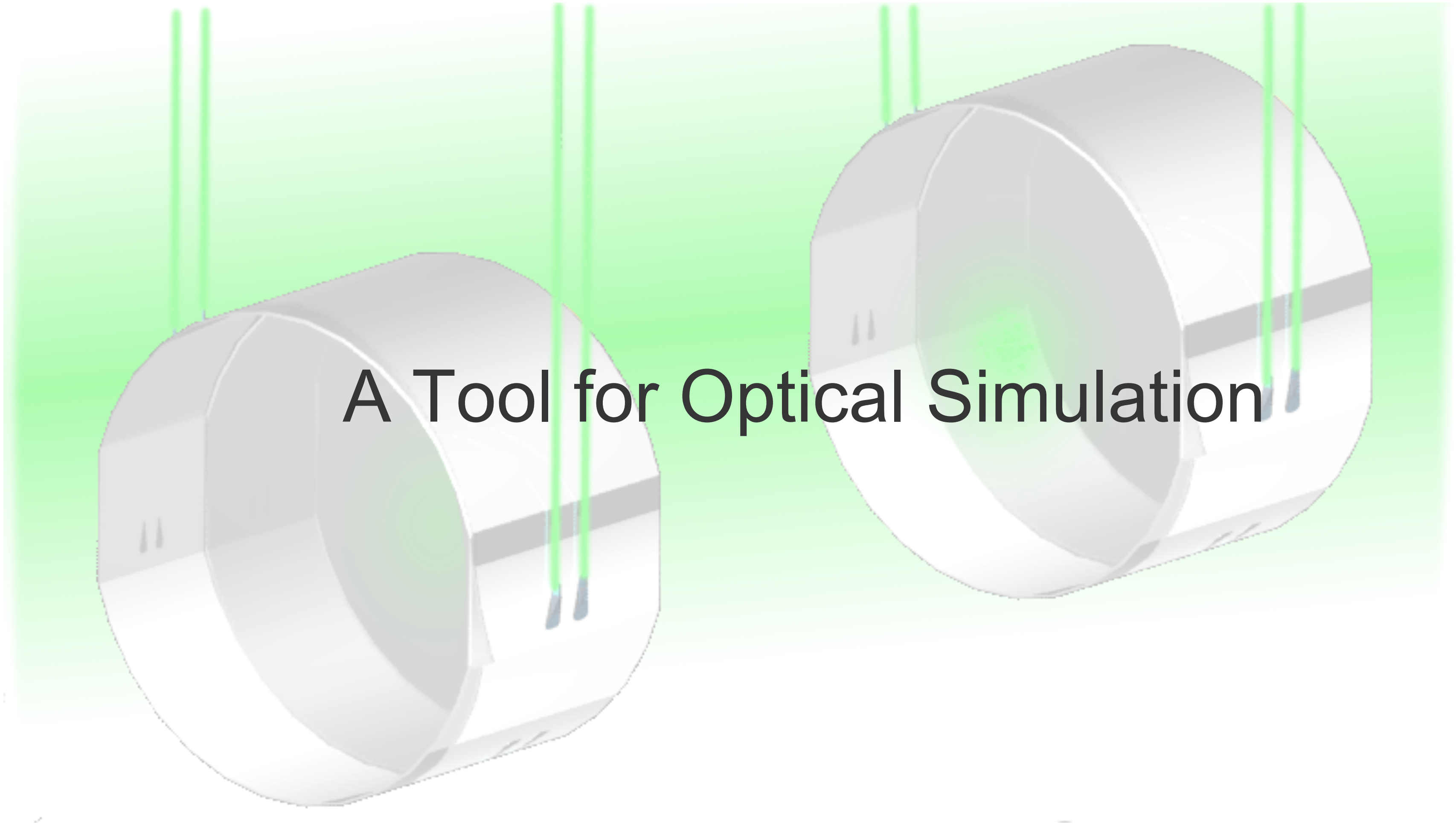
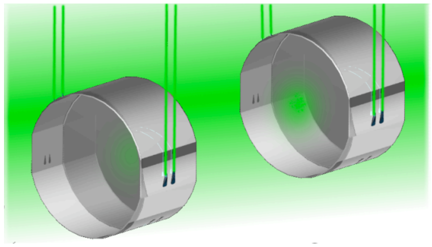
ISC Requirements and Conceptual Design Review Presentation

April 9, 2008
G080255-00

Optickle

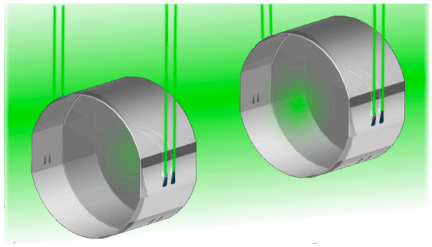


A Tool for Optical Simulation



What can it do?

- Simulates a well aligned, well matched optical system
- Modular structure allows for many interferometer configurations
- Computes longitudinal and angular transfer functions, including radiation pressure
- Computes DC signals, and quantum noises

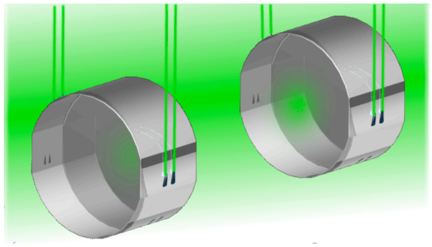


How does it do this?

- Optickle provides structure around the simple matrix equation

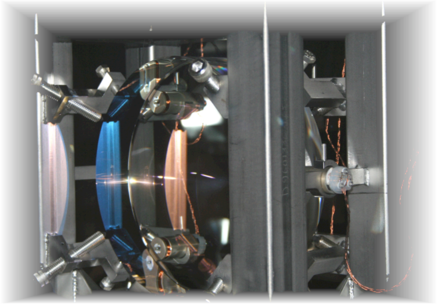
$$\vec{v}_{out} = M_{out}(I - M_{opt})^{-1}\vec{v}_{source}$$

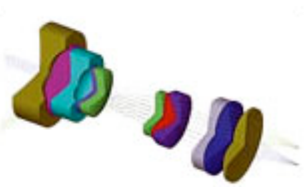
- This equation propagates source fields through an optical system to a set of output ports
- Optickle provides the
  - building blocks of an optical system and ways to connect them
  - framework necessary to apply this equation in the presence of many optical components and many fields
  - interface between fields and measurable quantities (signals)

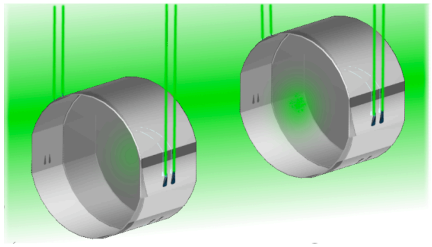


Optickle Building Blocks

- Mirror
- Beam Splitter
- Source
- Sink
- Modulator
- RF Modulator
- Telescope

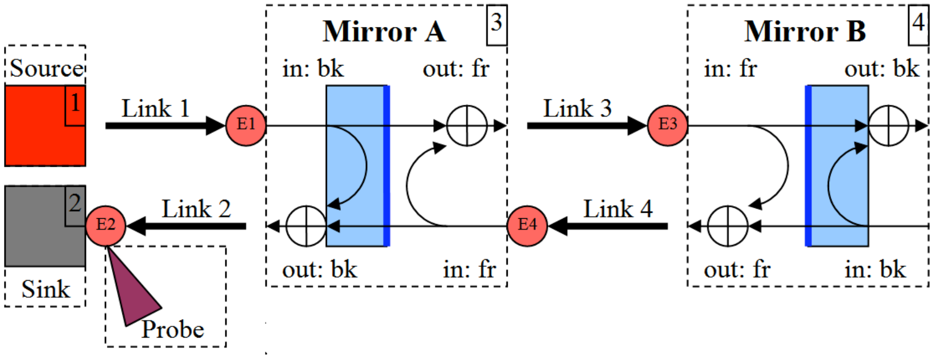


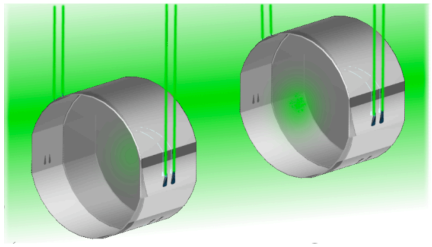




Optickle Glue

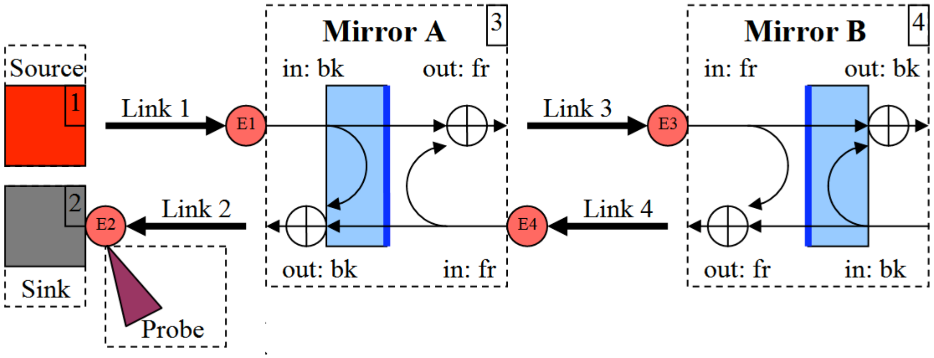
- Links
  - Used to define the relationships between the optical modules
  - Connect from one module output to another module input, with some length

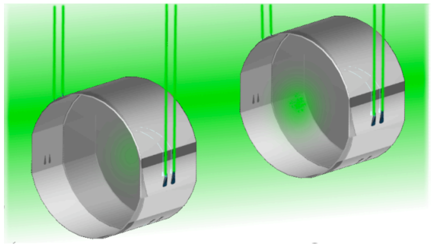




Optickle Output

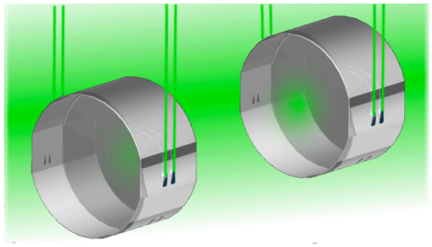
- Probes
  - Used to extract information about the fields in the simulation
  - Often attached to the input of a Sink, thus making a photo-detector





Conclusion

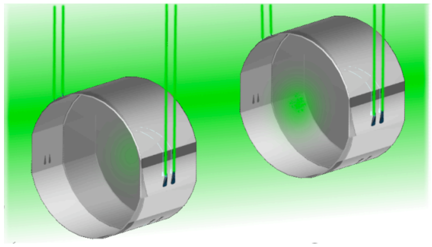
- Optickle was written to facilitate advanced interferometer design where
  - Radiation pressure effects are large in both longitudinal and angular responses
  - Quantum noise is not easily divided into shot noise and radiation pressure noise



What is already out there?

