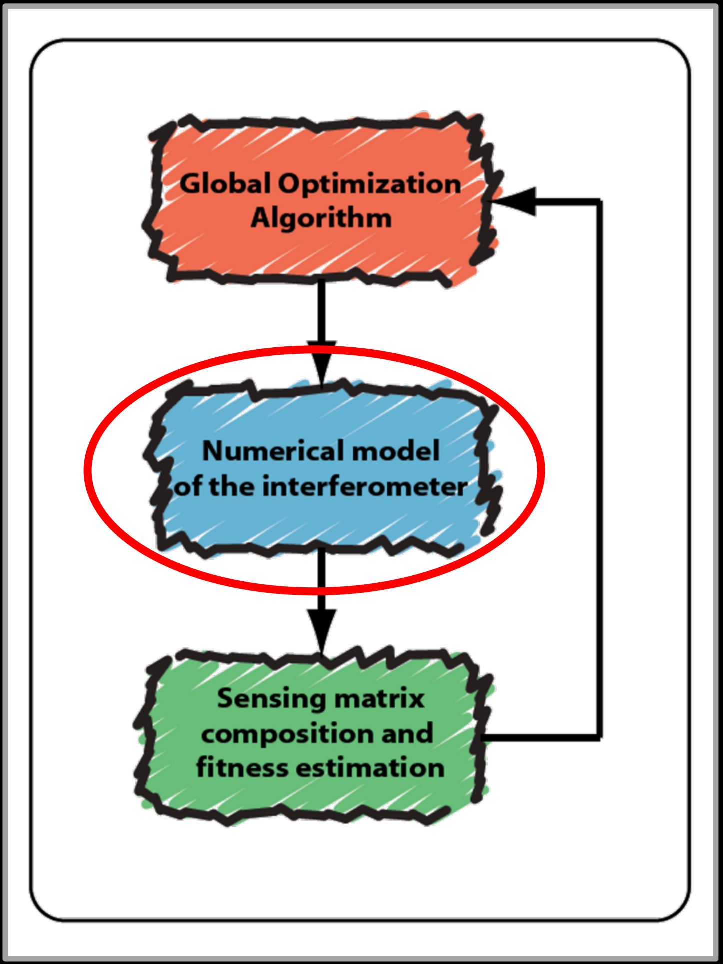
Global optimization algorithm



Global Optimization algorithm:

- Many different algorithms available, focussing on "Genetic Algorithm" (GA)
- Properties:
  - Based on natural selection as in biological evolution
  - Generates "population", i.e. set of sensing parameter vectors
  - Parameter used to simulate a sensing system whose performance is evaluated by a subsequent stage
  - Best "individuals" of a population are allowed to reproduce
  - "Mutation operator" to prevent uniformity of a population
  - Population evolves towards optimum over successive generations

Sensing system optimization

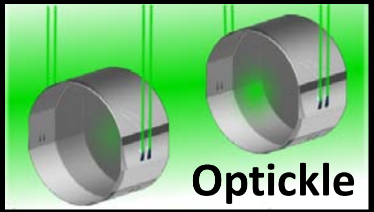


The numerical IFO model:

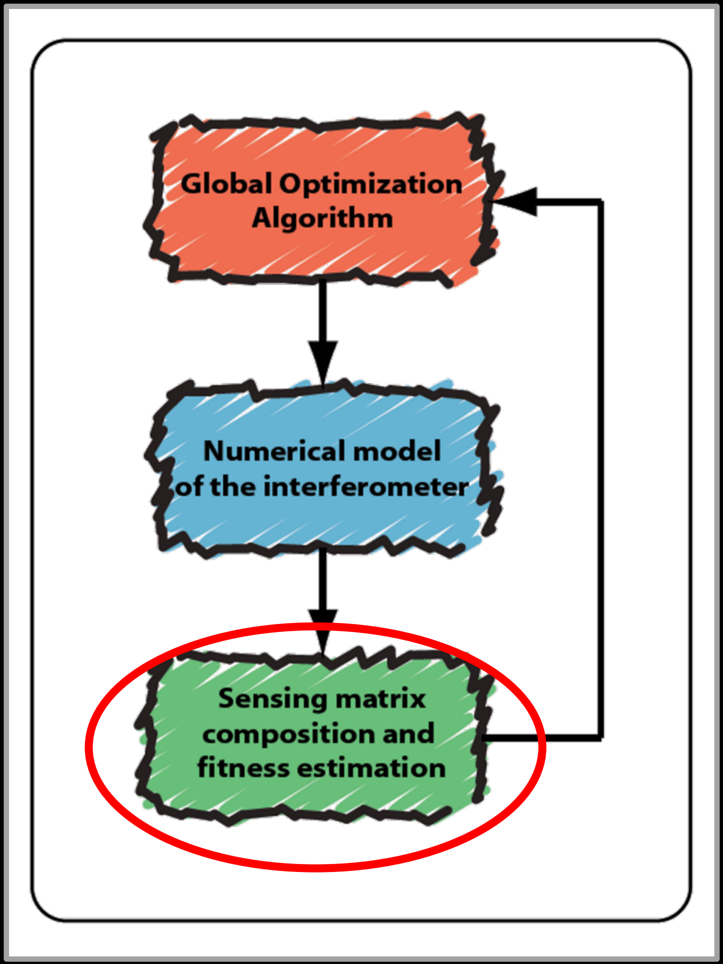
- Optimization module was built around SubSQL IFO Optickle model

