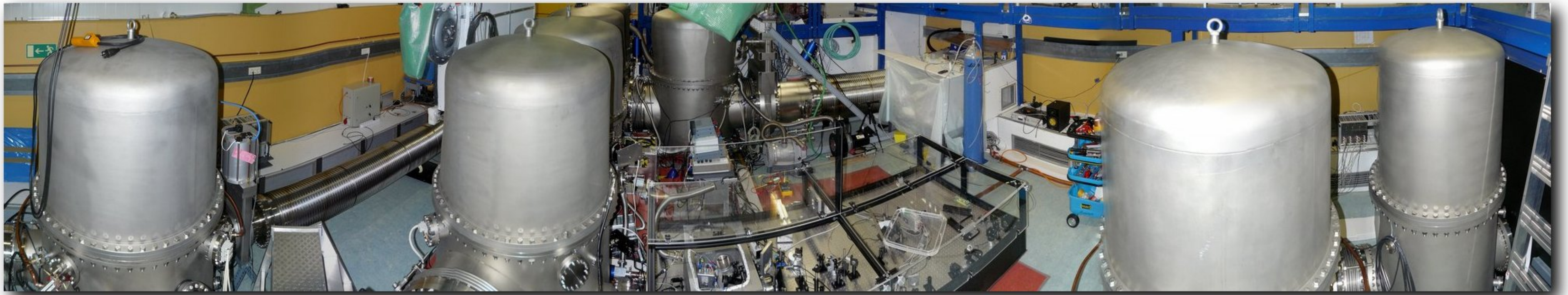
DC-readout with tuned and detuned Signal-Recycling



Stefan Hild and Hartmut Grote for the GEO-team

Definitions

<u>Tuning/detuning of the Signal-Recycling cavity</u> (microscopic length)

- ***tuned:*** carrier is resonant in SR-cavity
- ***detuned:*** carrier is off resonance in SR-cavity (550 Hz or 1 kHz)

<u>Readout system</u>

- ***heterodyne:*** LO from RF sidebands (Schnupp modulation)
- ***DC-readout / homodyne:*** carrier from dark fringe offset serves as LO

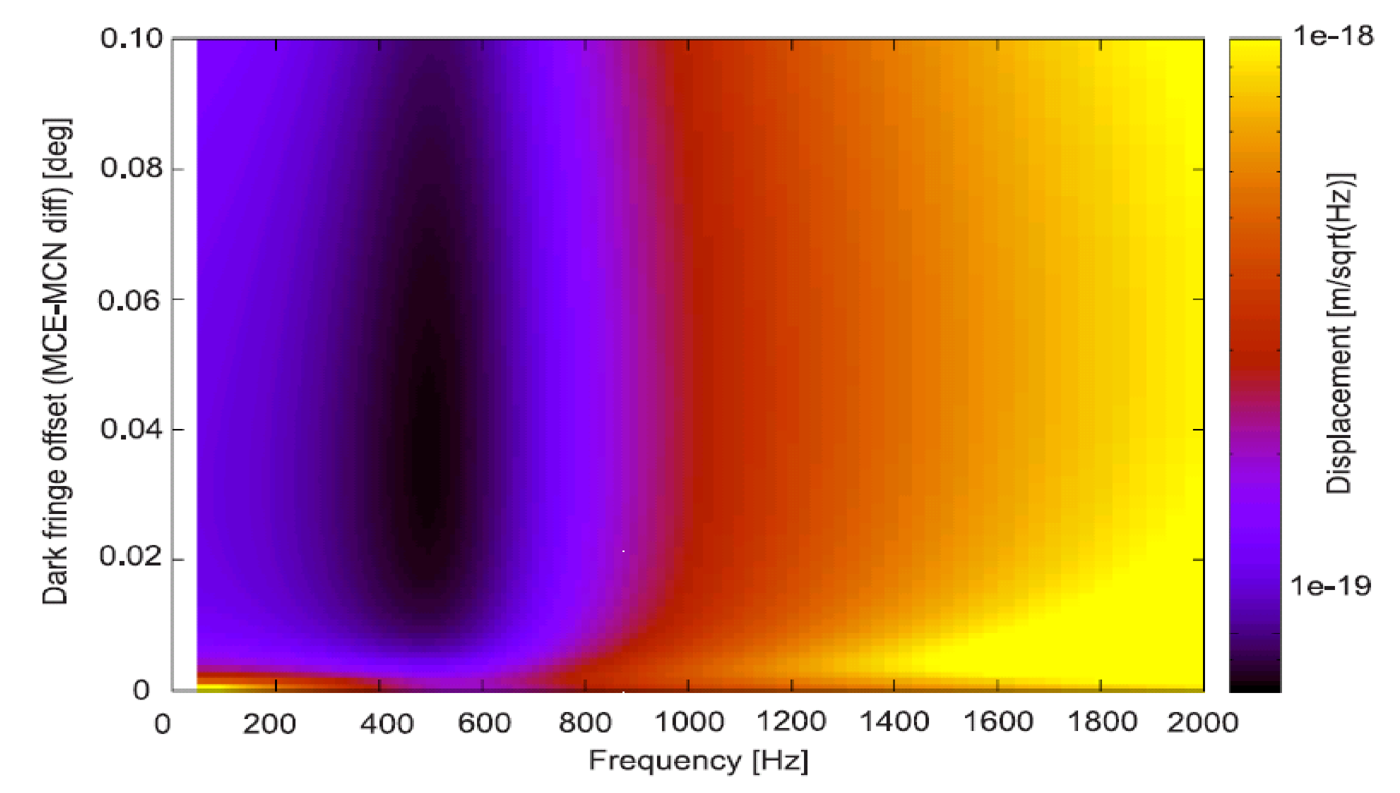
<u>Optical gain</u>

Transfer function from differential displacement to signal at the detection point.

Short reminder: Advantages of DC-readout

- **Recduced shotnoise (no 2f-terms)**
- **Get rid of oscillator phase noise and oscillator amplitude noise (and buy stronger laser intensity noise coupling)**
- **Simplify the GW detector**
  - easier calibration (GW-signal in a single data-stream, even for detuned SR)
  - easier circuits for photodiodes and readout electronics
  - Possibility to use photodiodes with larger area => reduced coupling of pointing
  - reduced number of beating light fields => simpler noise couplings
  - more intuitive thinking
- **Requires less effort for injecting squeezed light (=> useful precursor for GEO-HF)**
- LO and GW see the same optical system (storage time, filtering, spatial profile). => This is advantage is especially important for detectors with arm cavities.
- ***… finally: we are always looking for new fun***

Determine the optimal dark fringe offset



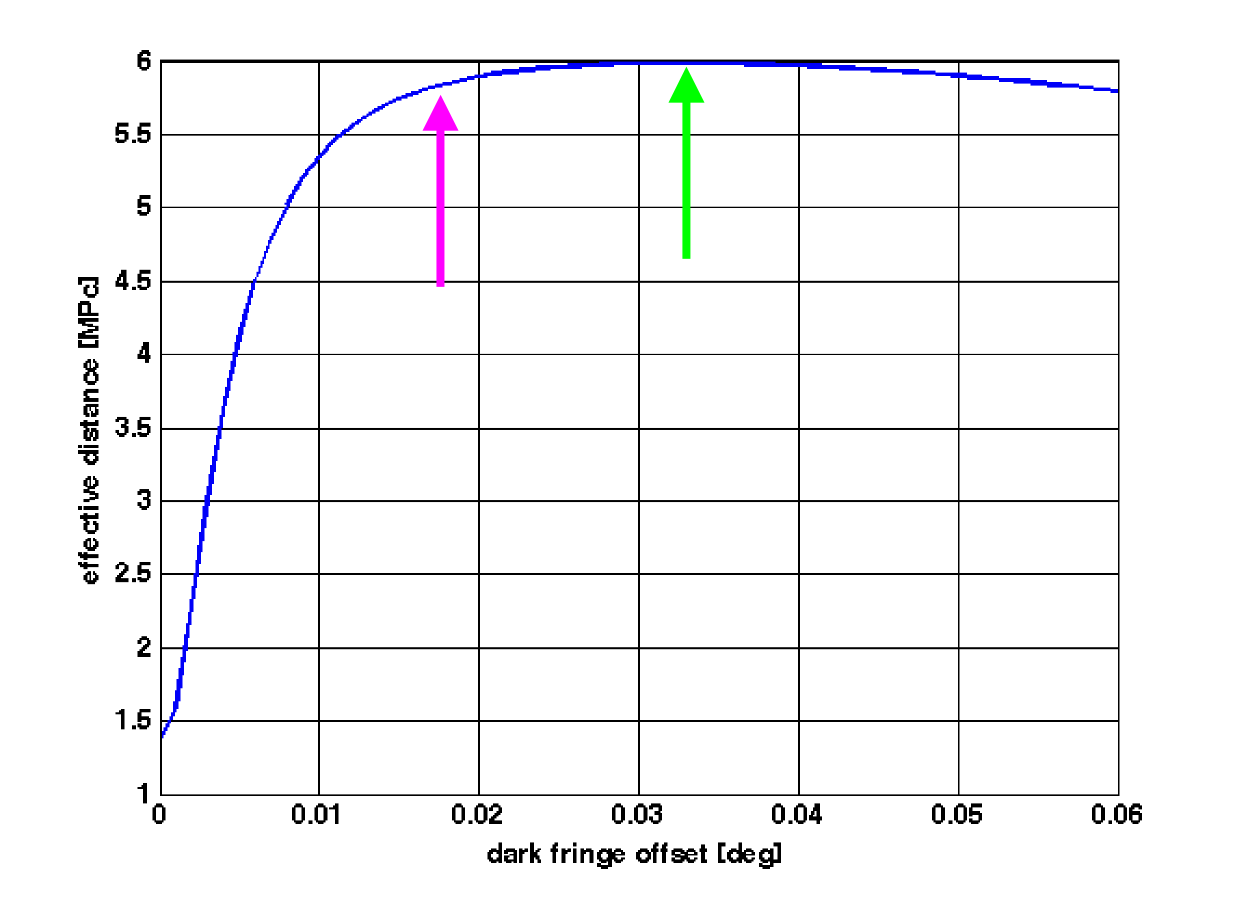
$$\xi_{\mathrm{df}} = \frac{|\Delta L_{\mathrm{n}}| + |\Delta L_{\mathrm{e}}|}{2}$$

$$\xi_{\mathrm{df}}\,[\mathrm{m}] = \frac{\lambda}{360\,\mathrm{deg}}\,\xi_{\mathrm{df}}\,[\mathrm{deg}]$$