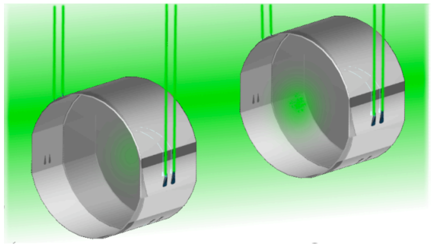
- Finesse
  - Many modes
- Static FFT models
  - Non ideal optics
- E2E, Siesta
  - Time domain

- Optickle
  - TEM00 and 01 only
- Optickle
  - Ideal optics
- Optickle
  - Frequency domain



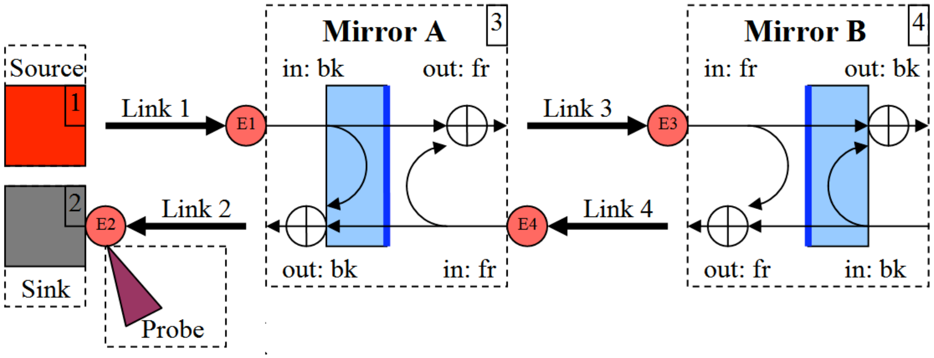
Why Opticle?

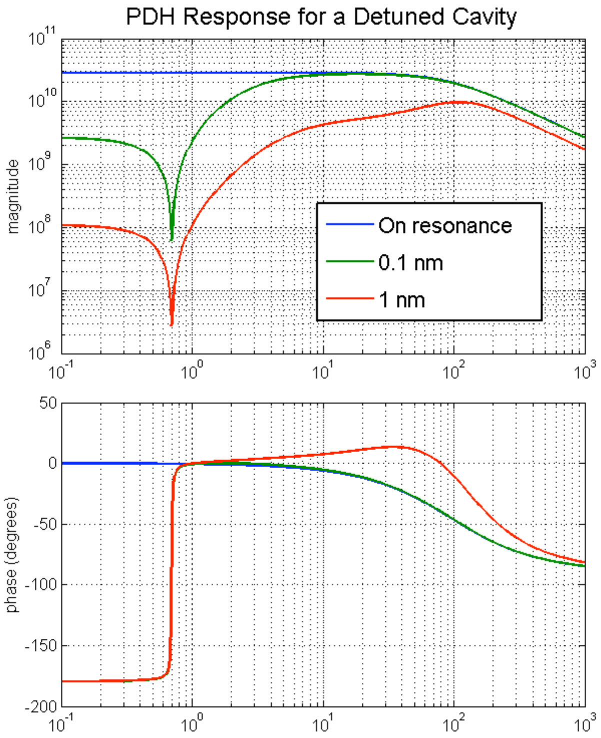
- Includes radiation pressure directly
- Computes quantum noises starting from vacuum fluctuations at all loss points
- Matlab based
  - Commonly used environment, especially for control system development and noise analysis
  - Convenient plotting and post-processing
  - Avoids many portability problems

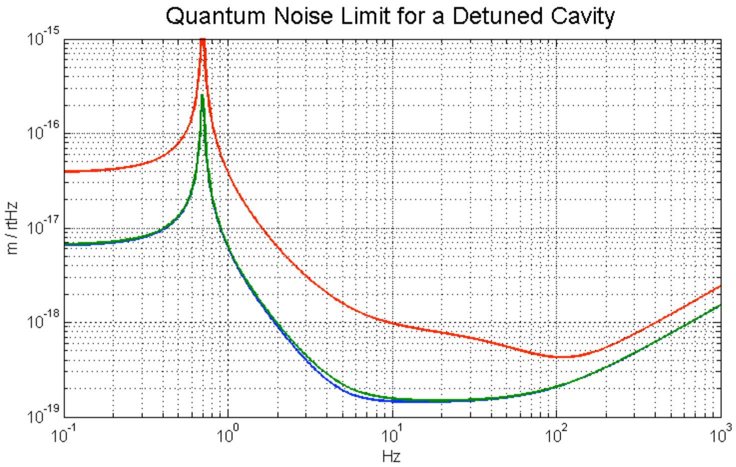


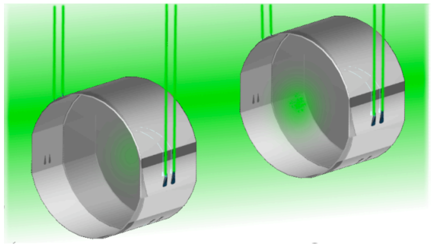
Longitudinal Example: Detuned Cavity

- Radiation pressure effects
- Quantum noise



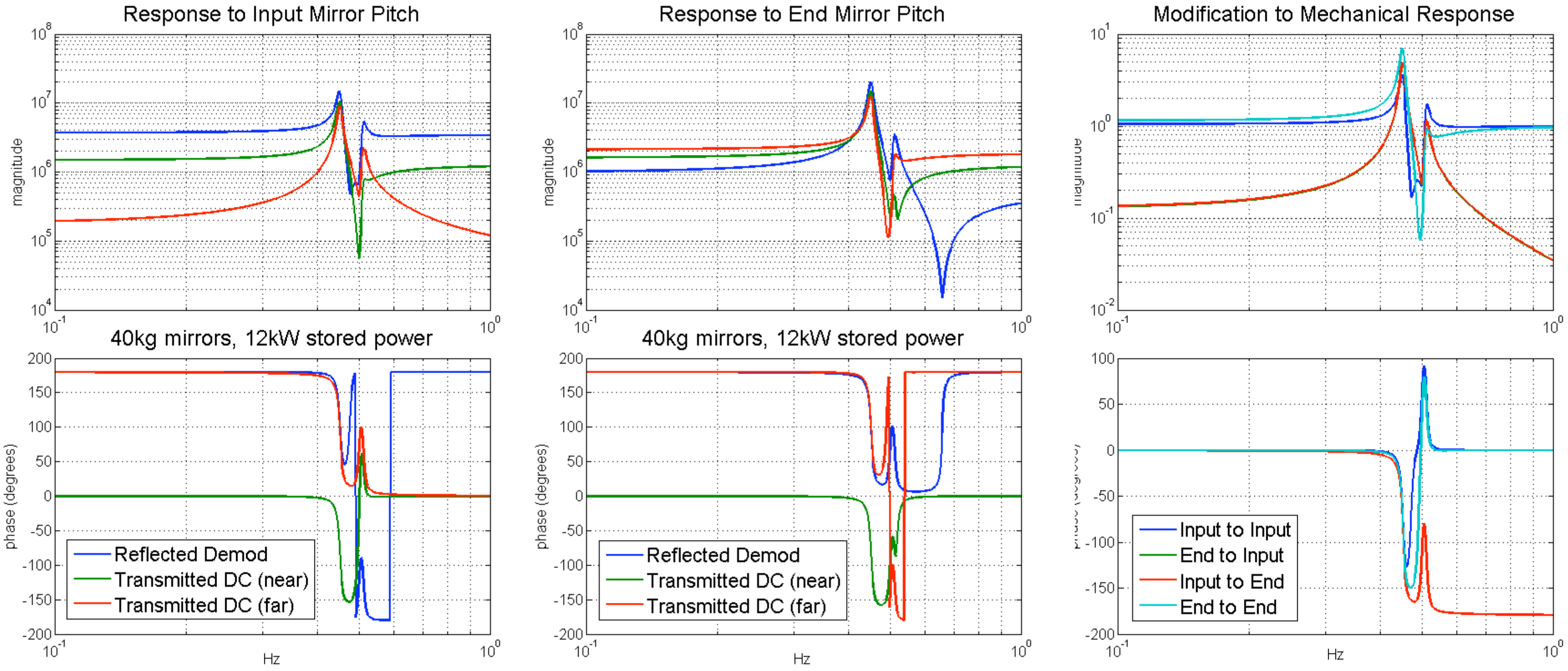


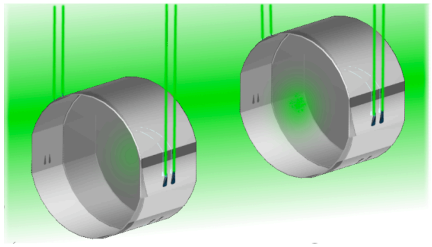




Angular Example: Flat-Curved Cavity

- Radiation pressure effects present in angular response





Optickle Interface

- Direct
  - Vector of DC signals from probes
  - Matrix of transfer functions from all drives to all ports (probes and drives)
  - Quantum noise at all ports
- Indexing can be painful
  - Functions for getting indexes by name
- Control loops added externally
  - e.g., looptickle

B. There seems to be a lot of modes of operations. Most of them are not worked out in detail, but it seems unrealistic that so many will be needed. We would like to hear some additional information. One might argue that the scientific justification for some of these modes is marginal. Improvement are usually only of the order of 30% in sensitivity, but degradation in other frequency bands is significant. In particular, there seems to be little reason to invest in detuned modes at this time.