- Can be easily replaced with any simulation with similar functionality

- Optickle is
  - AdvLIGO reference for frequency domain modelling
  - Written in Matlab, slow but easy to extend
  - Includes radiation pressure



Sensing system optimization



Evaluation of the quality of a solution:

- Receives signal vectors from numerical IFO model, one for each DOF

$$\#S = \#\mathrm{ports} \times (2 \times \#\mathrm{fm} + 1)$$

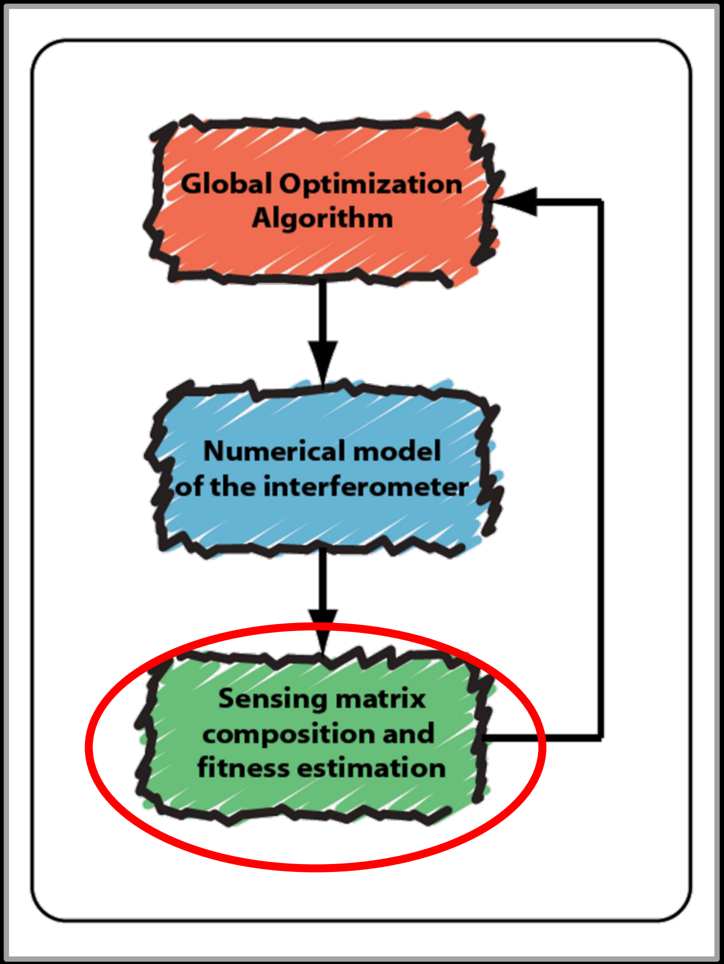
- Multitude of matrix realizations can be composed by taking all combinations of 5-element subsets of available signals in S

Numbers:

- 2 Ports + 2 RF frequencies => 10 signals => 10!/5!=30240 matrix realizations
- 4 Ports + 2 RF frequencies => 20 signals => 20!/15! ≈ 1.9 million matrix realizations

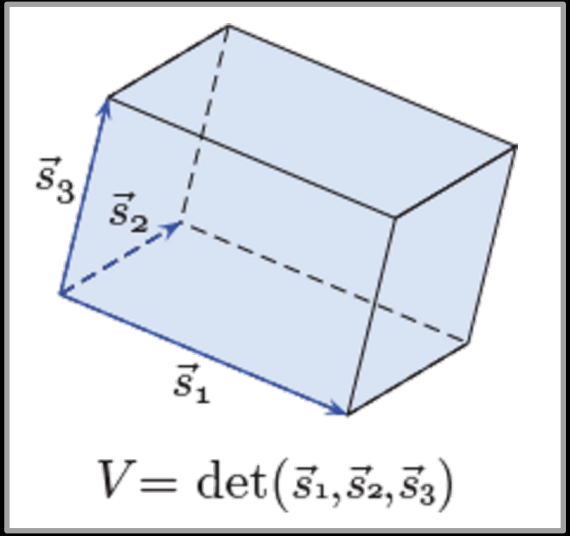
Constraints help to save computational cost!

Sensing system optimization



Evaluation of the quality of a solution:

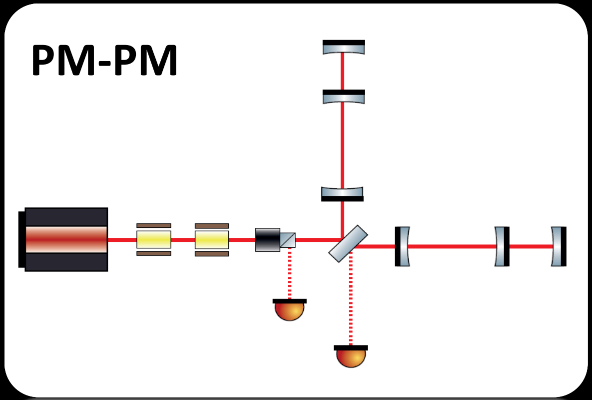
• Optimizer needs feed back of the quality of the current iteration
• Figure of merit for “diagonality“ of a matrix: volume spawned by it (normalized) row vectors, i.e. based on determinant of normalized matrix