Optimal offset: 0.036 deg (diff) => 104 pm

Nearly optimal already: 0.018 deg (diff) => 52 pm

Determine the optimal dark fringe offset from NSNS-horizon



NSNS-horizon:

- **sensitivity weightened by $f^{-7/3}$**
- **Integrated over frequencies up to last stable orbit (f = 1570 Hz)**

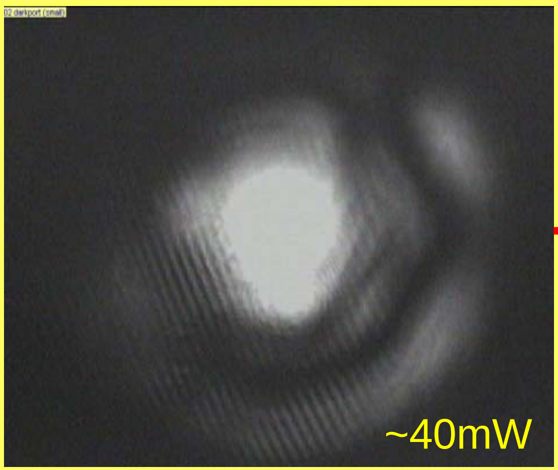
Maximal Horizon for =0.032 deg

For 0.018 deg we get already 97% of maximal horizon .

DC-readout without OMC

- Turning down the RF-modulation *(factor 10 is possible)*
- Using an offset from dark fringe *(of the order of 20pm)*