- We agree. We can immediately drop:
  - Mode 4: BH-BH optimization, with very poor sensitivity above 100 Hz, and only a few percent increase in source range
  - Mode 5: Narrow-band at 1 kHz
- We propose to concentrate on the zero-detuned modes, as suggested

B, cont’d. `Is mode 0 a stepping stone before including a SRM? How much of future ISC time will be used for developing some of these modes? Is it possible to go forward and concentrate on a single mode of operation?`

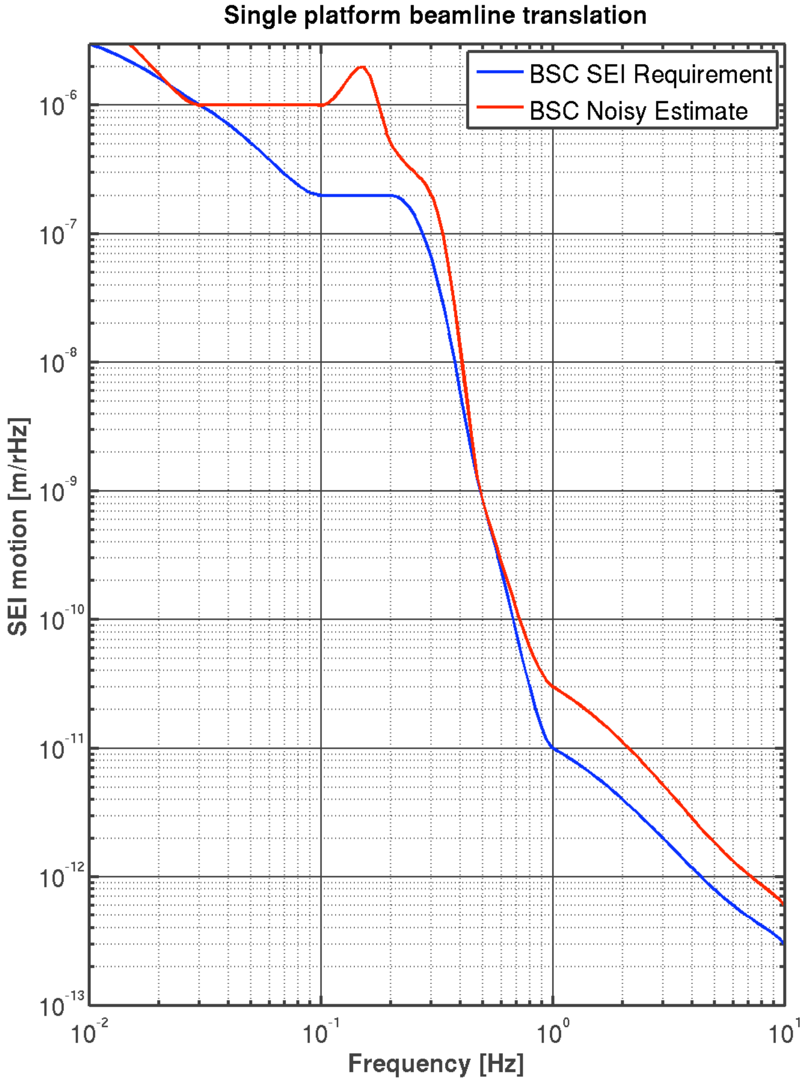
- Mode 0: depends what is meant by stepping stone …
  - Might very well want to make a science run in this mode
  - Still need to analyze controls for this mode; may want to increase asymmetry, e.g.

C. The requirement lists availability goals, but nowhere are they worked into the conceptual design. How do these requirements drive the design? What steps will be taken to ensure that they can be met? What kind of lessons have been learned with initial LIGO and how do they effect the current design? What steps are taken to address maintainability?

- Controlled acquisition algorithm
- Following good engineering practices on electronics design for high reliability

D. What exactly is the interface with SEI? How certain are we that the provided performance numbers will be met? Especially at very low frequencies? Are we talking about average or worst cases? How are we doing in the 5-10% percentile?

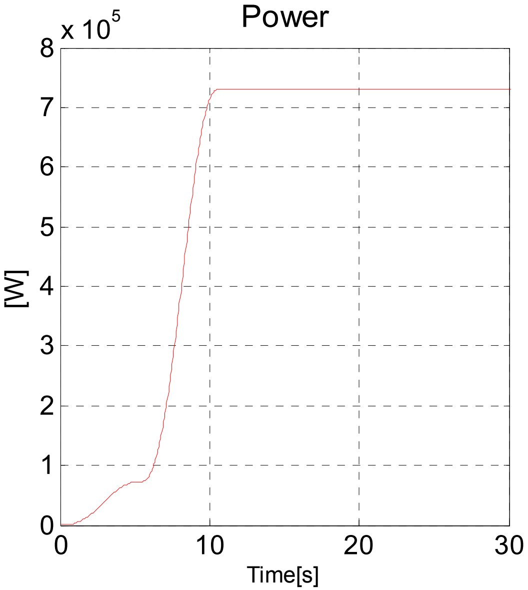
- Interface: slow feedback can be applied to SEI stages, if useful
- Performance: modeling uses elevated input for test masses (BSC ISI)
- However, HAM ISI not yet added to model; needs to be done



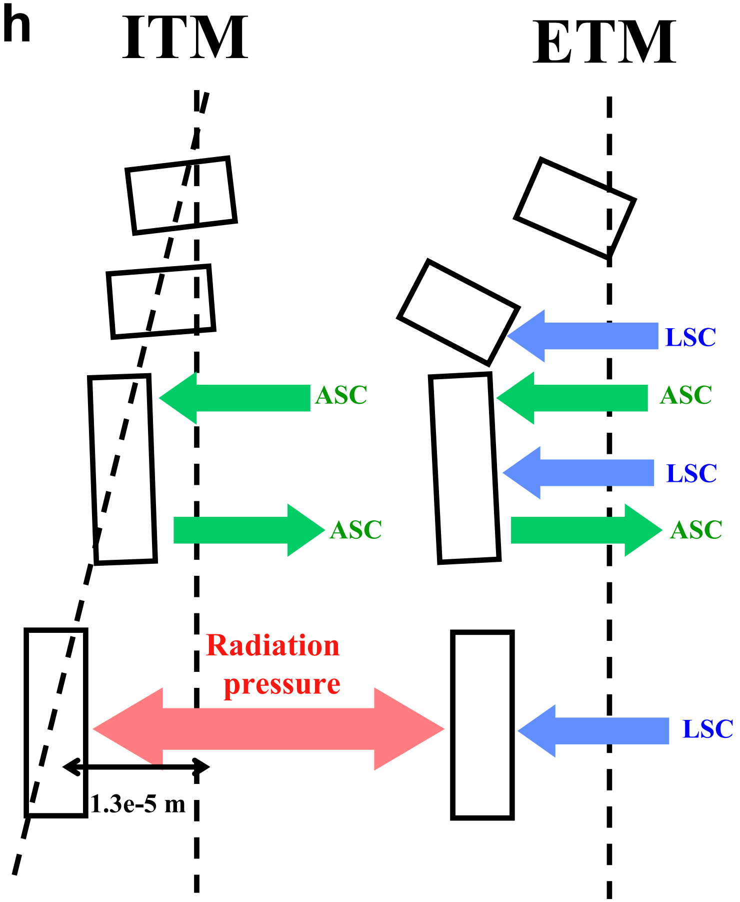
`Is there enough force to deal with radiation pressure---both longitudinal and due to the Sidles-Sigg angular instability? In particular during times of heightened seismic activity which presumably leads larger than usual power and angle fluctuations. What is the headroom to deal with non-stationary environmental disturbances?`

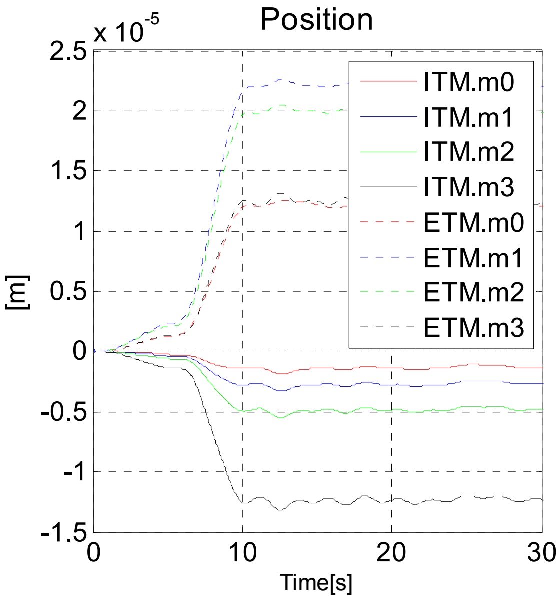
- Longitudinal:
  - static force is compensated at the Top Mass: ~10 microns out of 100 micron range
- Angles:
  - Osamu Miyakawa did some E2E modeling of an arm cavity at full power
  - Let’s look at some of his results, from G060396-00 …

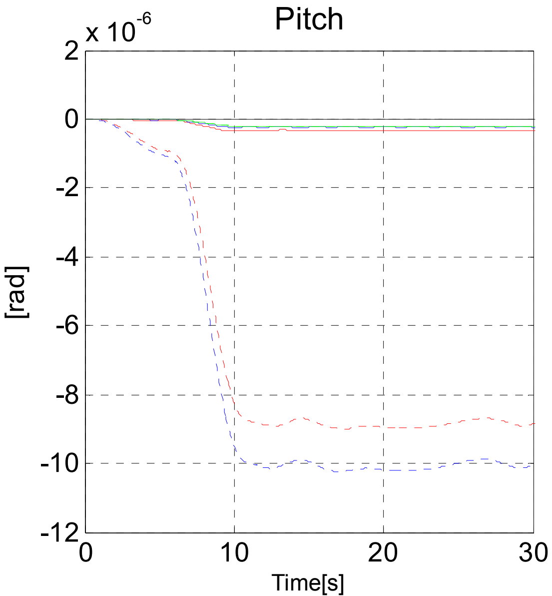
Test mass alignment control through M2 with radiation pressure