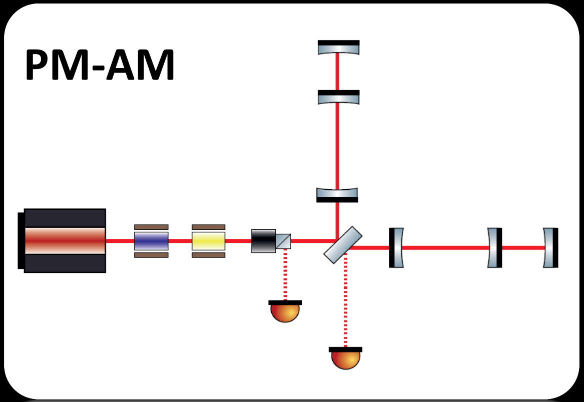


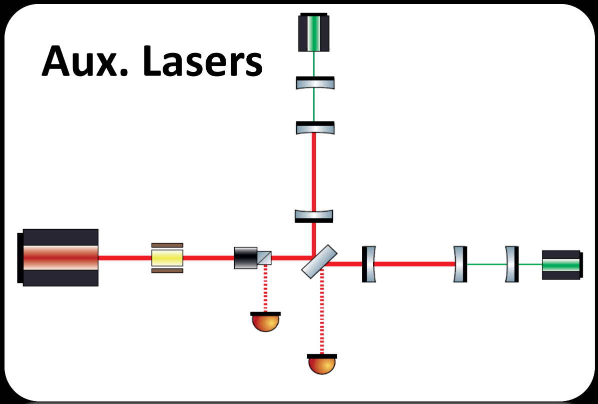
Sensing system optimization outlook

What's next:

- Second numerical model (Finesse) for double checking of results
- Parallelize code to run configurations with realistic no. of sensing ports
- Questions to be answered:
  - Can we control the 5-DOF interferometer with frontal phase modulation? More "exotic" techniques required, e.g. double demodulation?
  - Do we need to access sensing ports besides the natural ones to obtain sufficiently decoupled error signals?
  - Do we have to complement the PM scheme with AM, auxiliary lasers, ... ?







10m Prototype IFO optical design

- Our reference for experiment outline: K. Somiya‘s conceptual design report
- Majority of parameters with an immediate impact on sensitivity goal are fixed
- “Technical“ parameters, e.g. Cavity lengths, RoCs, ... left to be determined
- Need to find configuration which can be stably operated

AEI Hannover / LIGO Scientific Collaboration

Hannover 10m Prototype 09/1/16

Conceptual design of an interferometer with a sub-SQL sensitivity ver. 2.0

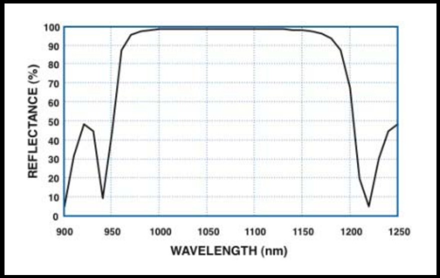
K. Somiya, J. Breyer, Y. Chen, K. Dahl, K. Danzmann, A. Freise, S. Goßler, H. Grote, G. Heinzel, M. Hewitson, F. Kawazoe, G. Kühn, J. Kullmann, H. Lück, K. Mossavi, H. Müller-Ebhardt, H. Rehbein, H. Ryll, R. Schnabel, K. Strain, B. Taylor, C. Torrie, A Wanner, A. Weidner, and B. Willke

This is an internal working note of the GEO Project.

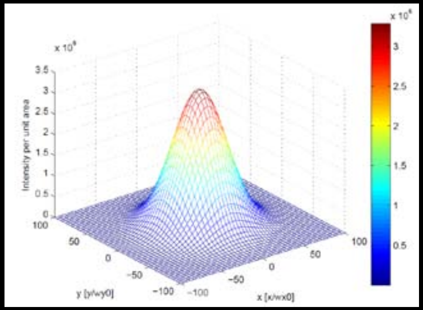
Fixed parameters

1. Mirror mass
   - Optimal mirror mass, m=12g
   - Mirrors with m=100g preferred

2. Mirror aspect ratio
   - Optimal radius: a=2.43cm
   - Optimal thickness: h=2.45cm



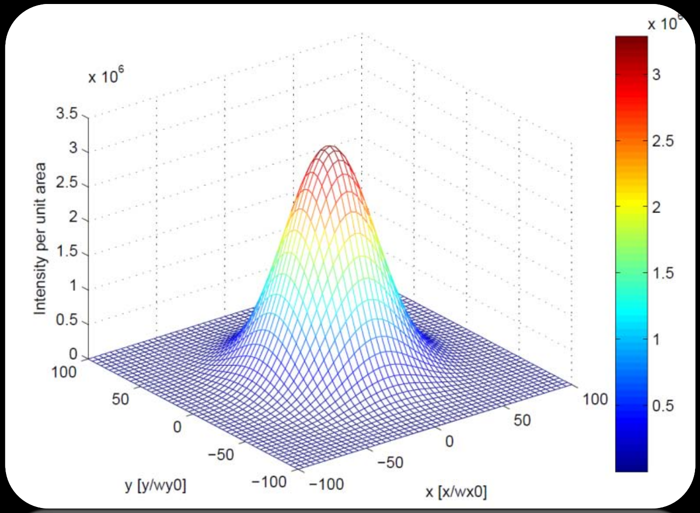
3. Mirror reflectivities
   - N=8, R=99.07% for IM
   - N=2, R=51.151% for IEM
   - N=15, R=99.997% for EEM