⇒ Dark port dominated by carrier light

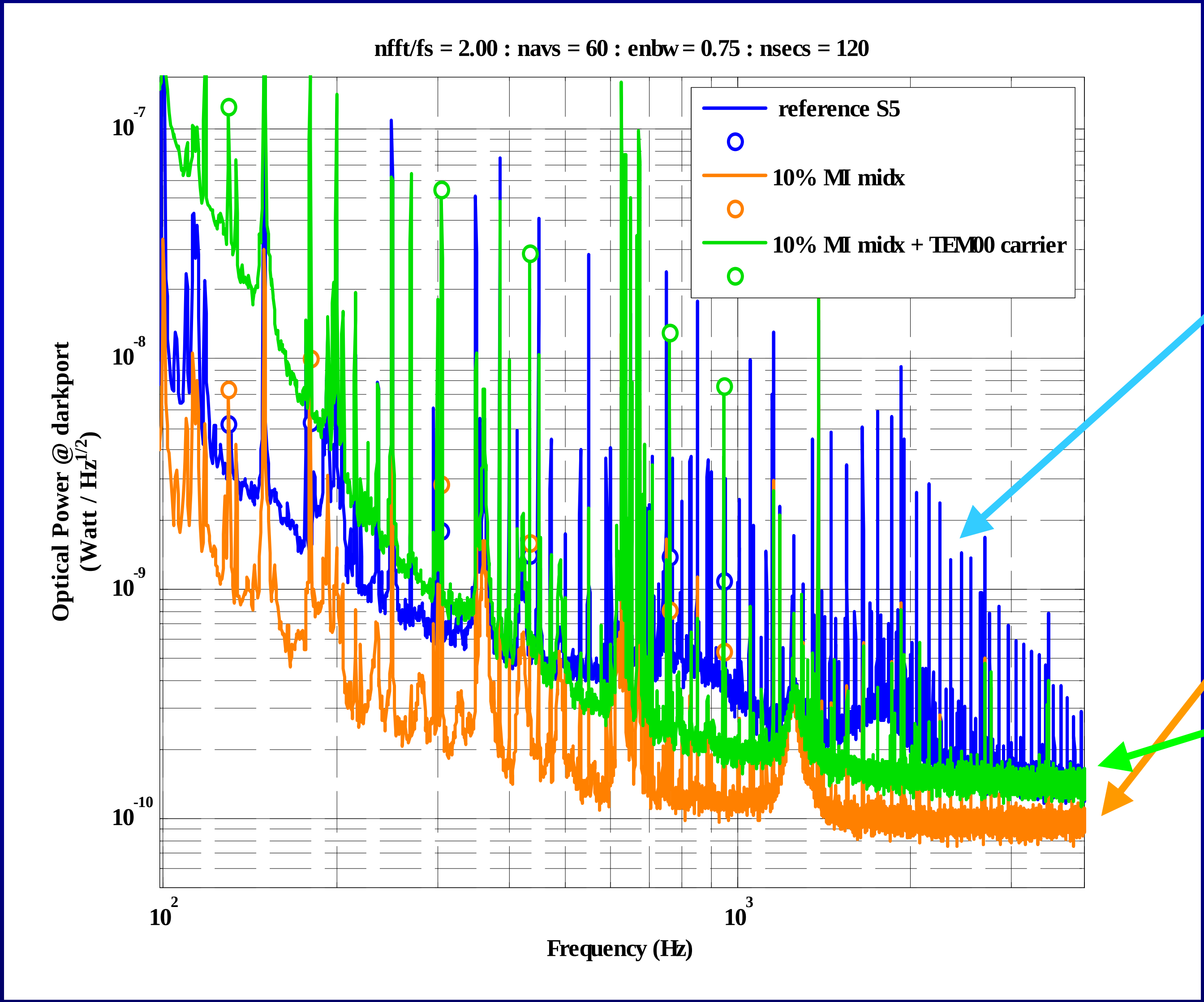


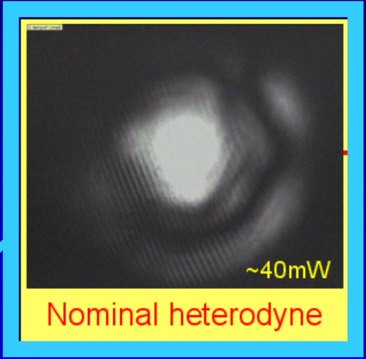
Nominal heterodyne

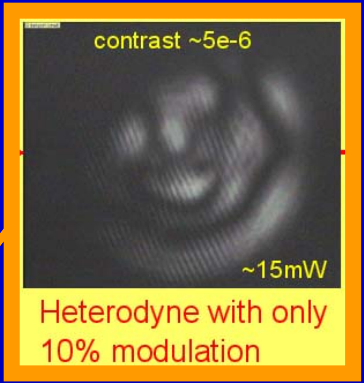
Heterodyne with only 10% modulation

Offset to dark fringe

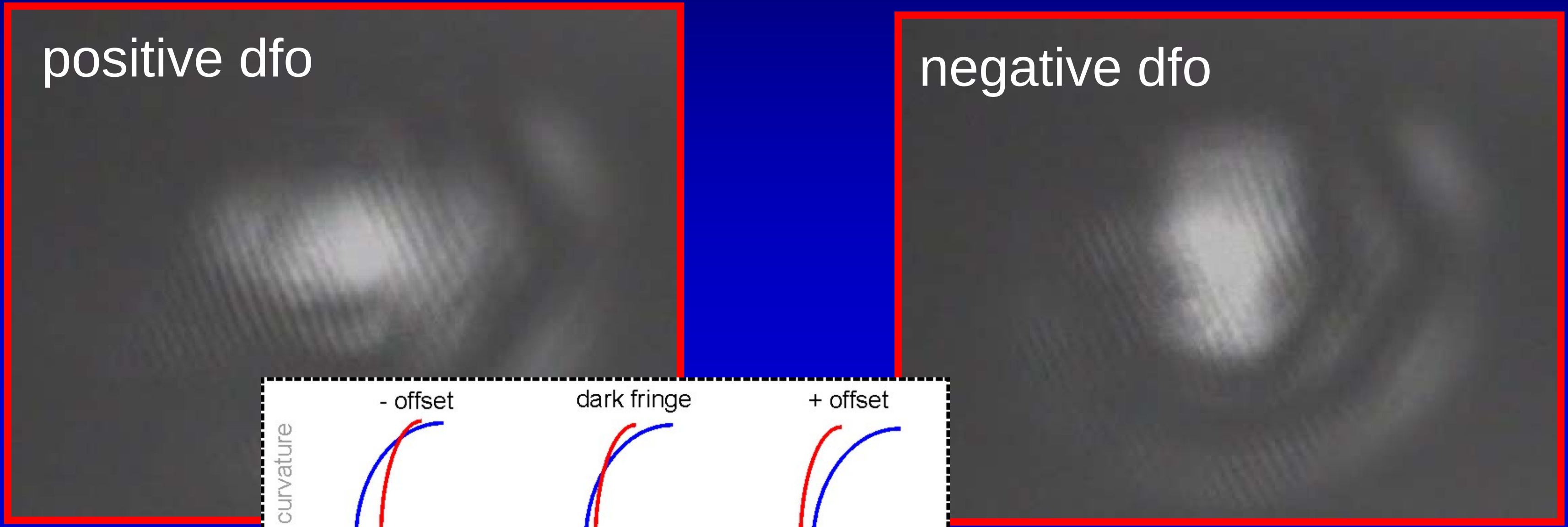
Optical power at the output port

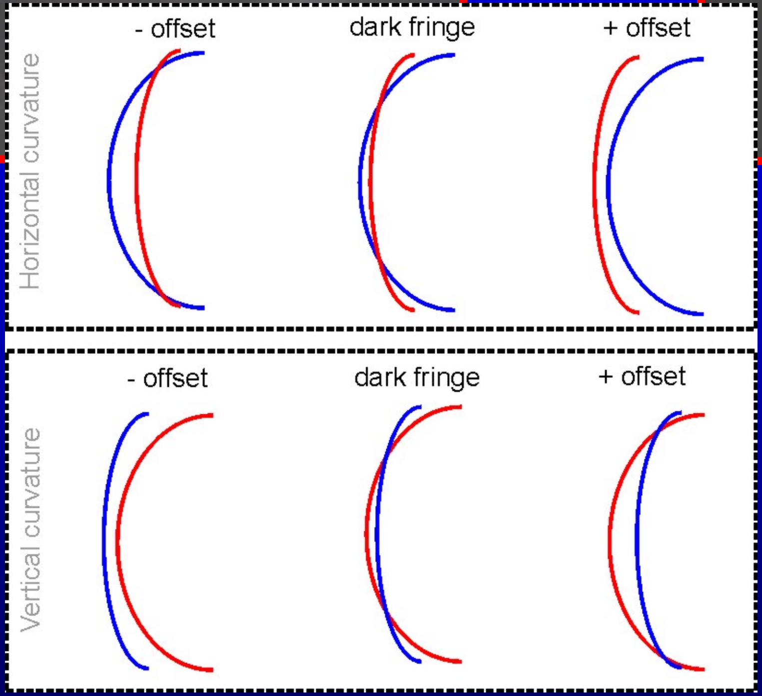






Output mode for positive and negative dark fringe offset





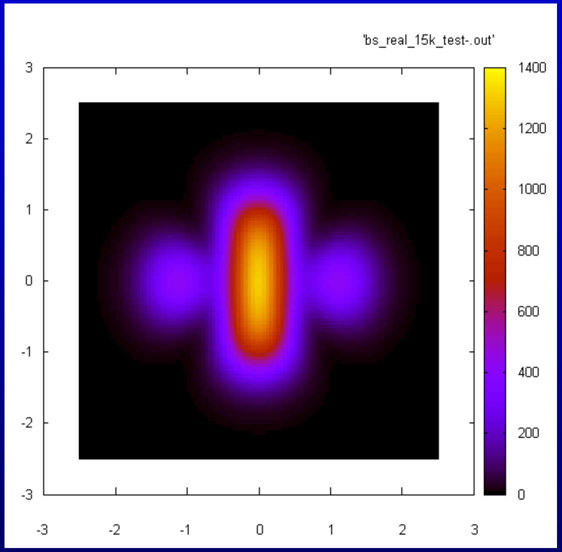
Wave front radii of returning beams @ BS:

horizontal: north > east

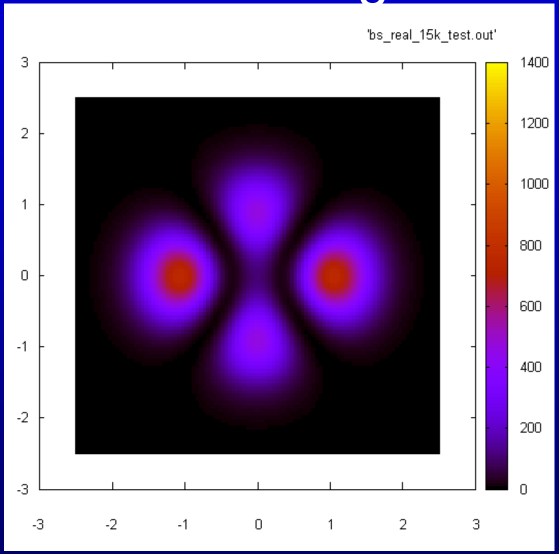
vertical: north < east

Simulated output mode for positive and negative dark fringe offset

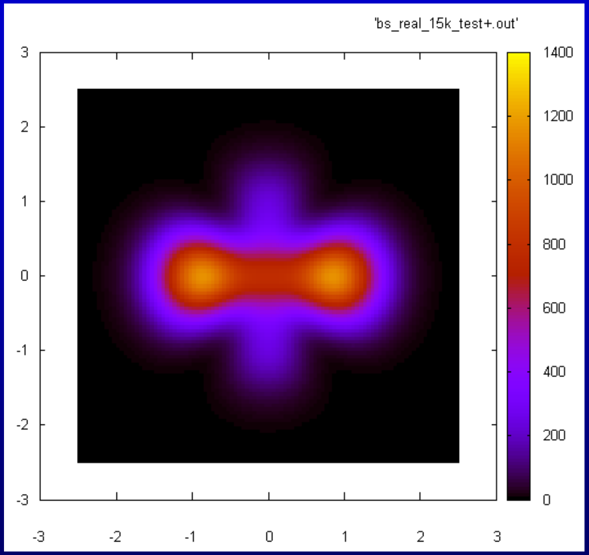
negative dfo



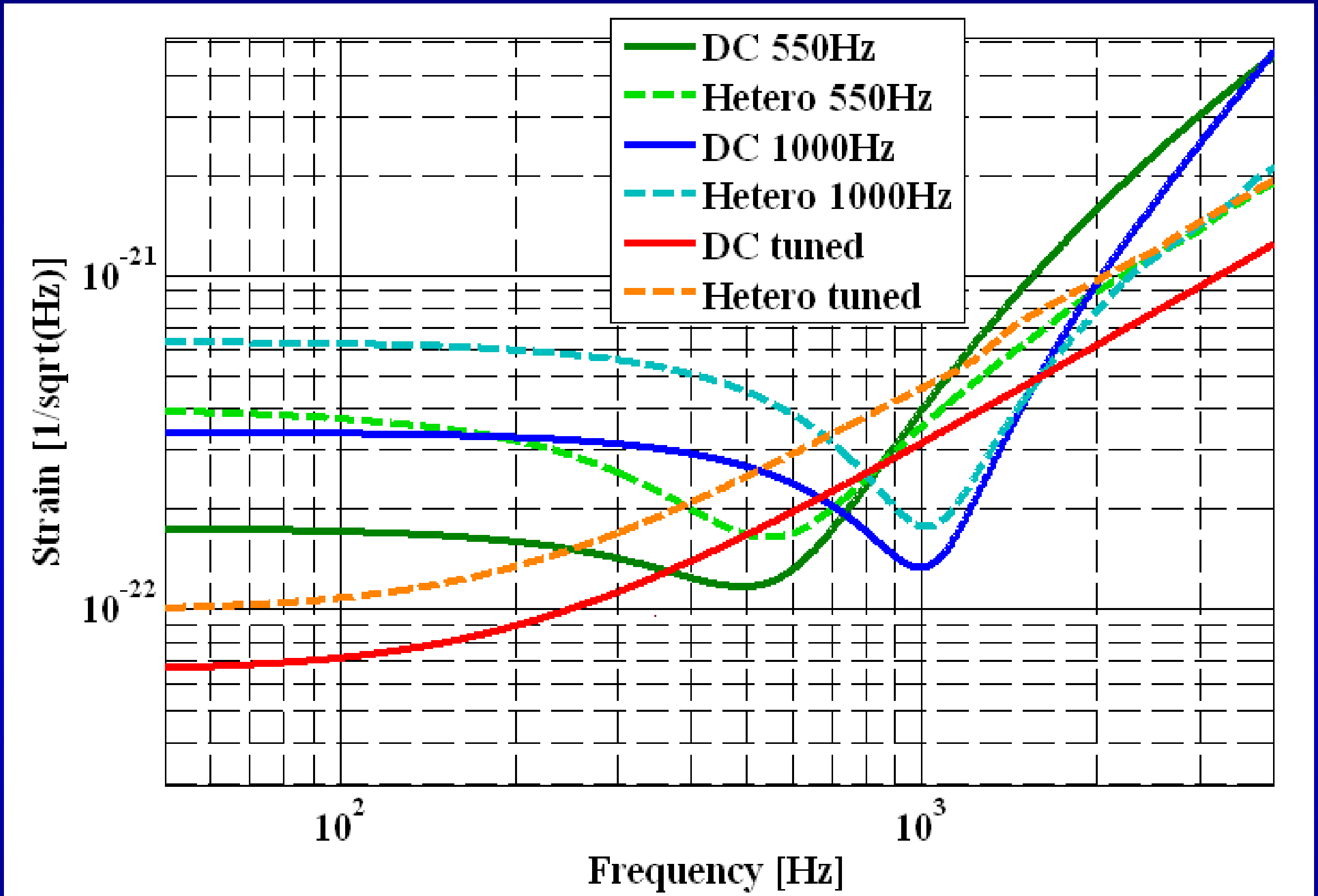
dark fringe



positive dfo



Simulated shotnoise heterodyne vs DC-readout for various tunings.