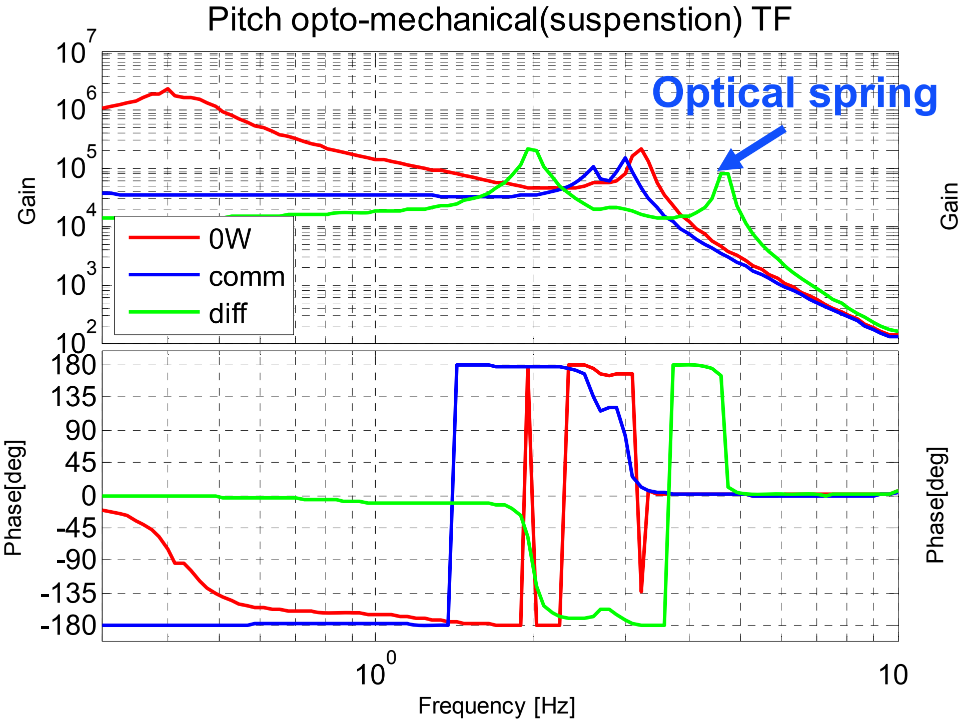
- **Control M3 through M2**
- ***f*** ^{3} **filter**
- **Boost at 2Hz**
- **10Hz control band width**