4. Laser spot size
   - Spot radius of w=9.7mm on arm cavity mirrors

Laser spot size requirement

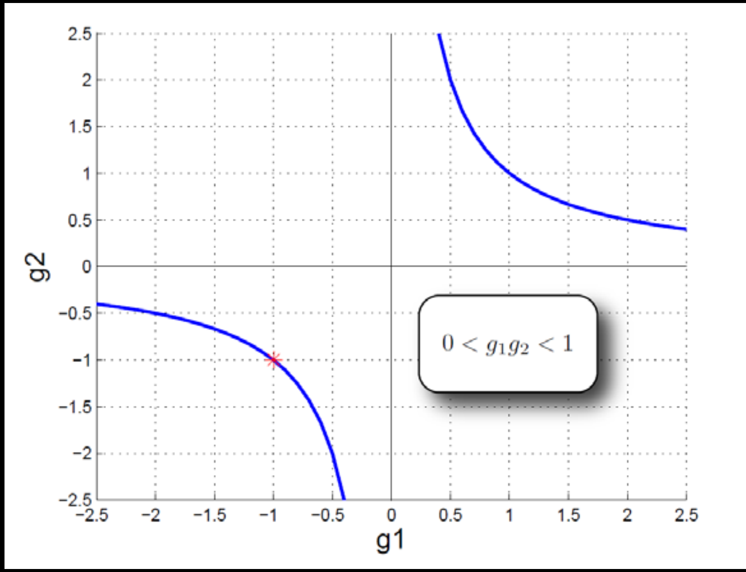
- Larger spot = lower power density per unit area, desired to reduce CTN and STN
- Upper limit is set by tolerable diffraction loss
- Conceptual design suggests to go for w=a/2.5=9.72mm which corresponds to a diffraction loss of approx. 2.25ppm
- Complicates finding a stable configuration

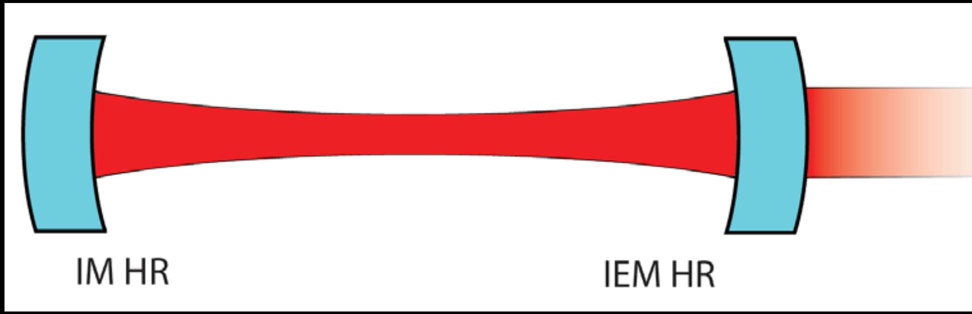


The arm cavity

SubSQL IFO-style arm cavity:

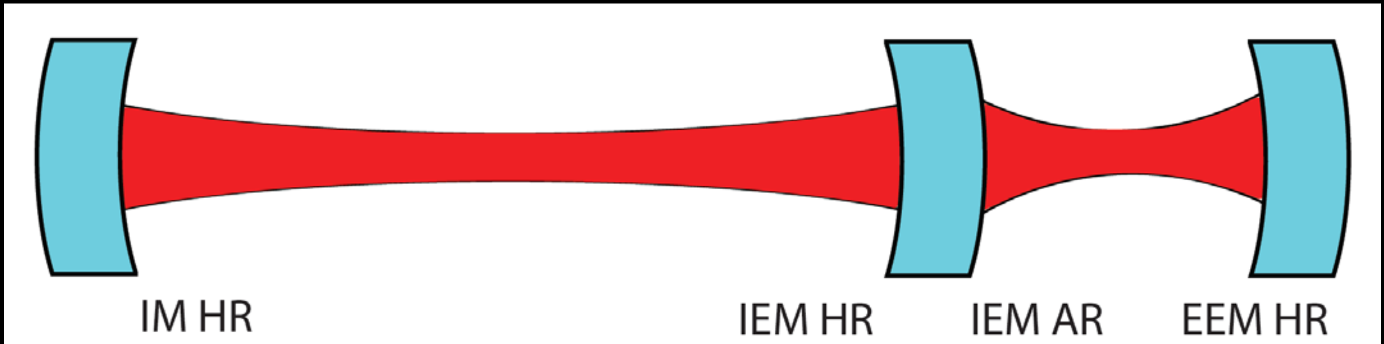
- Feasible length due to spatial constraints: 10.03 m – 11.26 m
- Choose a symmetric, nearly concentric configuration with RoCs slightly larger than L/2 to fulfill spot size requirement
- Stability: $g^2(L_{min})$= 0.9987 ; $g^2(L_{max})$= 0.9984