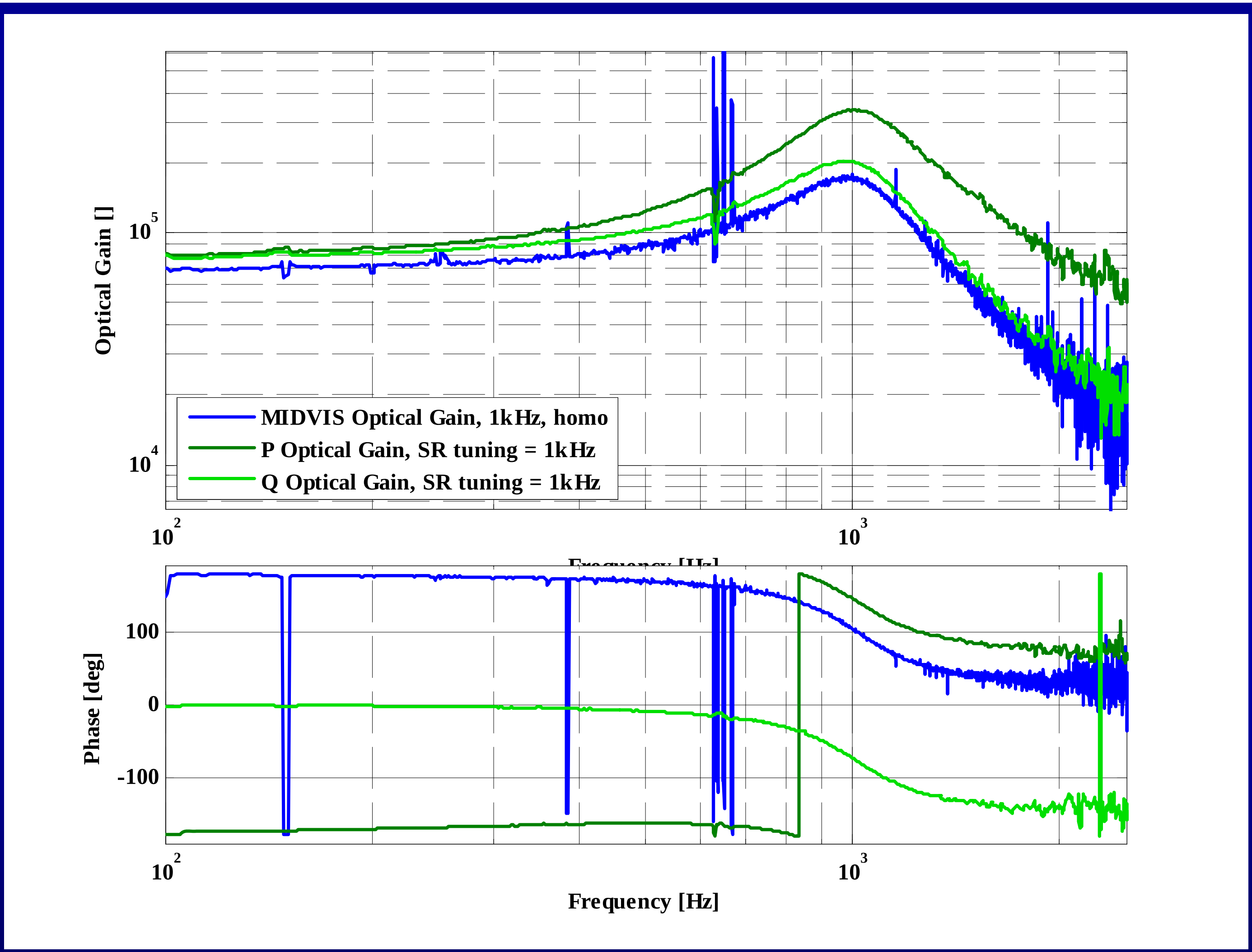


- Shot noise in DC-readout smaller than in heterodyne readout
- In detuned Signal-Recycling the shape of the detector response is different for heterodyne and DC-readout => In DC-readout the shape rotated counterclockwise around the peak sensitivity.

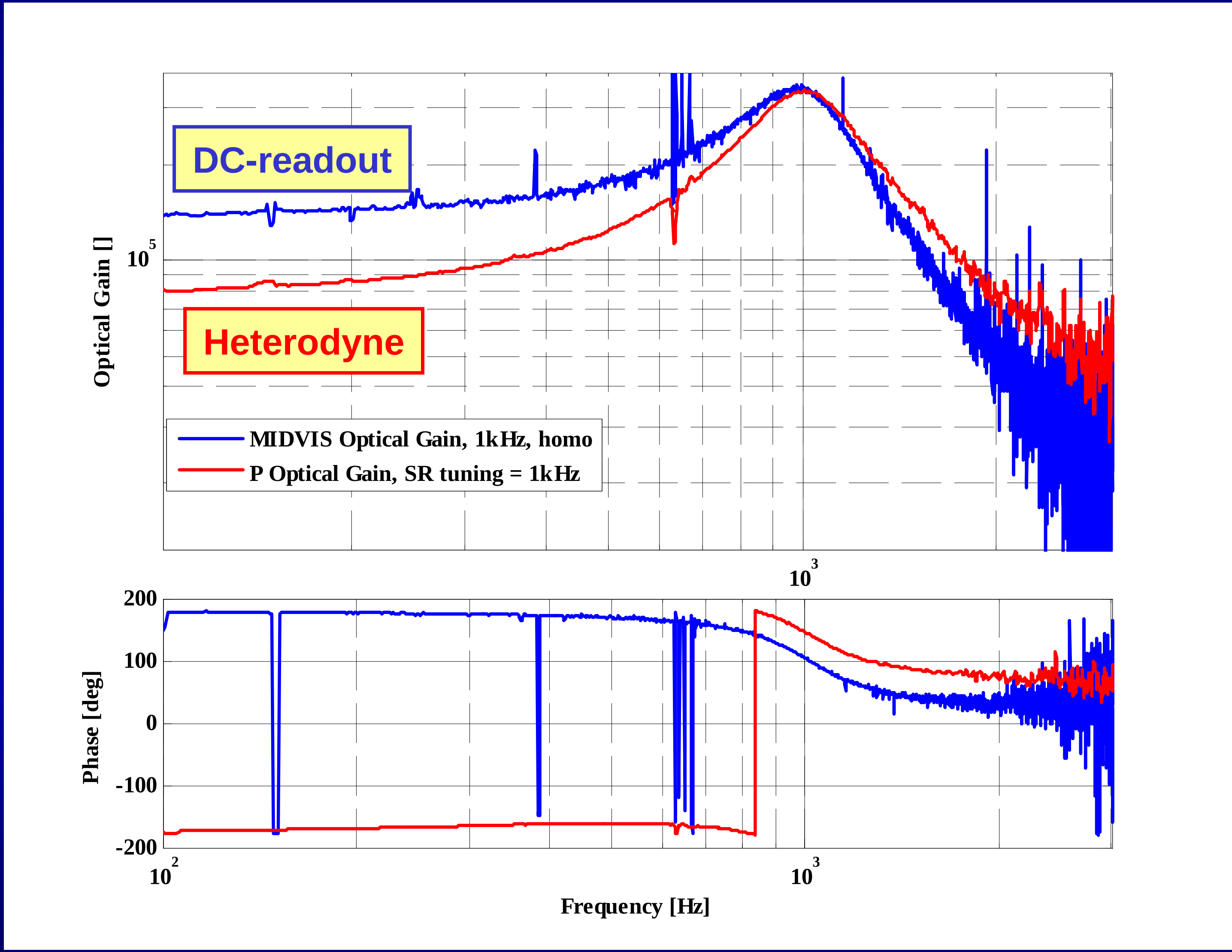
1 kHz tuning

Optical gain for heterodyne and DC detection and 1kHz tuning

Optical gain = MIDVIS/MID_FB_MCE-MCN (for a time of injected noise) .* MIDVIS_dewhitening ./ ESD_dewhitening / ESD_response

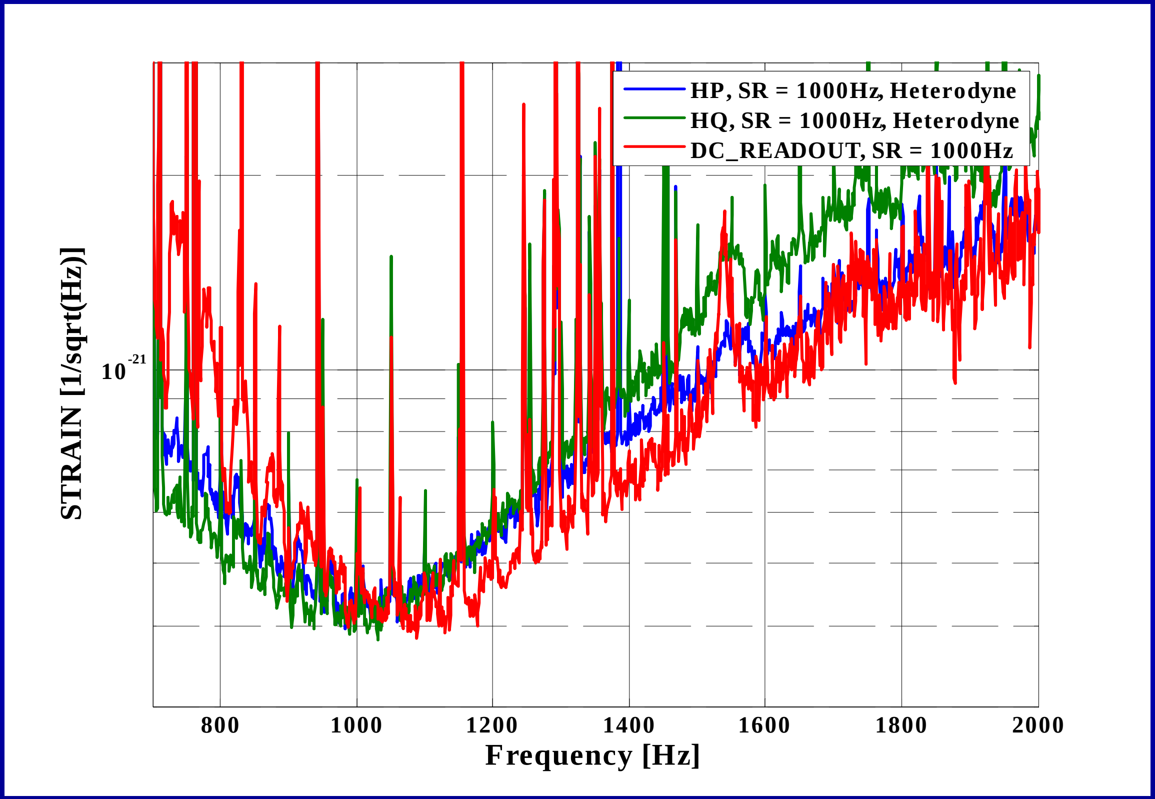


Rotation of optical gain (measurement)