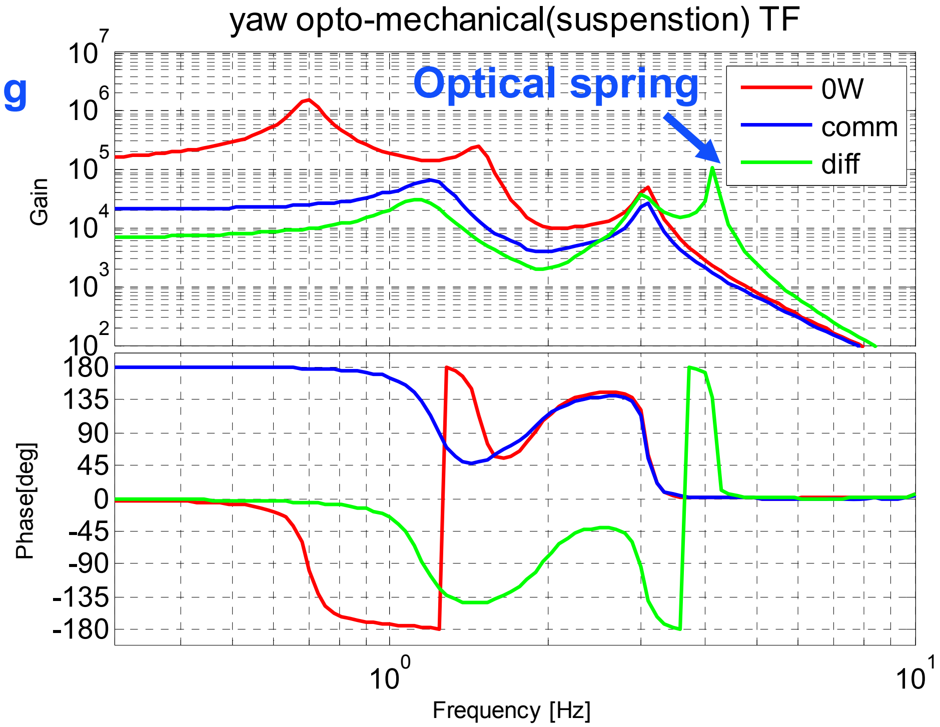




Opt-mechanical (suspension) TF


Pitch opto-mechanical(suspenstion) TF

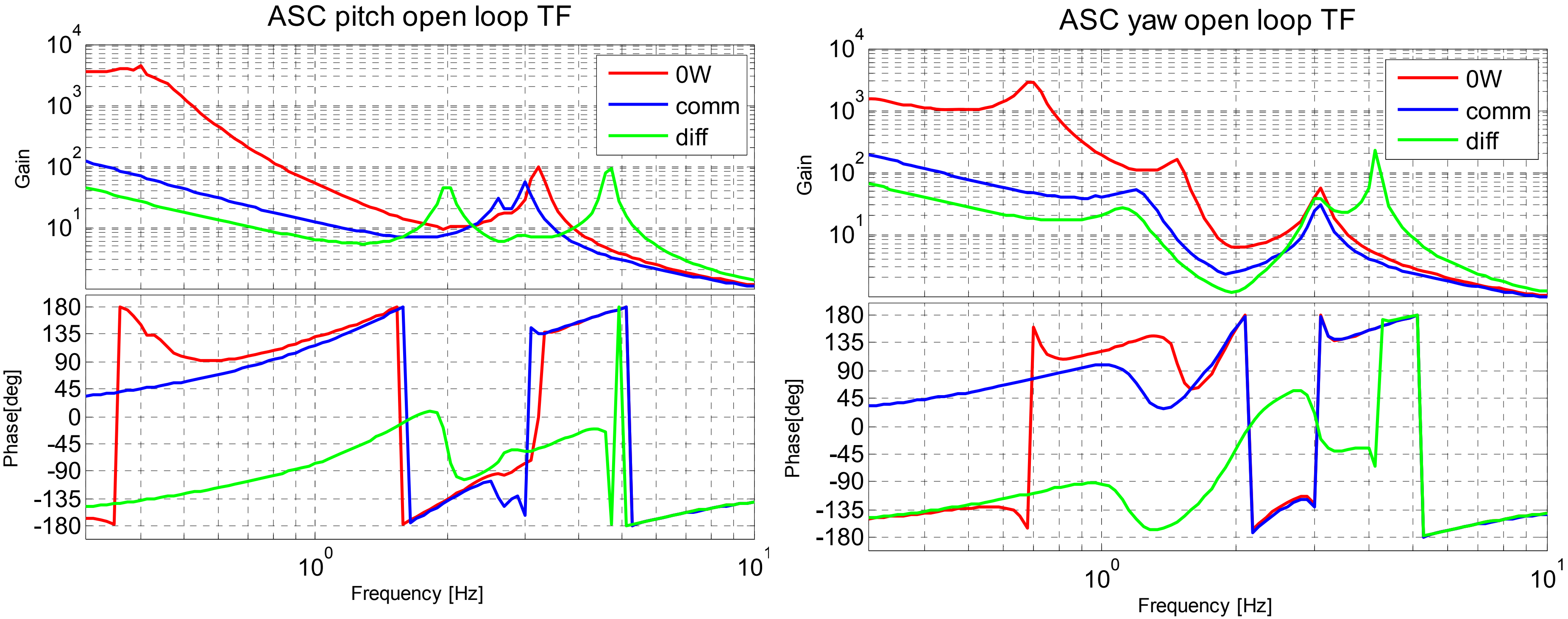
Optical spring


yaw opto-mechanical(suspenstion) TF

Optical spring

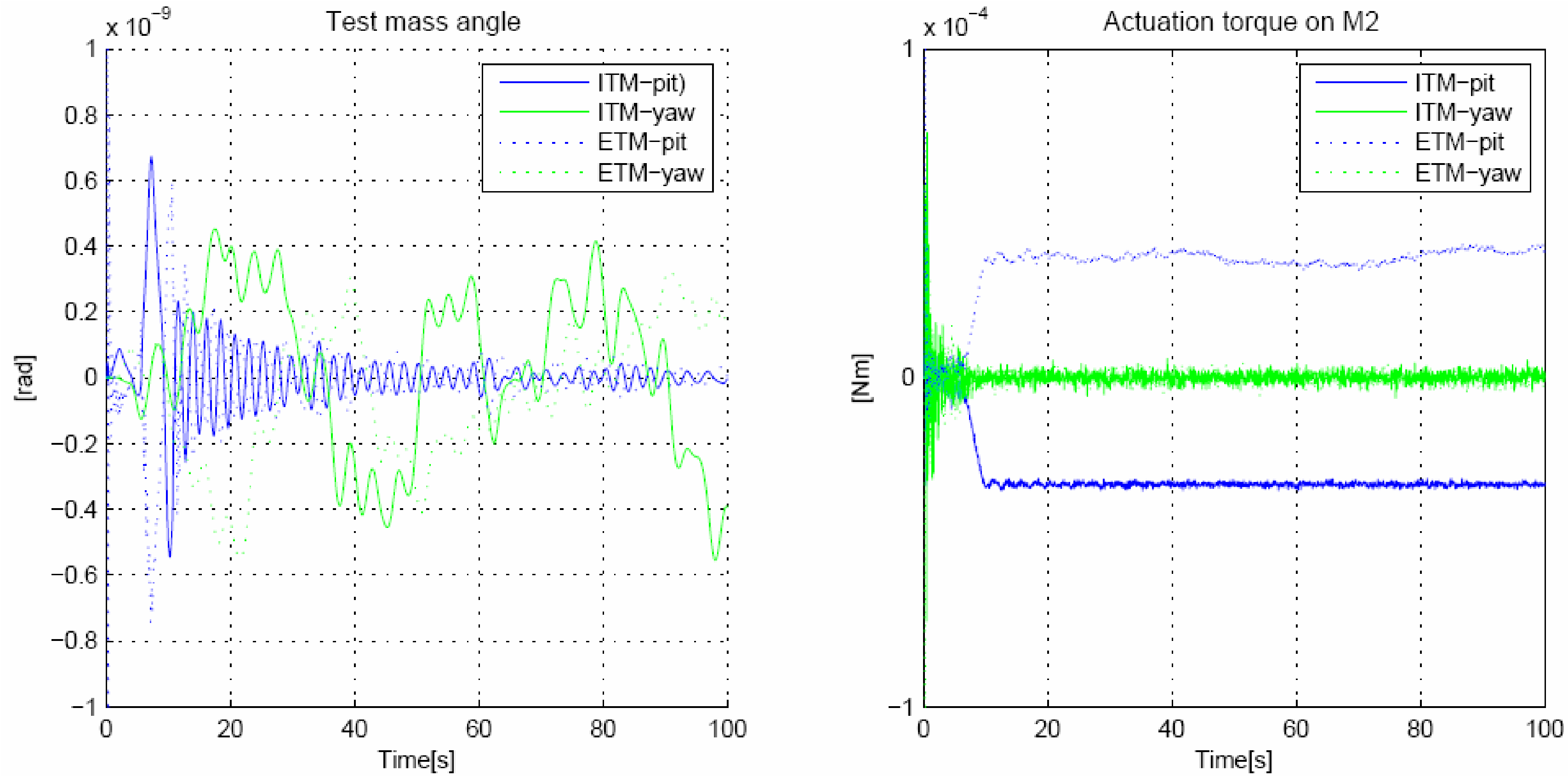
- **TF from M2 actuator to WFS error signal, simulated in time domain.**
- **Low frequency gain and peak are suppressed.**
  - **Needs compensating gain for full power**
- **Optical spring in differential mode at 4.5Hz for pitch and 4.1Hz for yaw.**
- **Control BW must be higher than optical spring frequency.**

Open loop TF of ASC



- **10Hz control band width**
- **Gain in low frequency is suppressed a lot by radiation pressure**

Noise performance



- **Residual RMS: <10^{-9} rad (depends on servo) of 10^{-9}rad requirement**
- **Actuation torque(force): 3x10^{-5} Nm (1x10^{-4} N) on M2 OSEM (max 20mN)**

E. We would like to see a list of the highest risk items---both technical and schedule. What steps are taken to address these risks? On what time scale will they be retired? What is the contingency if we fail to meet them? Are there viable alternatives?
Two items in particular: the DC readout scheme and power handling.

- DC readout: eLIGO
- Power handling:
  - eLIGO (angular control, e.g.)
  - PD power: 2-3x iLIGO levels (more for WFS); testing on an ifo would be good
- Lock acquisition:
  - SPI
  - Testing 3f scheme at 40m
- In-vacuum detection is new
  - eLIGO experience will help

F: There should be additional discussion about the sensing matrix and their 'problematic' elements.

- **Do we rely on gain hierarchy?**
- **Could there be problems because some of the elements are not stable enough, say, during power up?**
- **The effects of higher order modes, sideband on sidebands, sideband imbalance, etc.**

Lets start from the bottom.

ASC:

Detailed analysis is (obviously) not yet done

Higher order modes:

- The Optical Levers will reduce the tilt to a fraction of the scaling angles which reduces the 10-mode amplitudes to ~2e-3 rms. The remaining HOMs can easily be ignored.
- The mode matching between the recycling cavities is expected to be limited by the wedge in the beam splitter which generates an astigmatic beam with a mismatch of ~2% (Details pending). This will create a difference of a few degrees in the optimal Gouy phases. This hasn't been included in the analysis yet (see also next slides).

ASC:

Detailed analysis is (obviously) not yet done

Sidebands on sidebands:

- **The sidebands on sidebands are not included in the analysis, however we calculated the WFS that would be generated by the spurious sidebands and compared it to the current WFS (See also Q36)**
  - **The amplitudes of the signals (diagonal elements) caused by spurious sidebands is several orders of magnitude smaller than the signals in the real WFS.**
  - **Most off-diagonal elements are not affected except for the differential test mass contributions to the SR signal. Their magnitude will not change but they will be redistributed a bit. Does not appear to be a problem at this moment but needs to be included in a later analysis.**

ASC:

Detailed analysis is (obviously) not yet done.

Sidebands imbalance:

- **The sideband imbalance will create RF-signals on all RF photo detectors (ISC and ASC) at the locking point. This appears to be more of a challenge for ISC as the ASC takes the difference between two nominally identical RF signals at the locking point. Still certainly an area of concern.**

Gain hierarchy:
f1-Signals for PR, CETM, CITM

- The current WFS relies on gain hierarchy: The PR signal should be suppressed in the CETM and CITM channel using the PR signal. This could conflict with high bandwidth loops to suppress the spring using the CETM/CITM signals (pending on how we deal with them).

- A change of the Gouy phase by ~50deg in the CETM signal will reduce the PR coupling in the CETM by a factor 30 while reducing the CETM/CITM signals 'only' by a factor of 2. This would avoid gain hierarchy in this channel

- We have not found a way to avoid gain hierarchy for the CITM signal yet. Might look into the POX signal? Is the angular motion of PR small enough?

Gain hierarchy:

SR signal: The critical off-diagonal element is the CITM signal.

- This shouldn't be a problem because the angular motion of the test masses is smaller then the motion of the SR mirror
- We can also change the Gouy phase by 50deg which reduces all off-diagonal signals to <22% of the SR signal. The downside is a reduction in the SR signal by ~40%.
- Contributions of the SR mirror are small enough that they should not show up in the other channels.

Requires full analysis...

Could there be problems because some of the elements are not stable enough, say, during power up?

One of the advantages of stable recycling cavities are well defined spatial modes and Gouy phases. Power up should not be a problem (<u>except for the optical springs!</u>).

Still, we expect to see mismatches at least in the initial Gouy phase telescopes and tested the WFS against changes in the Gouy phases.

Reformulate the problem:
How well do we have to set up the Gouy phase telescopes (assuming we can fine tune the RF demod phases from the control room)?

- **None of the diagonal signals is very sensitive to the Gouy phase**

- **Minimizing off-diagonal elements is somewhat sensitive (see also Gain hierarchy)**

ASC design will keep us busy over the next years...

AUXILIARY LOOP CONTROL NOISE CANCELLATION

Correction paths in AdvLIGO

Known / dominant couplings (in meter/meter)

- MICH → DARM
  - Due to finite arm finesse

$$K_{\mathrm{MICH}} = \frac{\pi}{2F},$$

- SRCL → DARM
  - Parameterized Optickle result
  - Low frequency part due to radiation pressure:

$$K^{(1)}_{\mathrm{SRCL}} = 0.012 \left(\frac{10\ \mathrm{Hz}}{f}\right)^2 \left(\frac{P_{\mathrm{arm}}}{750\ \mathrm{kW}}\right) \left(\frac{0.014}{T_{ITM}}\right) \left(\frac{\mathrm{DARM}_{\mathrm{offset}}}{10\ \mathrm{pm}}\right)$$

  - High frequency part due to SRCdetuning:

$$K^{(2)}_{\mathrm{SRCL}} = 3 \cdot 10^{-5} \left(\frac{f}{100\ \mathrm{Hz}}\right)^2 \left(\frac{SRC_{\mathrm{detuning}}}{10\ \mathrm{degree}}\right) \left(\frac{0.014}{T_{ITM}}\right) \left(\frac{\mathrm{DARM}_{\mathrm{offset}}}{10\ \mathrm{pm}}\right)$$