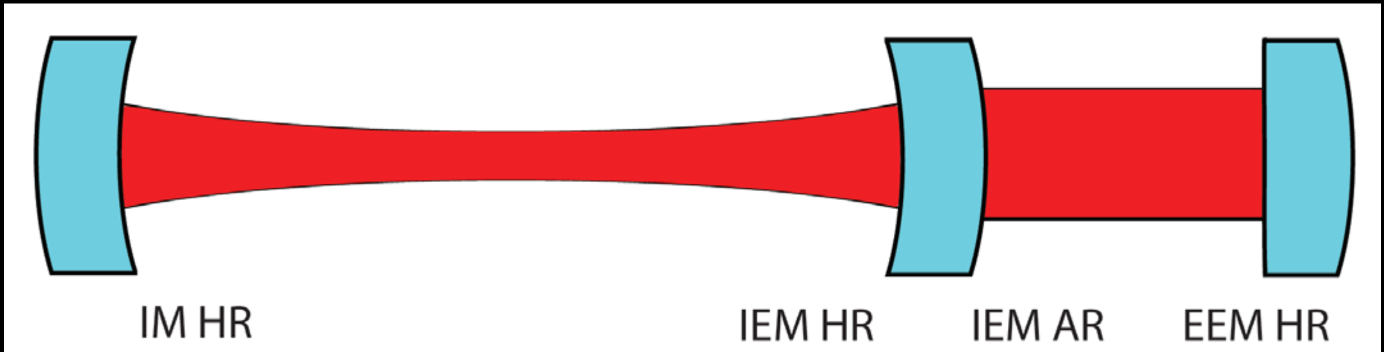


Configuration candidates

Strongly curved IEM AR side, second waist in KC



Modest IEM AR side curvature, nearly collimated beam in KC



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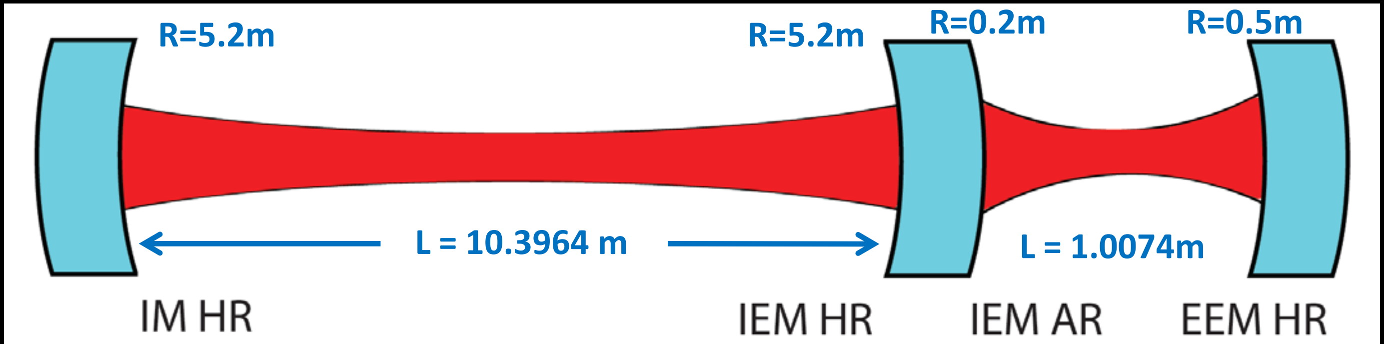