Results from first Experiments with DC-readout

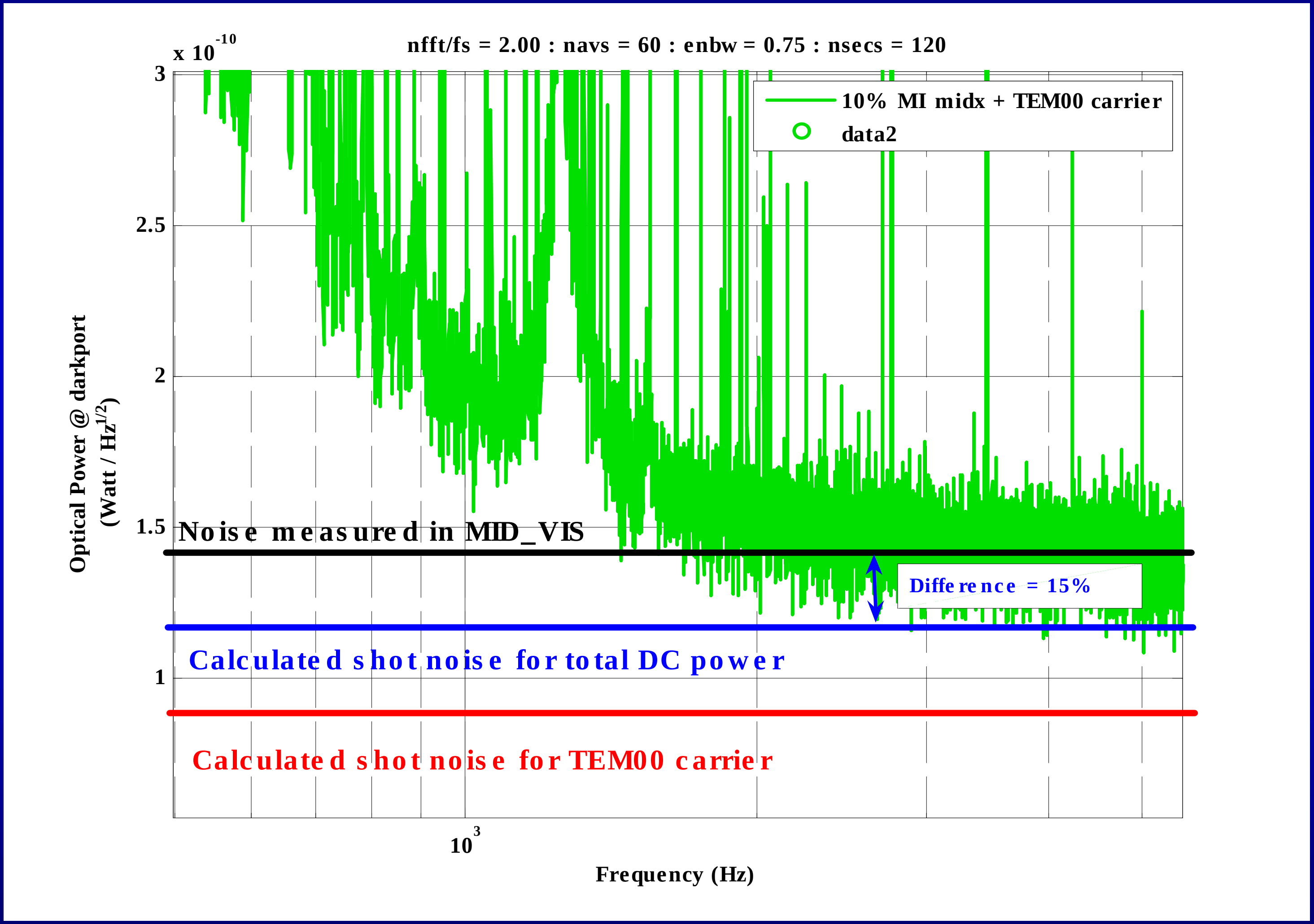
Strain = MIDVIS * MIDVIS-dewh / midvis-optical-gain / CLTF / 1200m



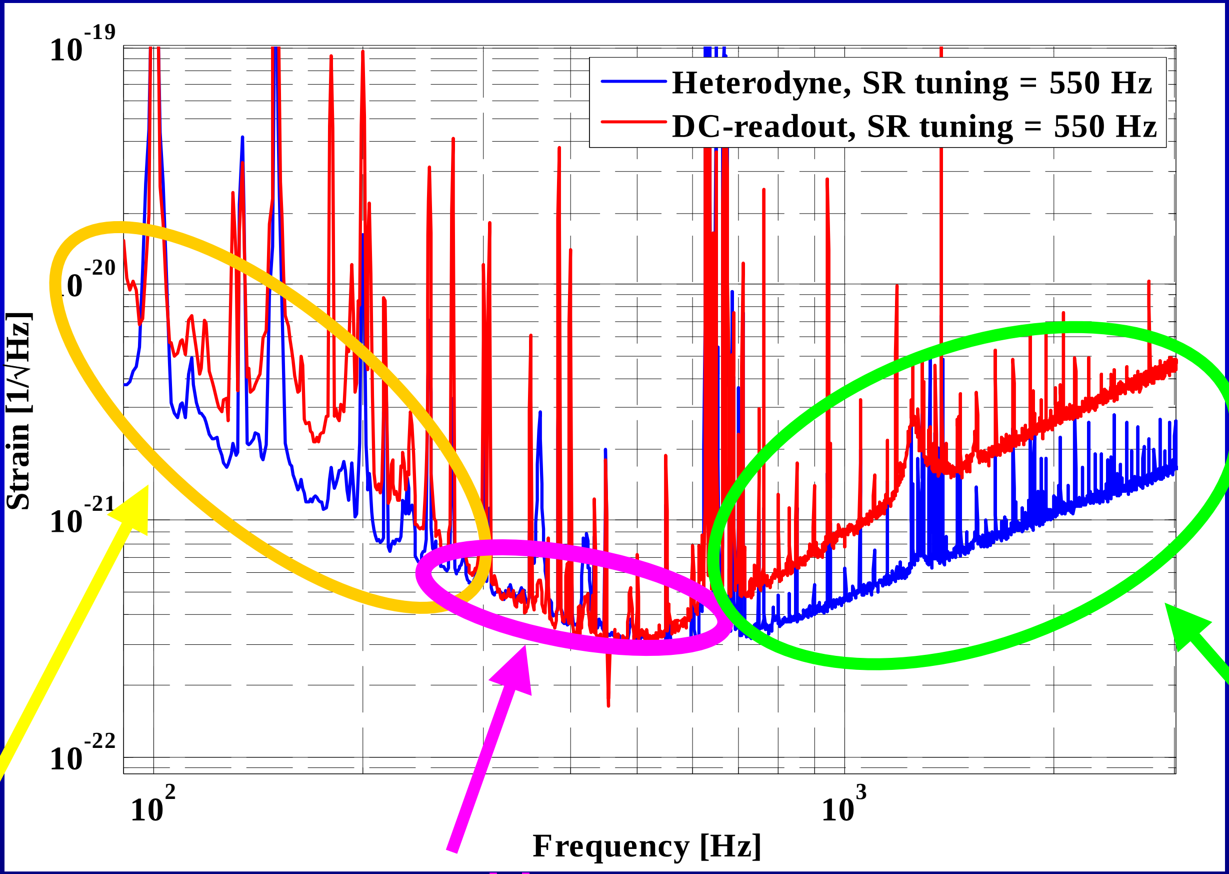
Above 1kHz a sensitivity competitive to heterodyne readout is achieved.

550 Hz tuning

Shot noise in DC-readout: Calculated from optical power vs measurement



Heterodyne vs DC-readout for 550 Hz tuning

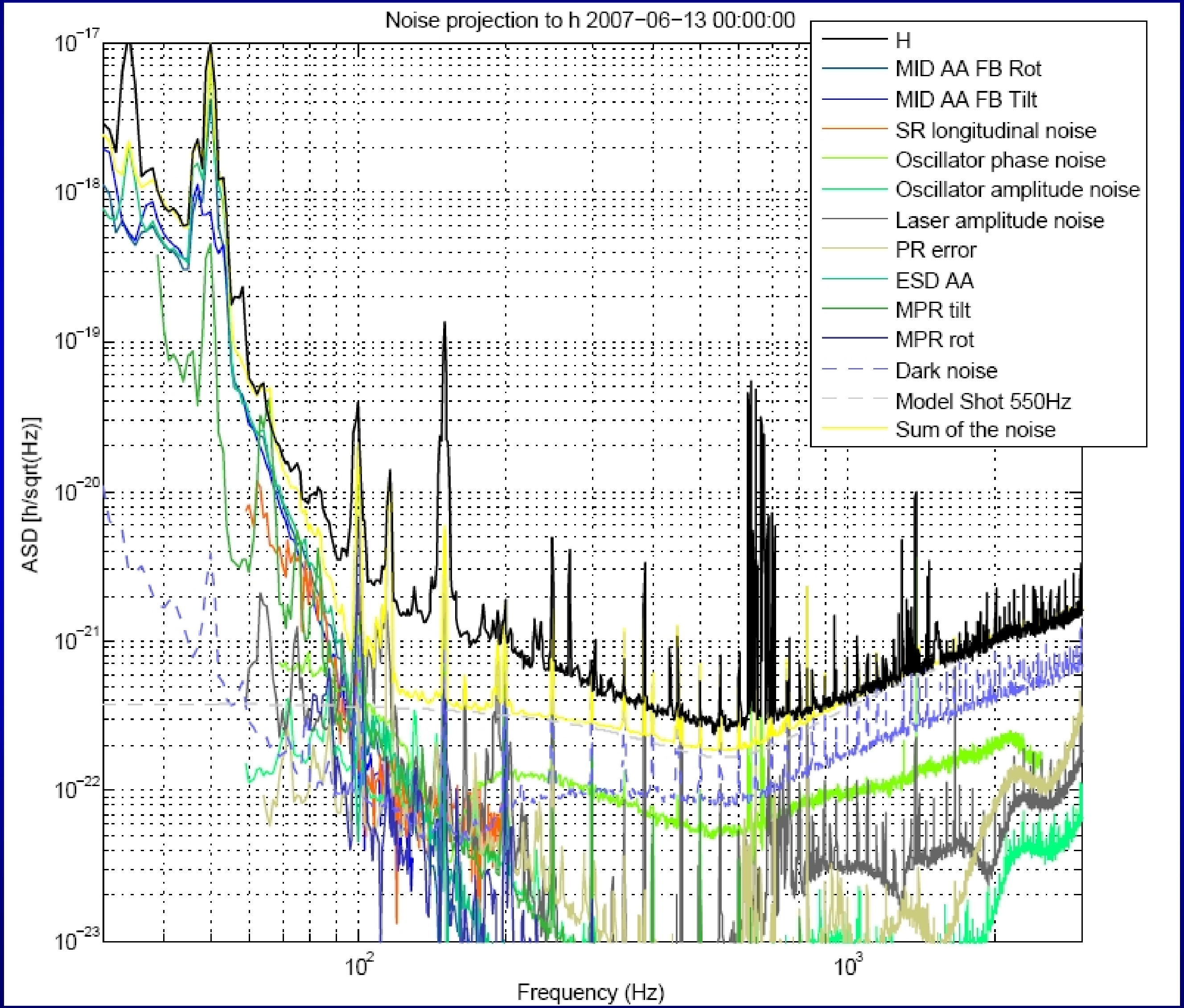


Laser intensity noise ?