The problem
MICH as example

- BS mirror motion above ~10Hz dominated by sensing noise

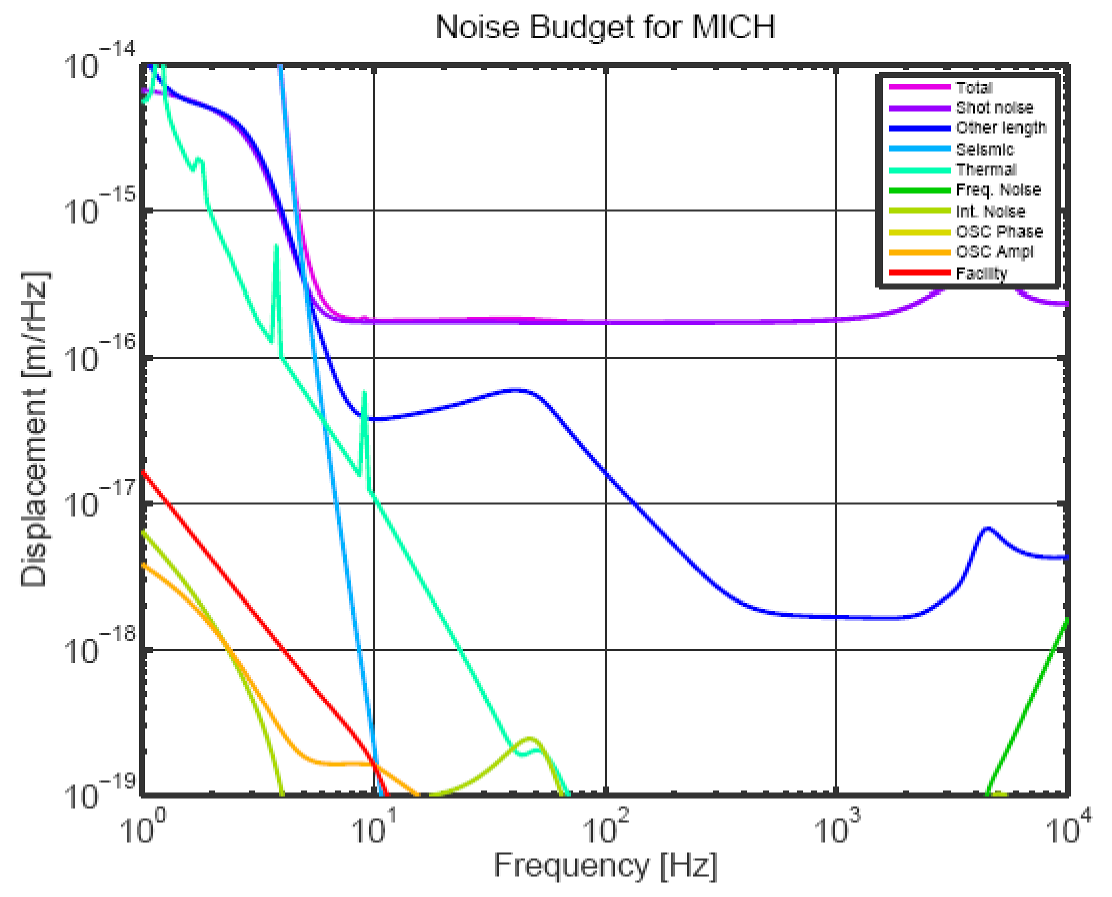
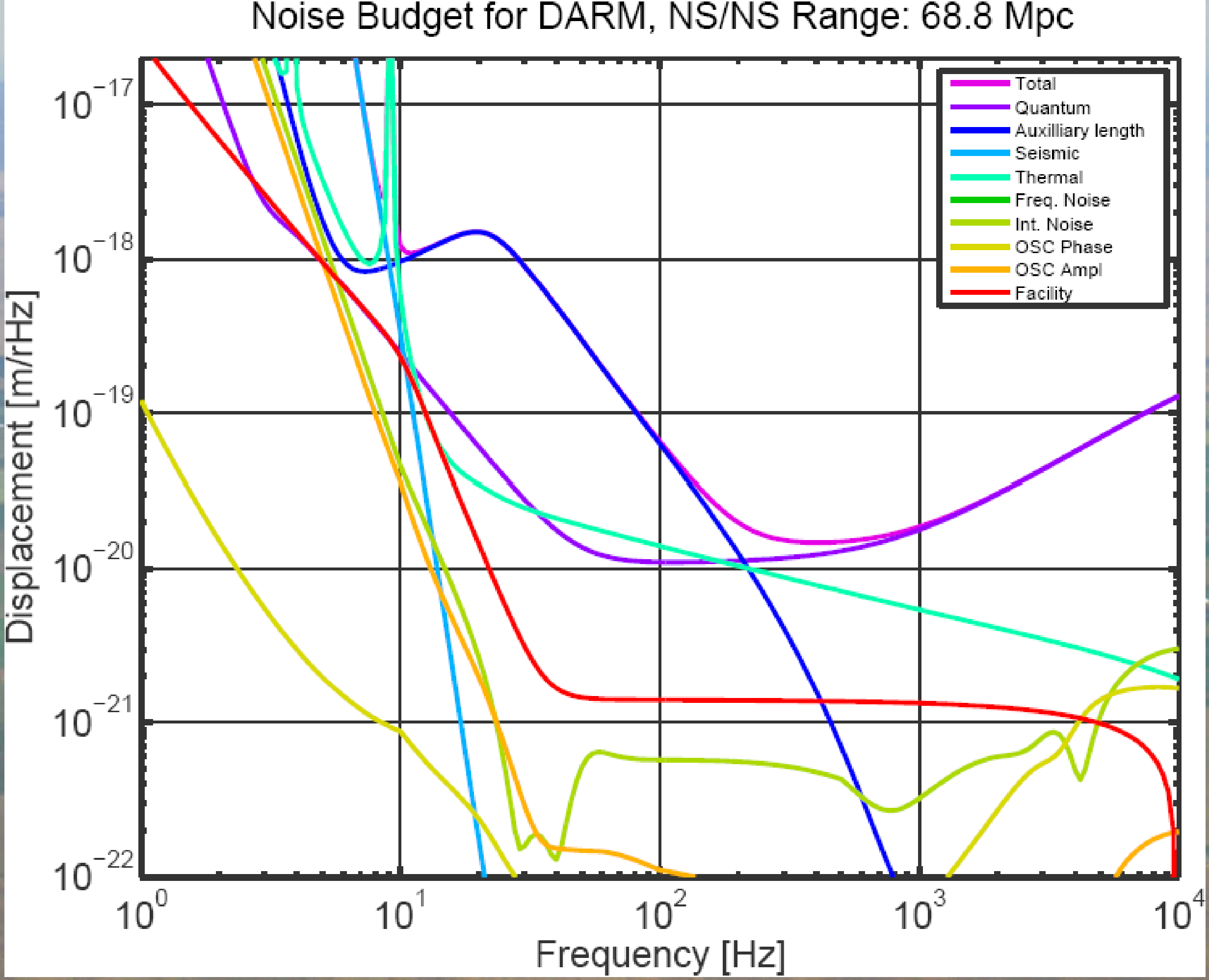


Figure 15: MICH noise budget for the zero detuning case.

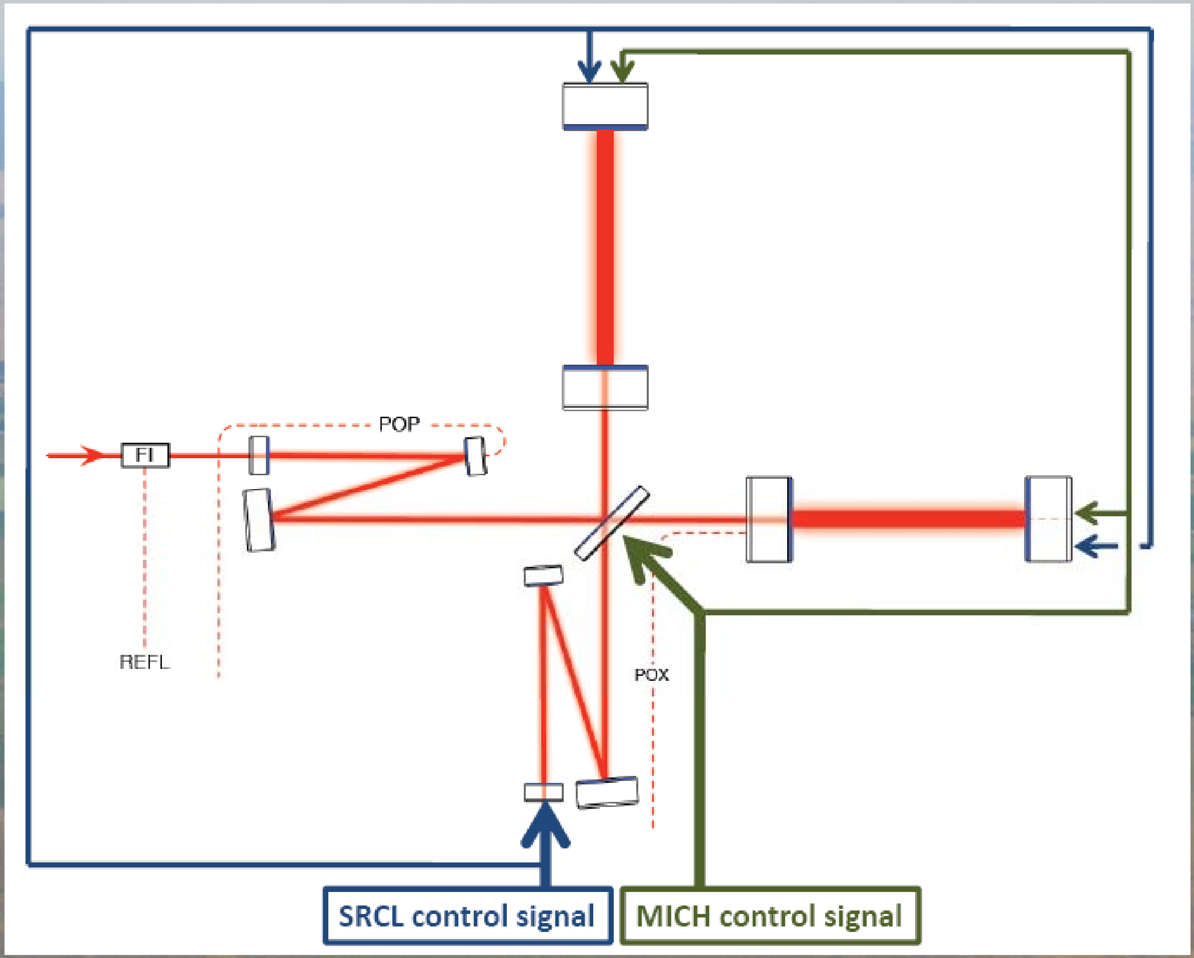
DARM noise budget without MICH CORR

- Can’t sell this…



Trick: feed noise to ETM

- Control noise is known!
- We can feed it back to the ETMs (with filtering)