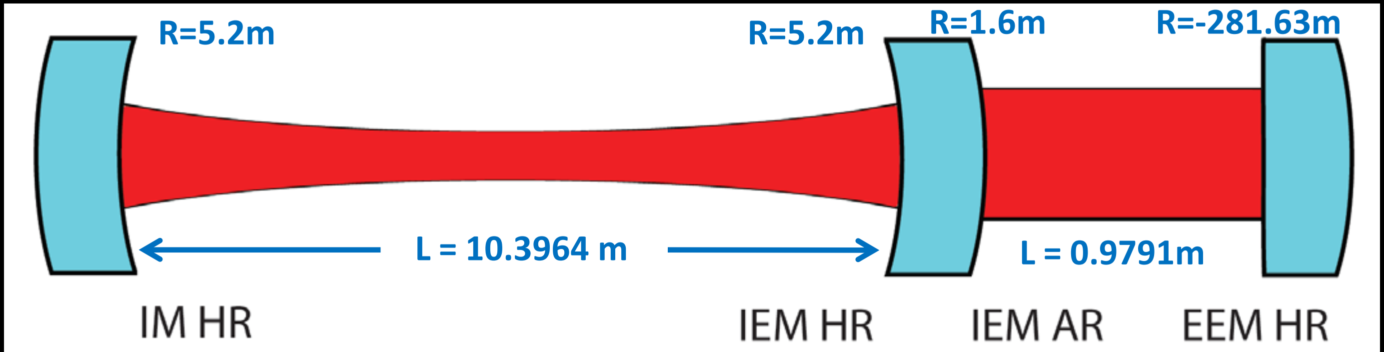

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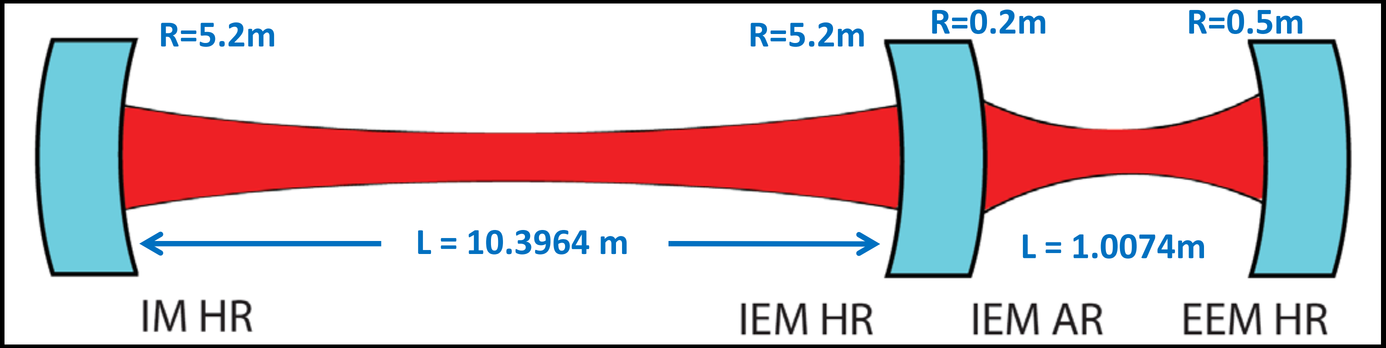
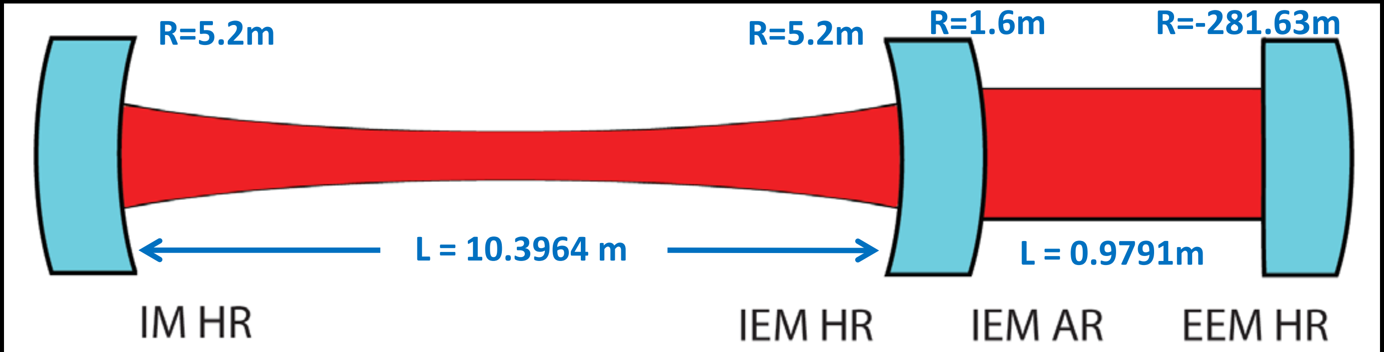


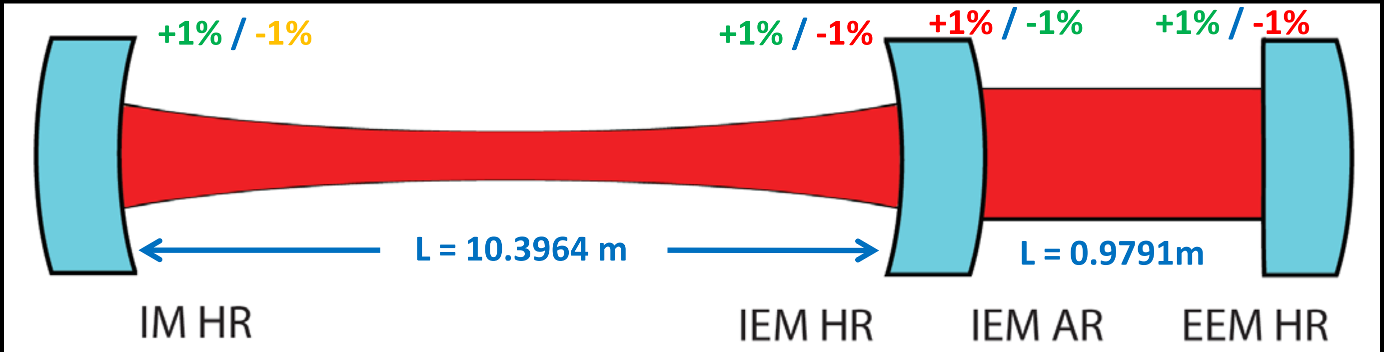
- Stability IM-IEM g ≈ 0.998; IEM-EEM g ≈ 0.99999
- KC stability highly susceptible to changes of the KC length: KC length increase by 3 micron => g > 1
- Apparently inoperable with nominal spot size