Roughly same as with heterodyne (2e-19m/sqrt(Hz))

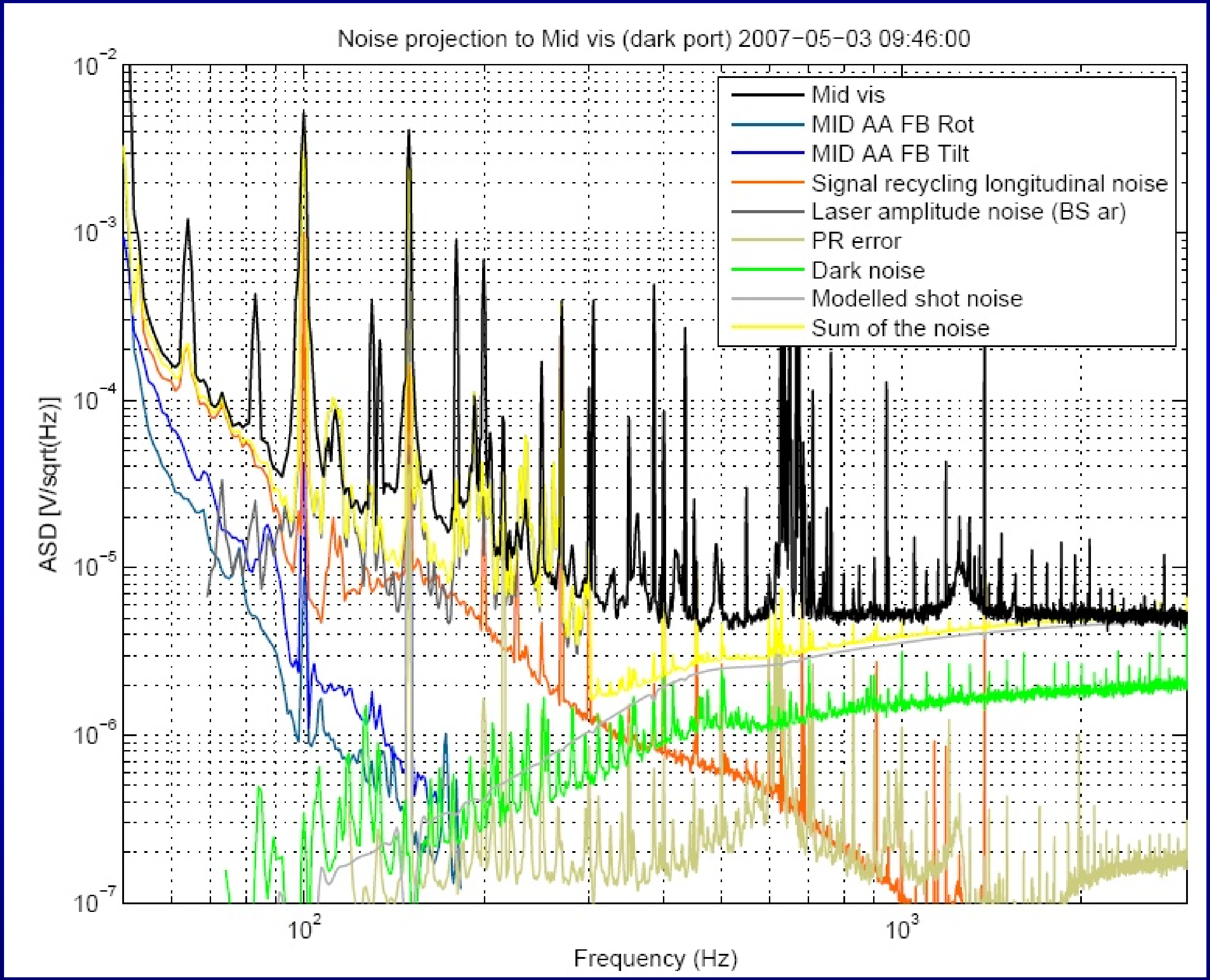
Shot noise
⇒Increased in DC-readout

Noise projections: heterodyne 550 Hz



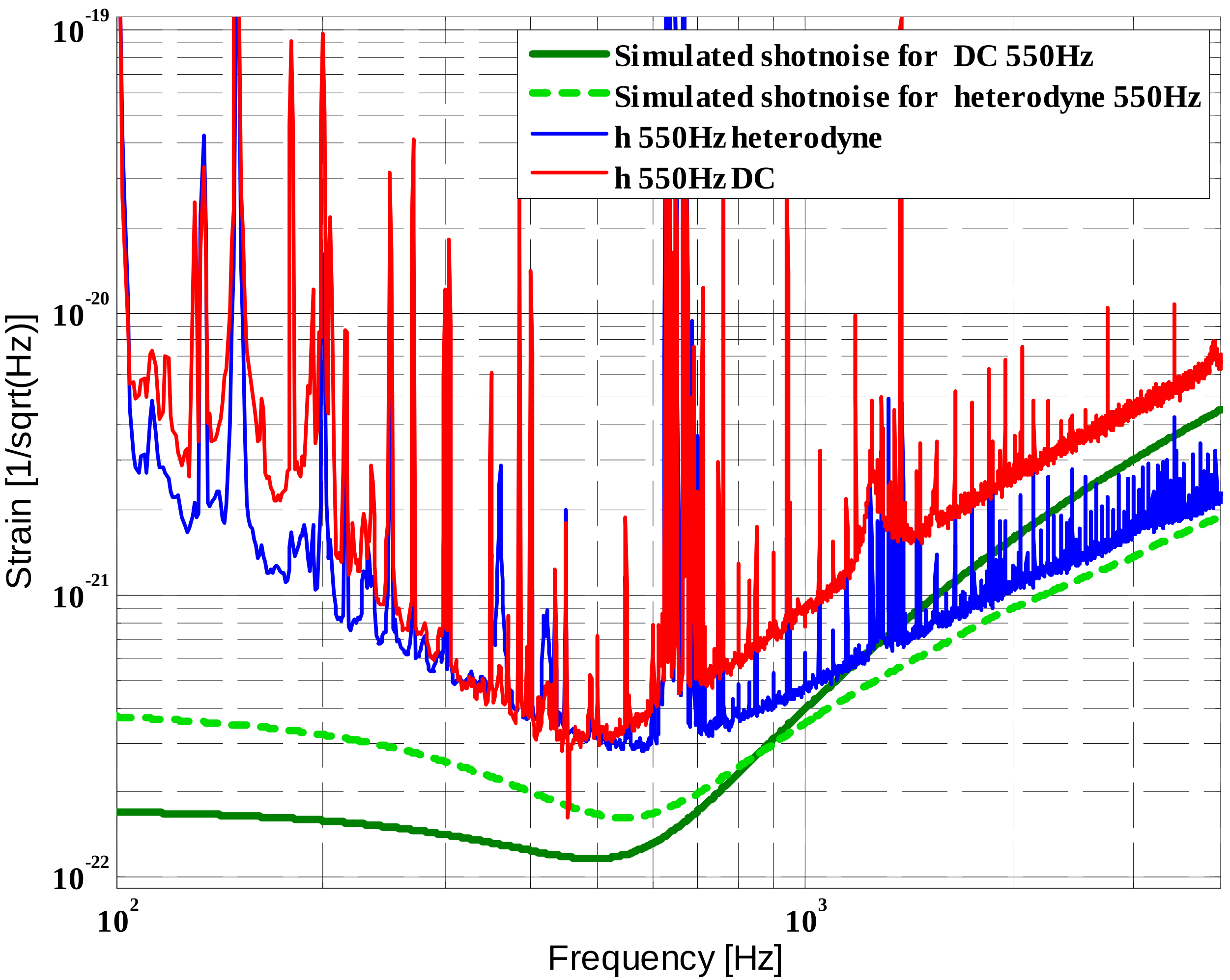
- Above 1kHz shot noise limited.
- Between 80 and 1000 Hz mystery noise is dominant
- At 500 Hz the gap between projected noises and h is about sqrt(2).

Noise projections: DC-readout 550 Hz



- Above 2kHz shot noise limited (calculated from DC power).
- Between 300 and 2000 Hz mystery noise is dominant
- At 500 Hz the gap between projected noises and h is about sqrt(2).

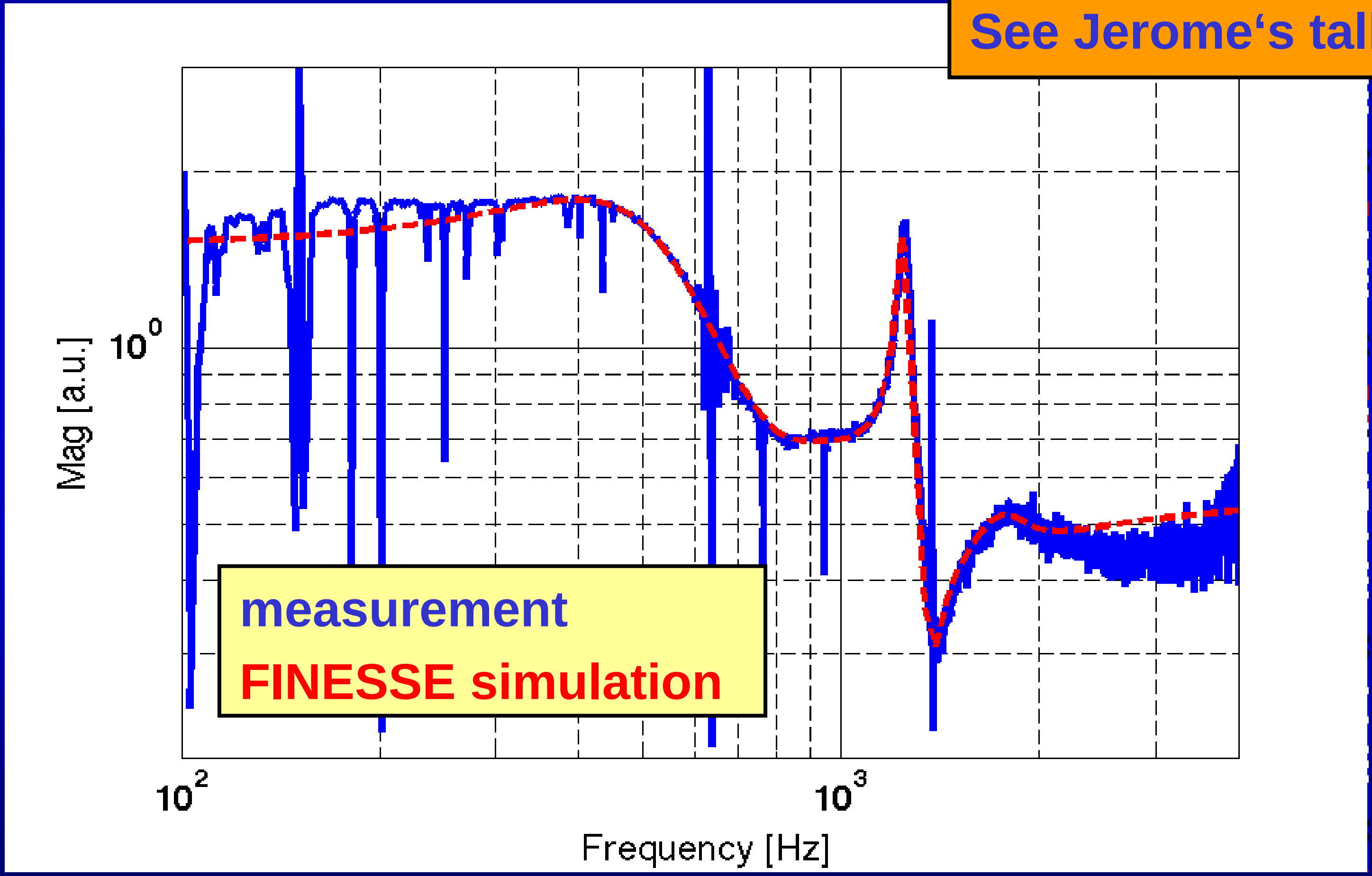
DC-readout and Heterodyne for 550 Hz Simulated shotnoise vs measured H.