With correction path

- Easier to sell this…

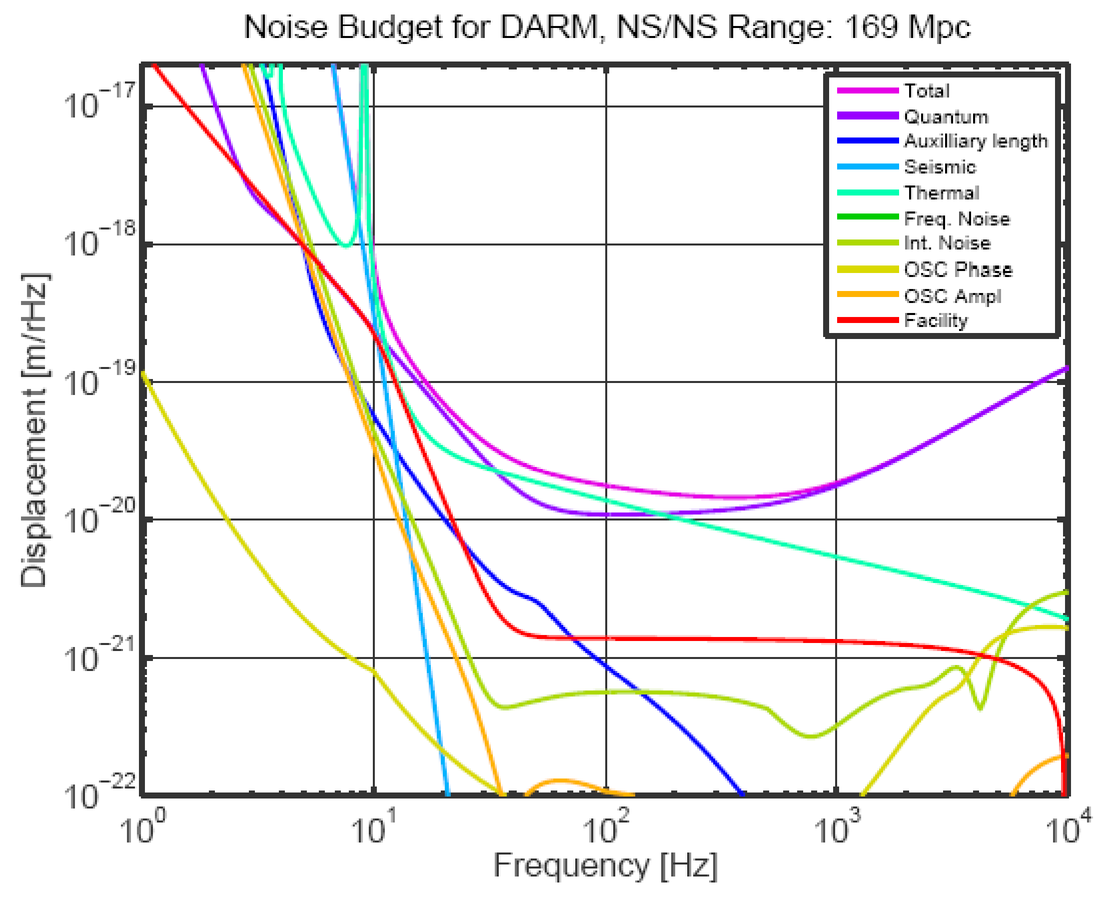
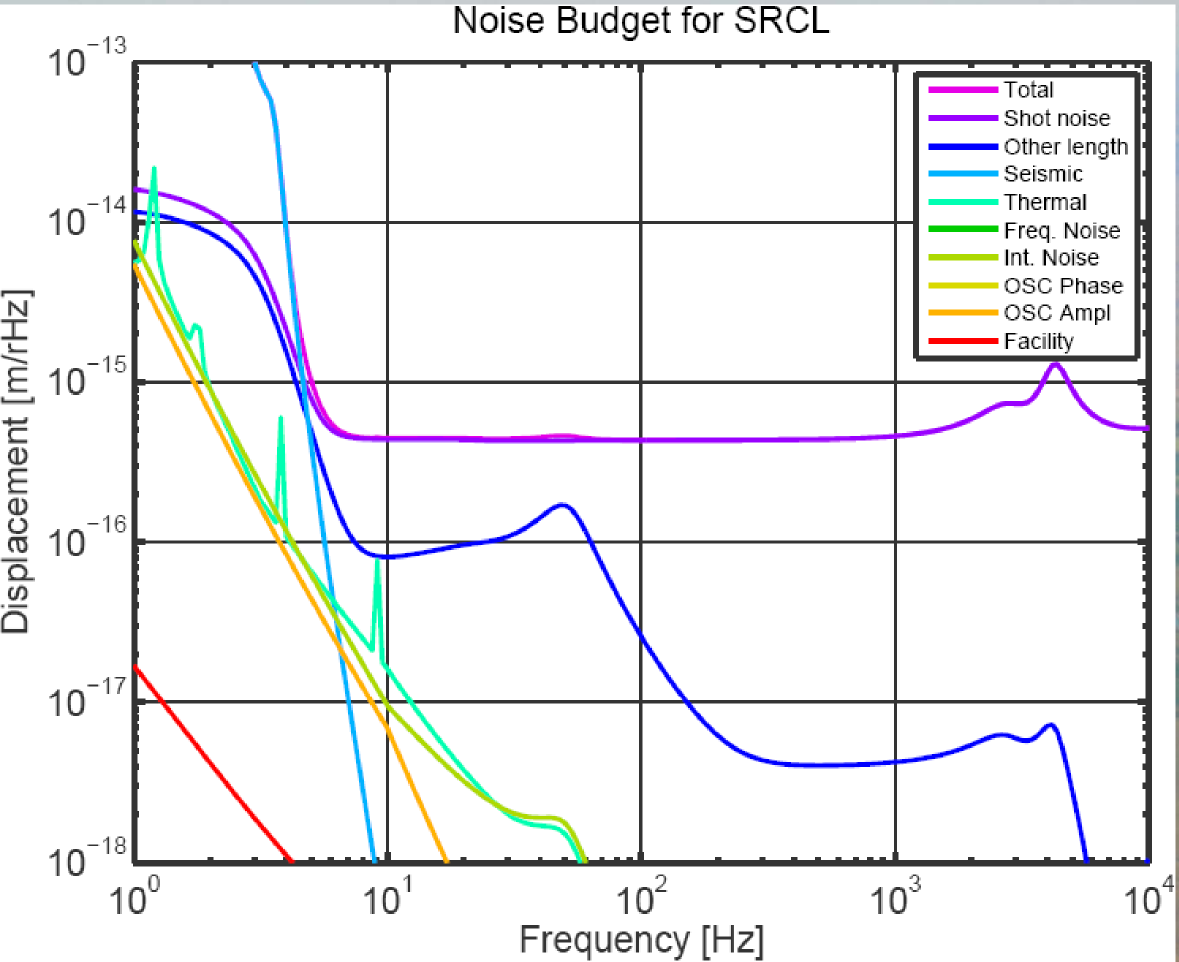


Figure 9: DARM noise budget for the zero detuning case.

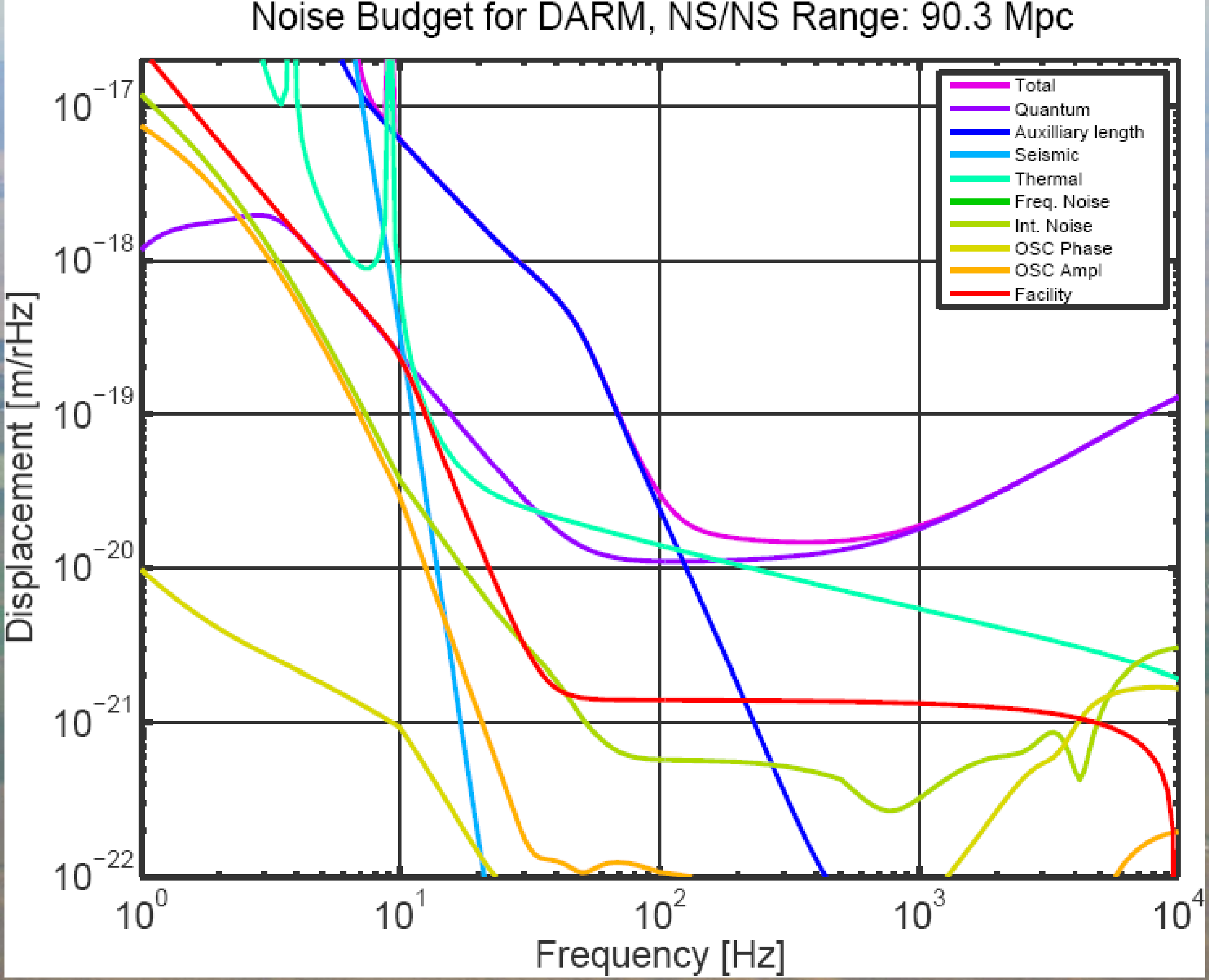
SRCL

- Same story for SRCL



DARM without SRCL CORR

- Same story for SRCL



Remarks

- Trick only works for sensing noise
  - "Physical" displacement noises can't be canceled this way
- We require a correction precision of O(1%)
  - Coupling depends on (fluctuating?) arm power
  - But we can "tune" the gain of the correction path (1% guess not required)
  - We DO require that all actuation transfer functions remain constant within 1%