Configuration candidates



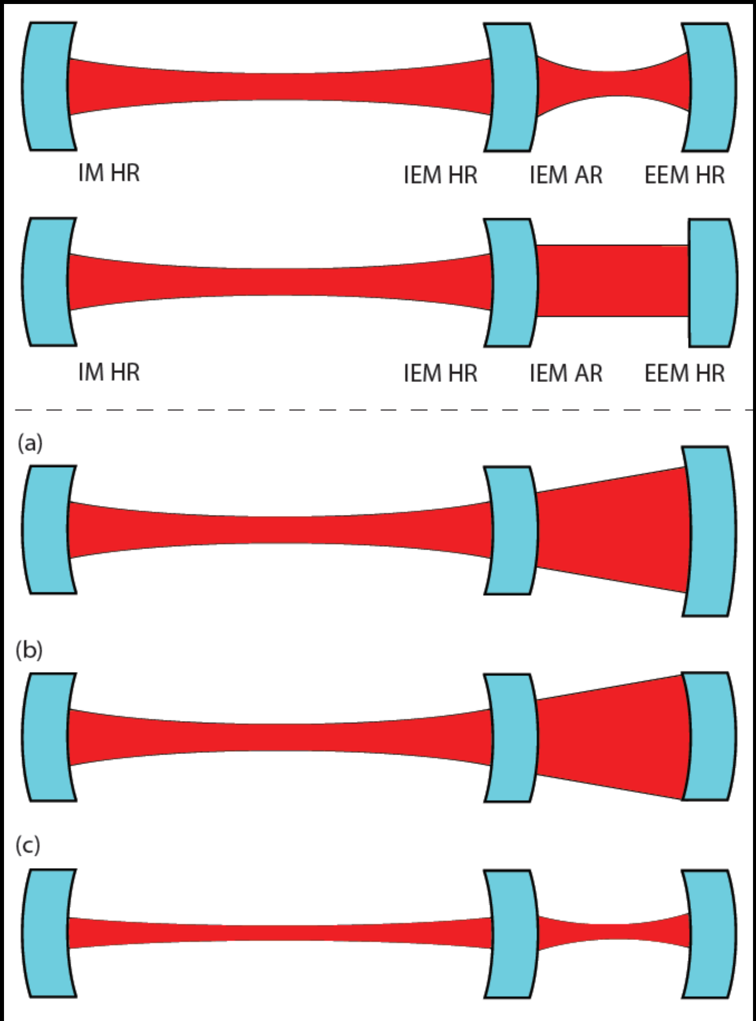
- Stability IM-IEM g ≈ 0.998; IEM-EEM g ≈ 0.99999
- KC stability highly susceptible to changes of the IEM AR RoC:
  AR RoC increase by ≈ 0.1 mm => g > 1
- Thermal actuation difficult, would affect IEM HR as well
- Loophole: compensate RoC error via KC length ?!

RoC "tolerancing"



- Change each RoC by +1% and by -1%
- If the corresponding cavity gets unstable try to recover stability by changing corresponding length
- Three different outcomes:
  - stability not affected
  - cavity gets unstable, stability can be recovered by shifting mirrors
  - cavity gets unstable, stability cannot be recovered by shifting mirrors
- Spot size requirement is violated in all cases but can be recovered

Cavity options



Alternatives:

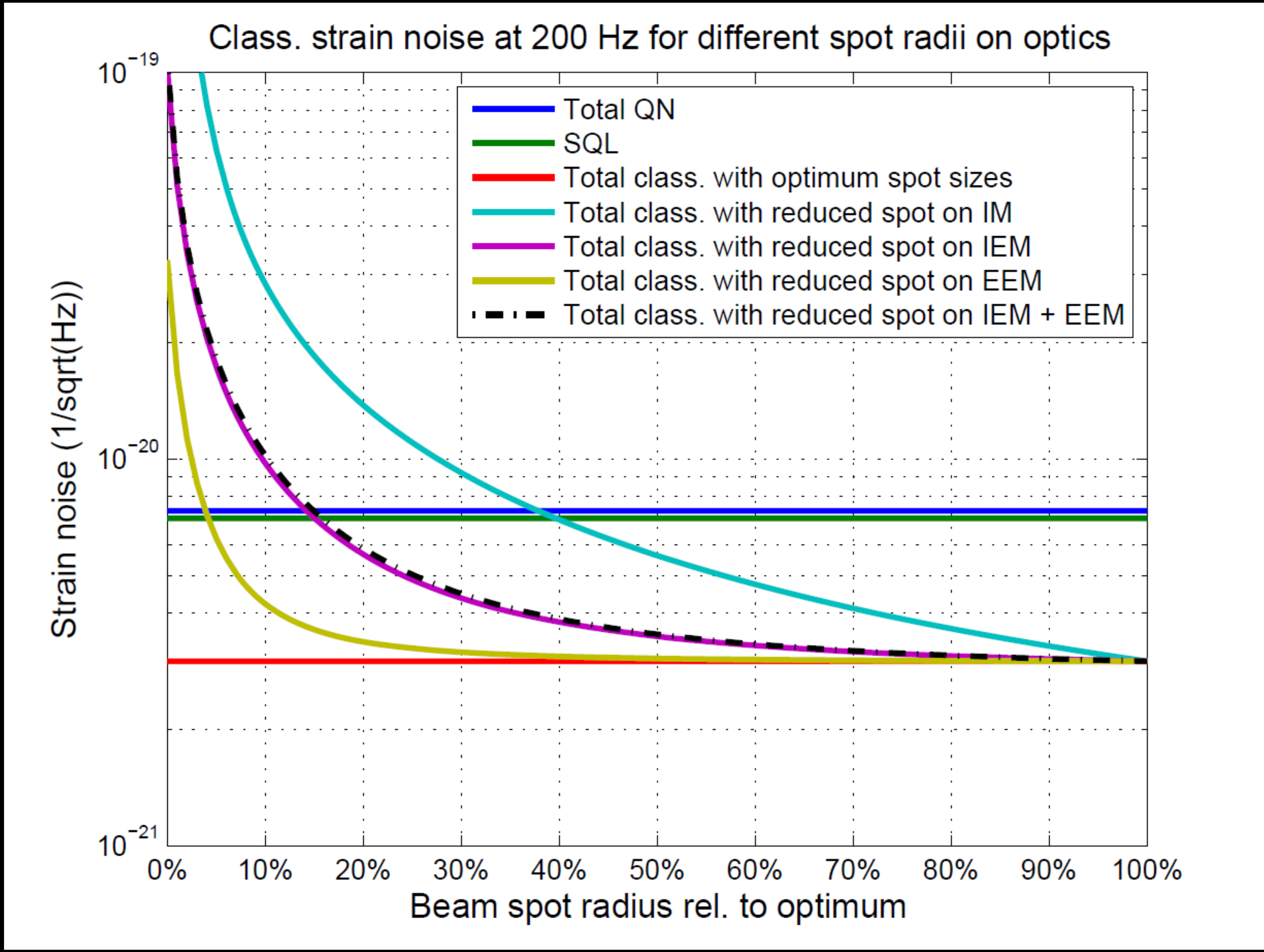
(a) No focussing of beam in IEM transmission, larger EEM to control diffraction loss => new suspension?