Laser Intensity noise TF for 550 Hz DC

Laser intensity noise transfer function from intracavity power to dark port power.

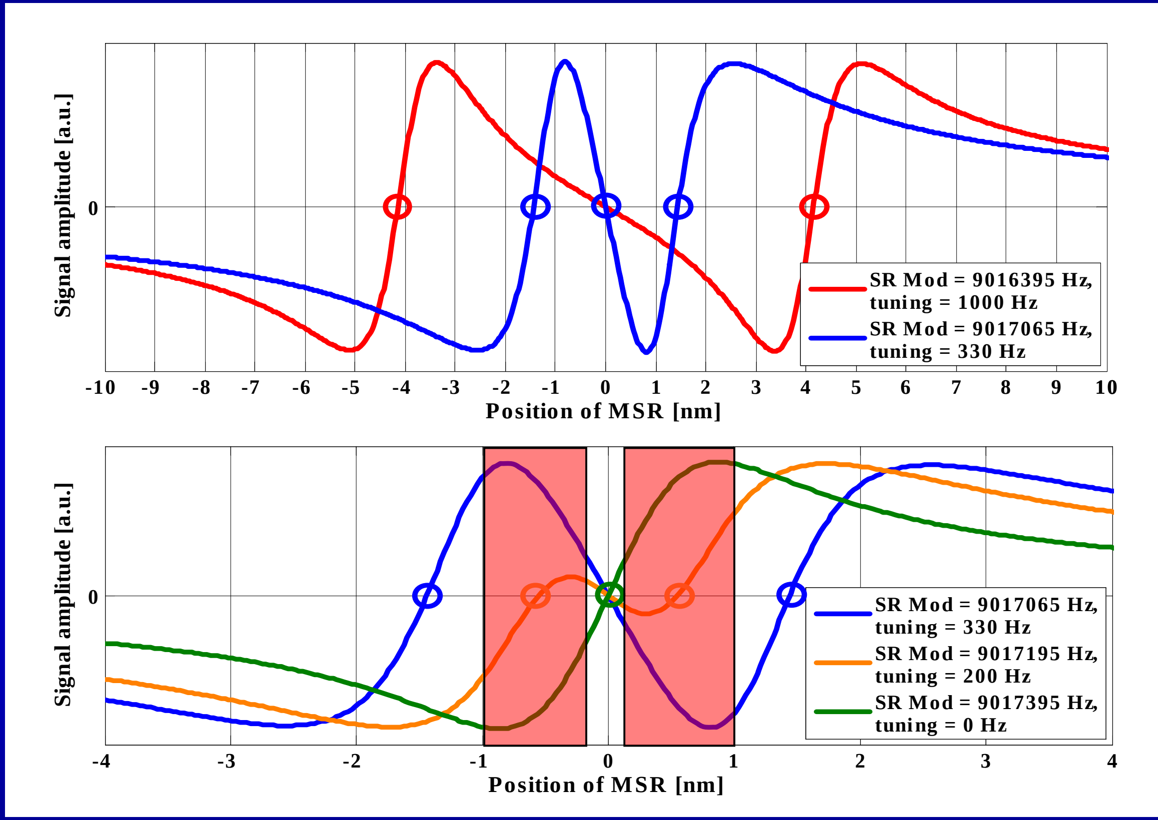
See Jerome's talk



Tuned SR

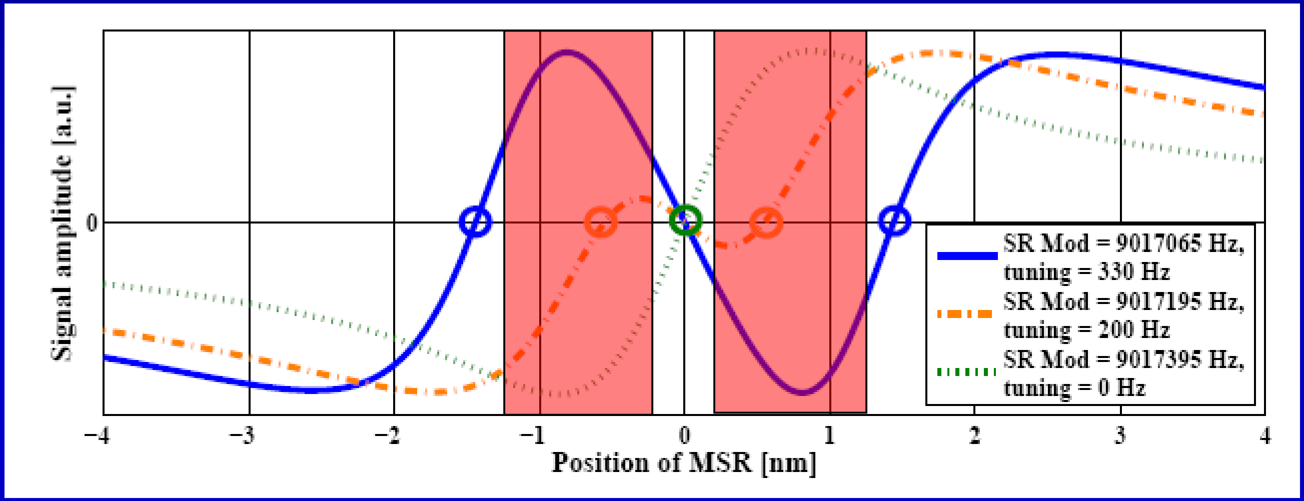
Realisation of tuned signal recycling

- For tunings < 250 Hz we cannot achieve a reasonable control signal.



- Developed a new technique: We ‘kick‘ MSR in a controlled way to jump to tuned SR, where a reasonable control signal can be obtained again.
- MSR is caught at the tuned operating point again.

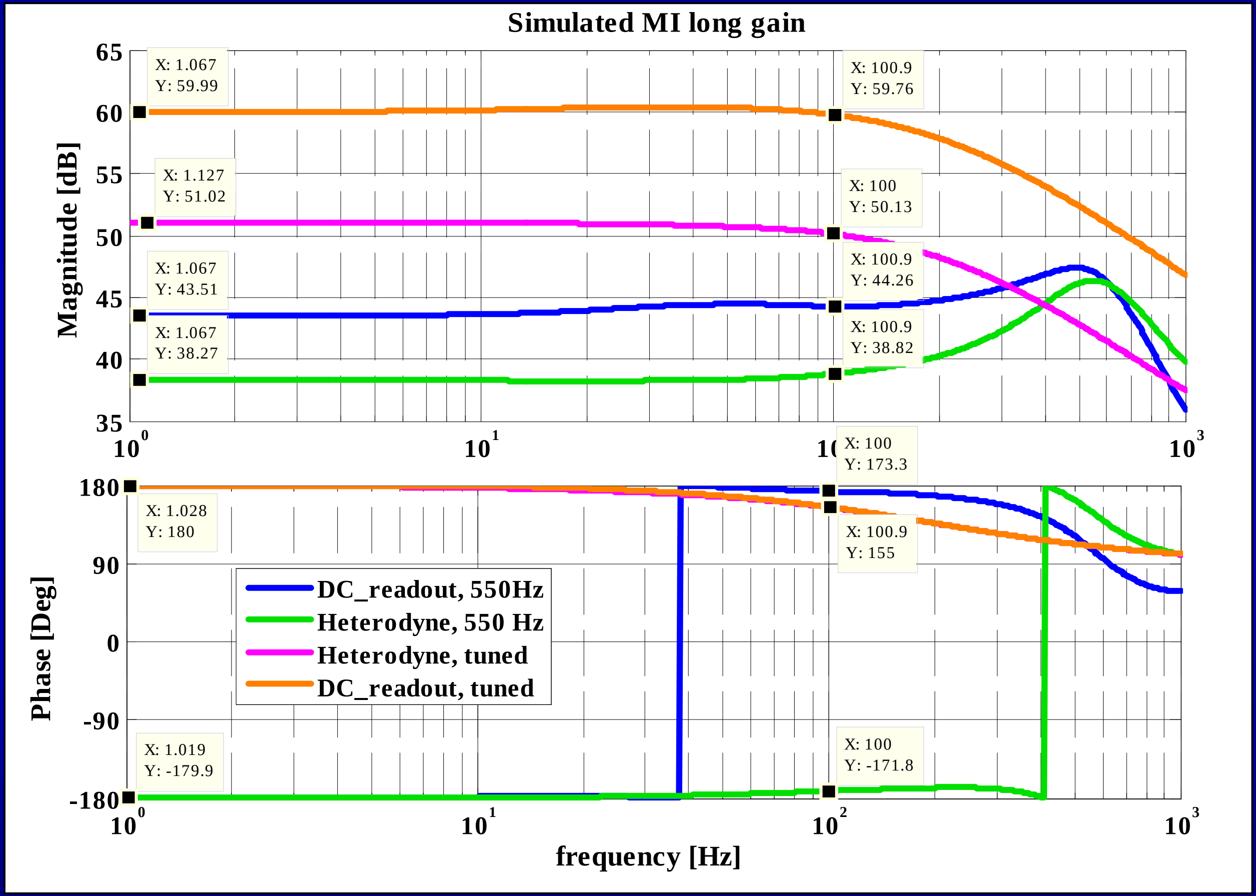
2 different possibilities for going to tuned signal recycling



1. Keep the modulation frequency and jump to center zerocrossing.
2. Change the modulation frequency (corresponding to 0 Hz tuning) => only a single zerocrossing exists.