Read-out Noise Requirements During Lock Acquisition

ISC Review – 9th April 2008

L. Barsotti, MIT

Read-out noise requirements during lock acquisition

- ☐ **Science mode:**

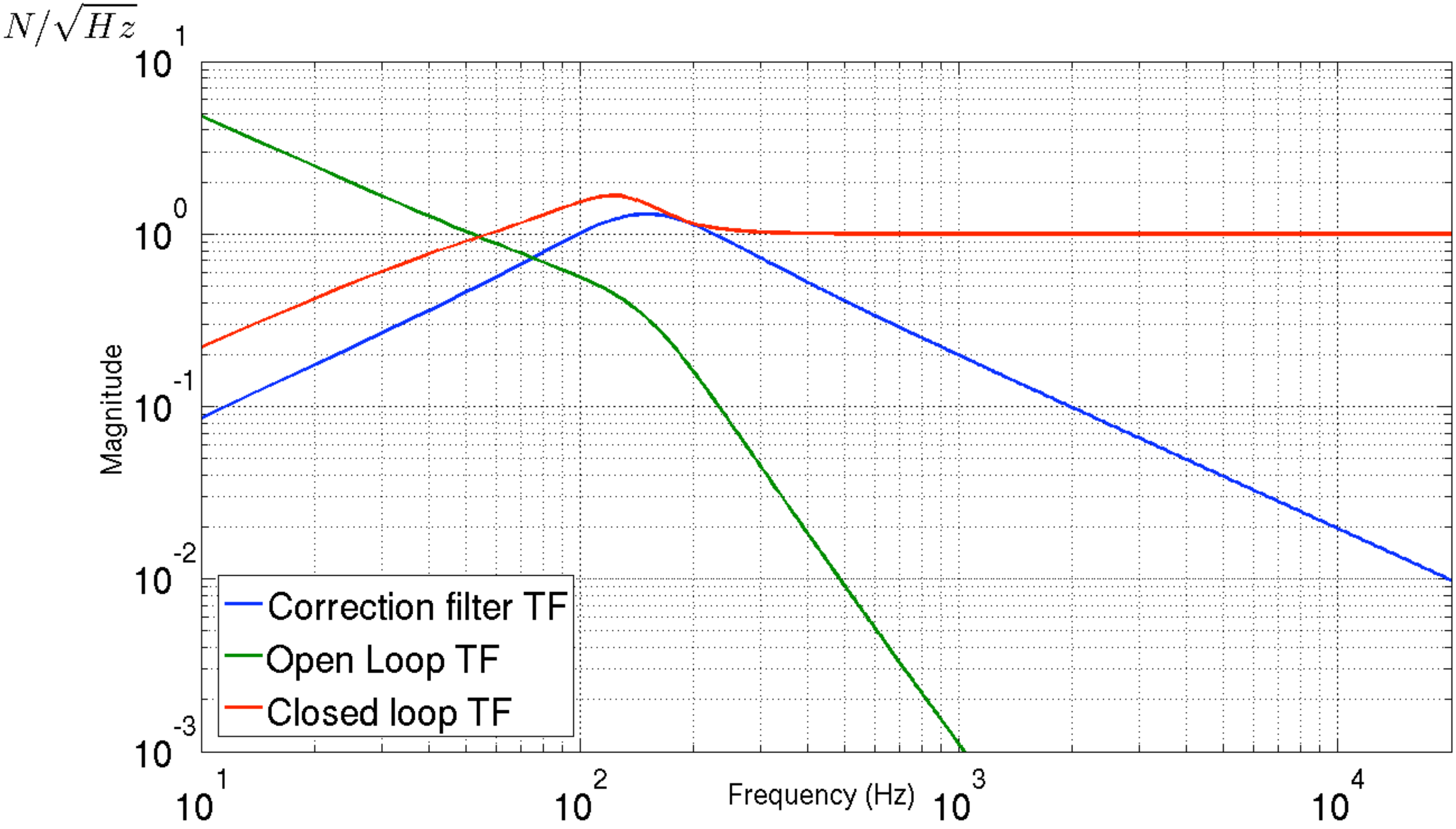
$$SNR = \frac{\tilde{P}_{shot}}{\tilde{P}_{elect}} \geq 4 \qquad \left(\tilde{P}_{shot} = \sqrt{\frac{2h\nu P_0}{\eta}} \; \frac{W}{\sqrt{Hz}} \right)$$

- ☐ **Lock acquisition**: the only requirement is that the RMS of the correction signal (shot noise + electronic noise) is at least a factor **~10** lower than the actuator maximum force

- ☐ Level of electronic noise tolerable during lock acquisition determined with respect to the shot noise level on each diode

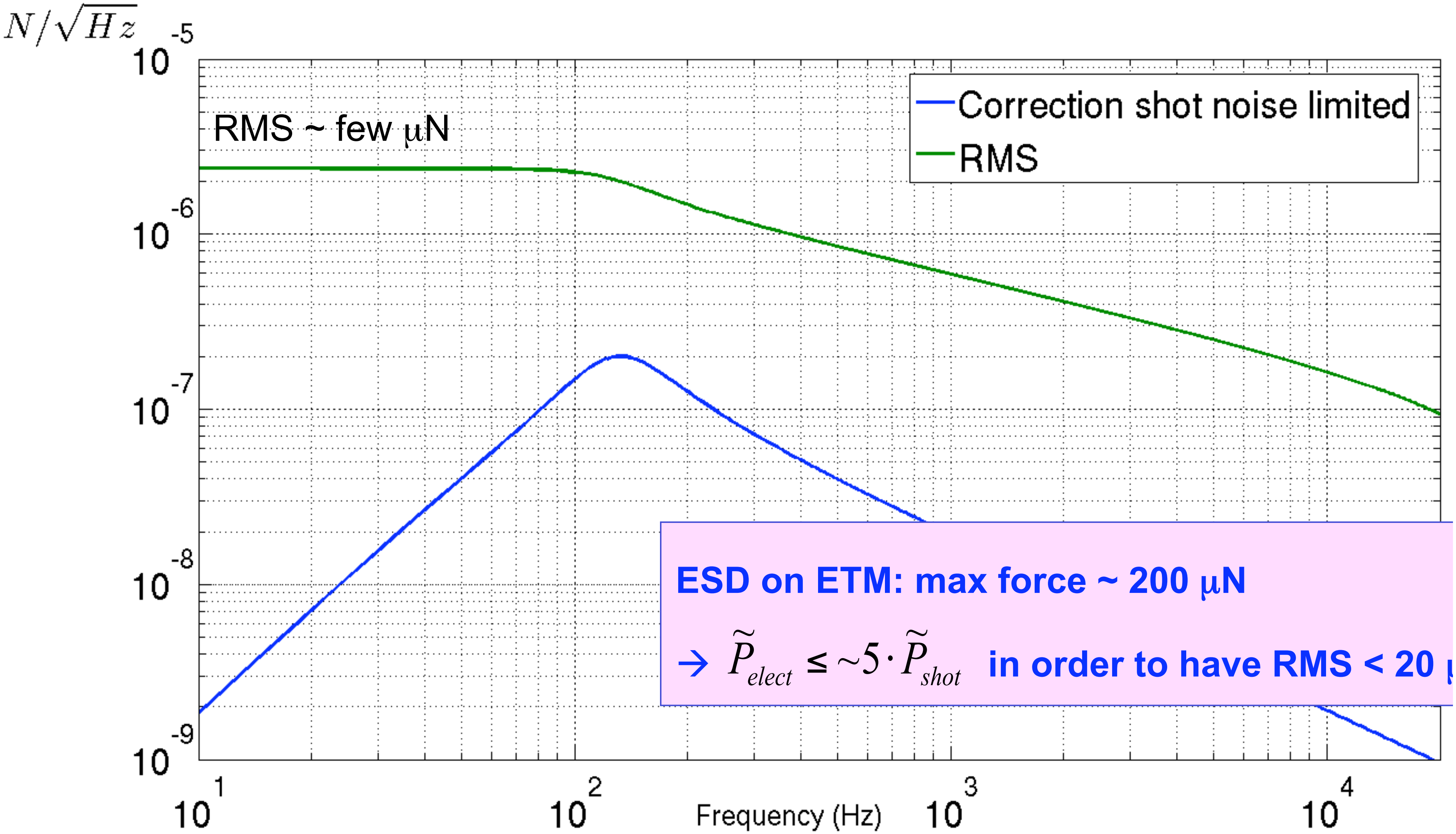
Read-out noise requirements during lock acquisition

Example: DARM transfer functions



Read-out noise requirements during lock acquisition

$$\tilde{P}_{corr}\left[\frac{N}{\sqrt{Hz}}\right] = g\cdot TF_{CORRfilter}\cdot TF_{CLOSEDloop}\cdot \tilde{P}_{shot}\left[\frac{W}{\sqrt{Hz}}\right]$$



RMS ~ few μN

ESD on ETM: max force ~ 200 μN

→ $\tilde{P}_{elect} \le \sim 5\cdot\tilde{P}_{shot}$ **in order to have RMS < 20**

Read-out noise requirements during lock acquisition

- Similar approach for the other degrees of freedom
- Max electronic noise tolerable for each diode

  (see table 19 sec. 9.4)
- Electronic noise of possible read-out solutions for

  Advanced LIGO (LIGO-T060268-02-C) is compatible wit

  lock acquisition requirements (PRELIMINARY)

I. What kind of programming effort will be required to implement the ISC code? Who is going to write it? Test it?

We'll use Borkspace, expect this will cover most or all of our needs.
Code for dither alignment: written for 40m, some testing done
New filter calculation (sos) algorithm under investigation

How are changes handled during commissioning?
No plans yet; ask again in 2011

Are there any regression test suits planned?

How much time will be needed for verification and qualification?

Guess it will be weeks to months …

One of the problems in initial LIGO is that there is no place to test new code except the full interferometer. Are there plans for a test setup where ISC code can be run and tested independently?

Would like to make the 40m a place where this can be done.

Is there an need for a real-time interferometer simulator?

Need -- no. Perhaps would be useful, but we don't see a way to commit our current team to doing this and still deliver the real stuff; could be something another LSC group could pick up