(b) No focussing of beam in IEM transmission, live with increased diffraction loss => can we afford this?

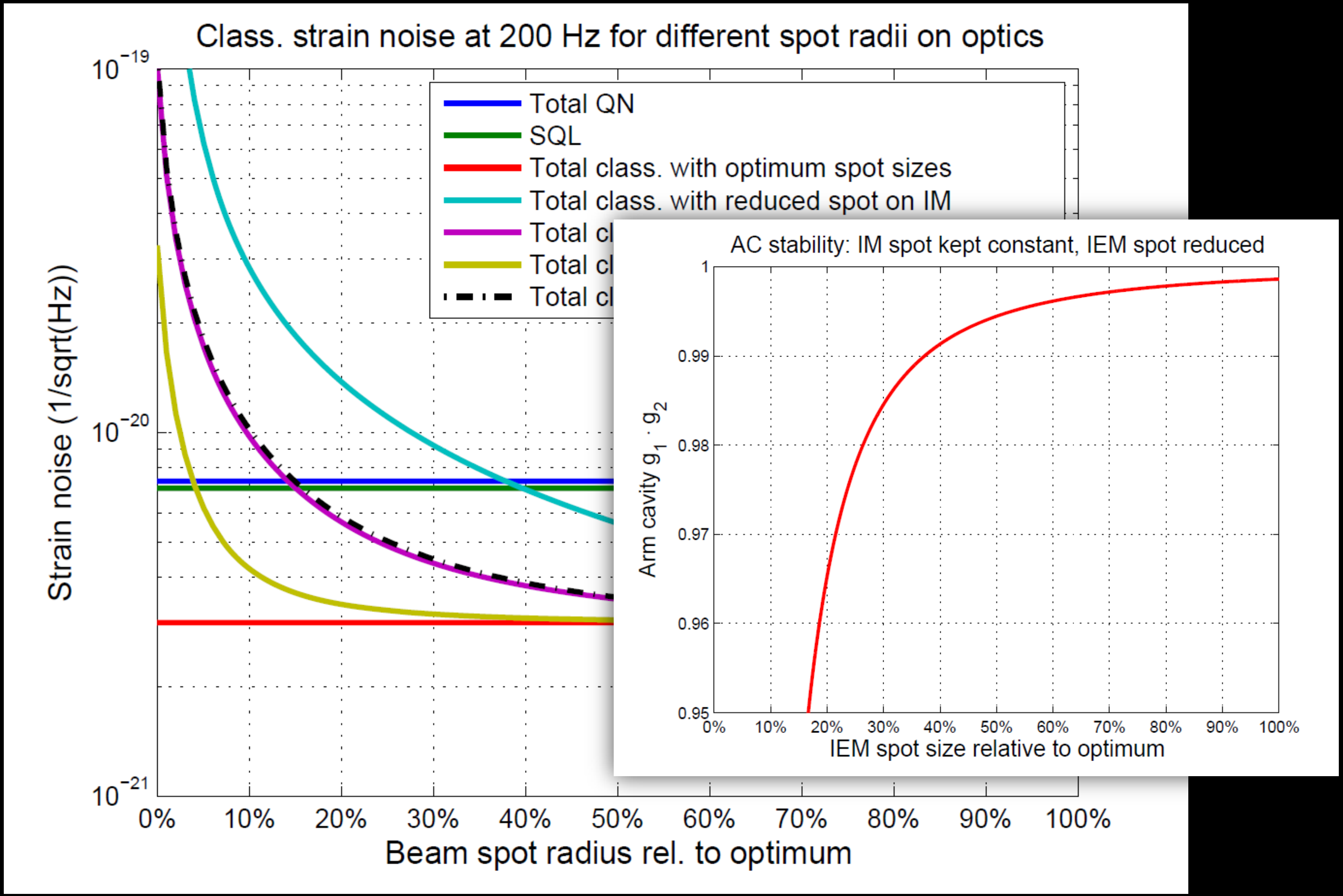
(c) Reduced spot sizes on one or more HR coatings => increased thermal noise

(d) “Off-nominal“ design + online tuning to nominal op. mode

Relaxing the spot size requirement



Relaxing the spot size requirement



THANK YOU FOR YOUR ATTENTION

Visit us at http://10m-prototype.aei.uni-hannover.de