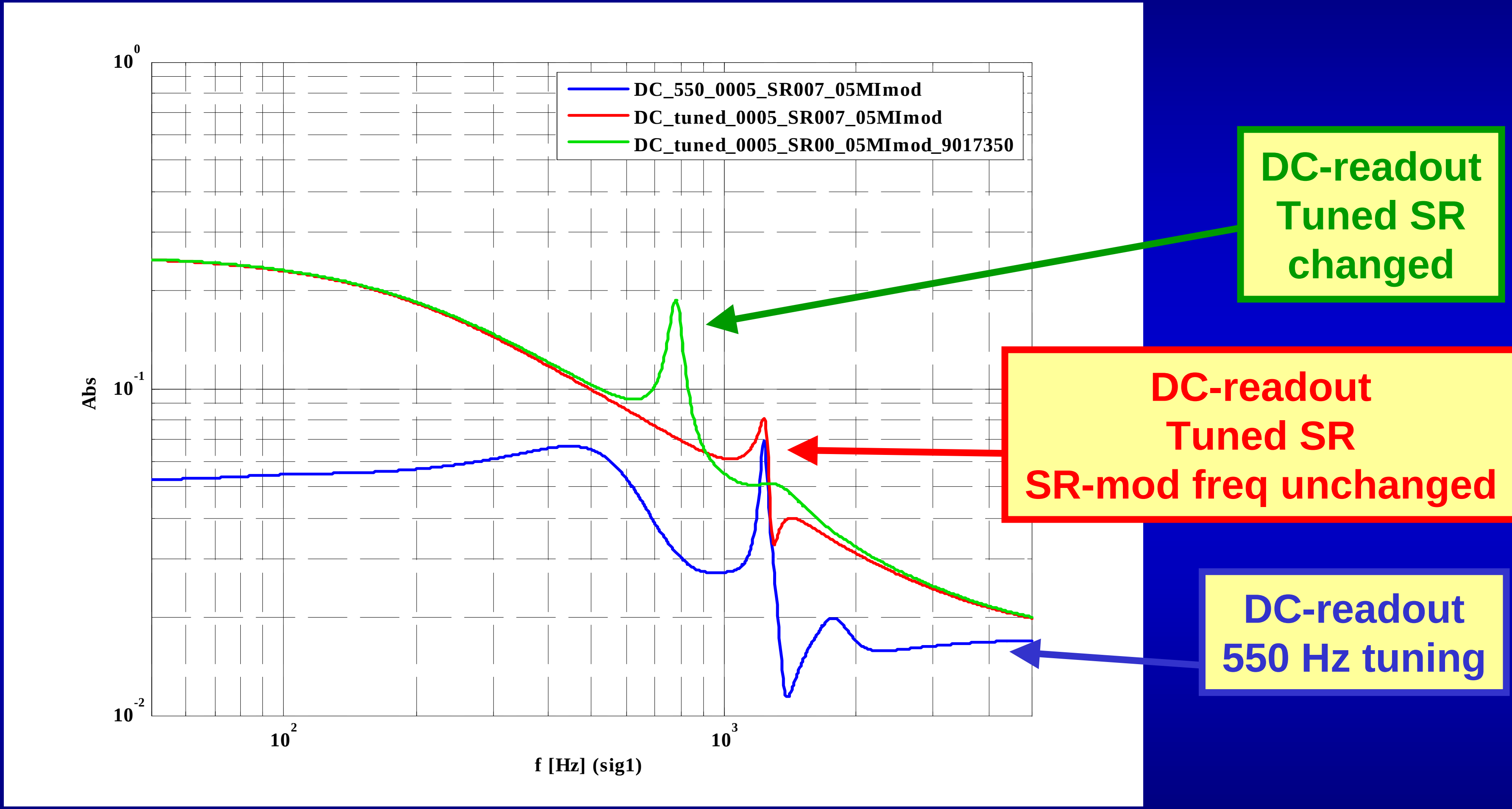
Simulated gain of Michelson differential

- Michelson gain (overall and shape) depends on readout method and SR-tuning.



- Need to adjust the servo-filters on the fly

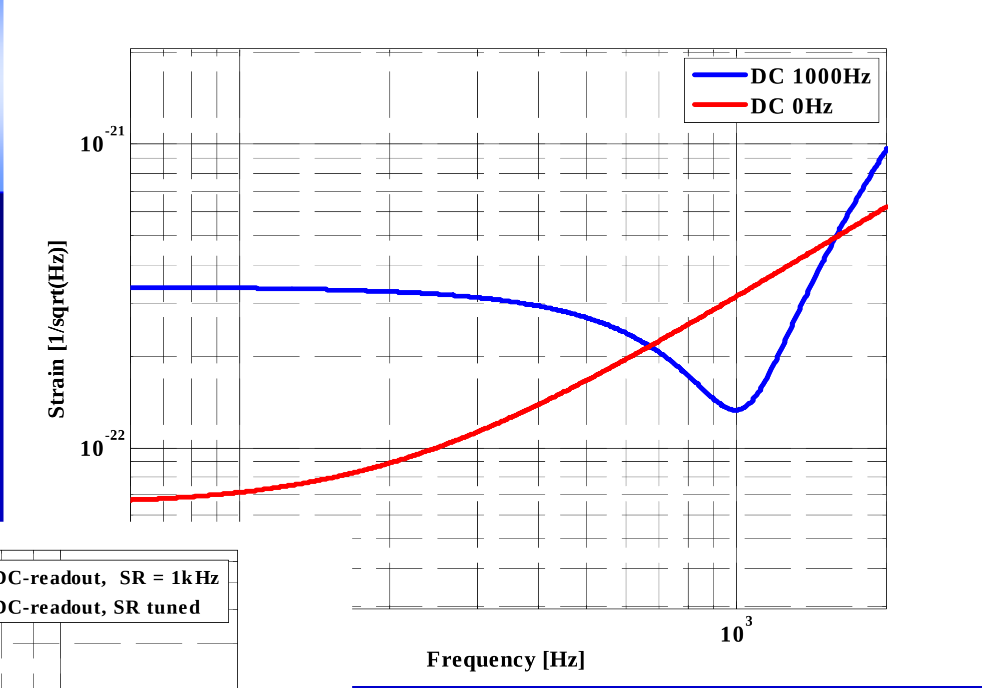
Simulated Laser intensity noise coupling

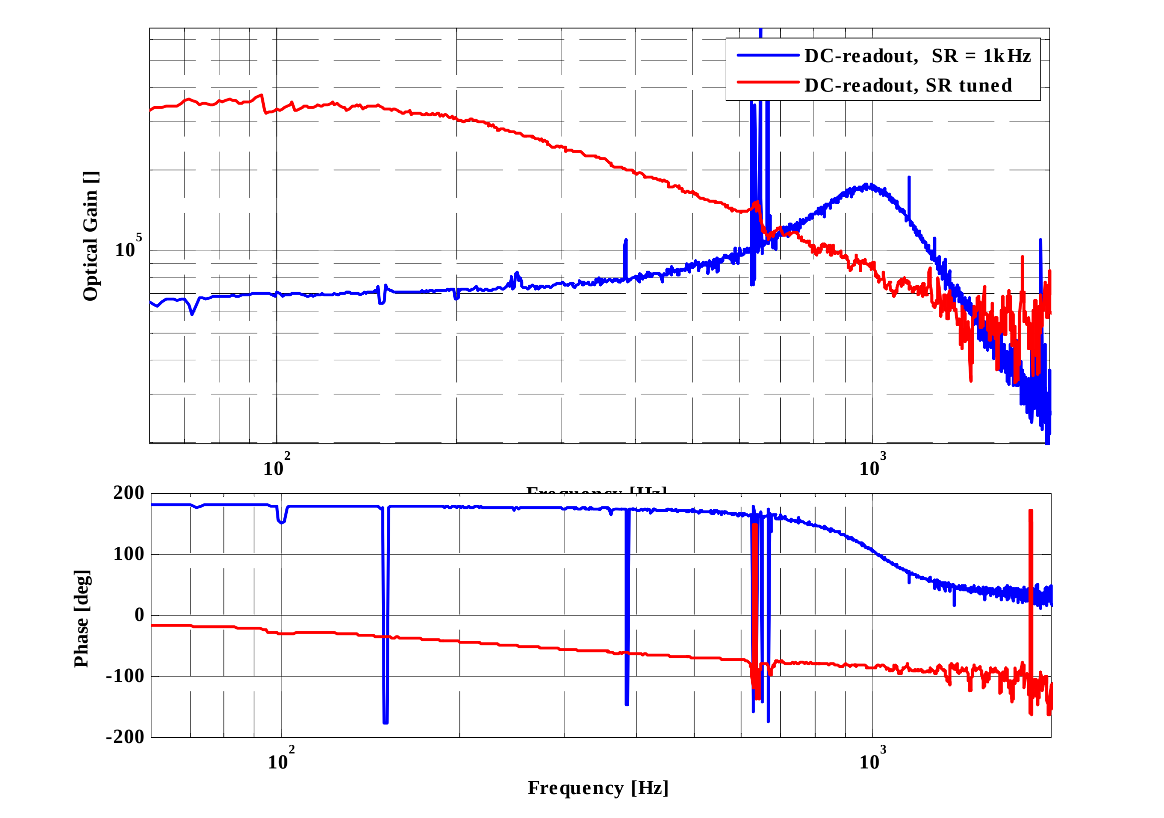


For tuned SR Laser intensity noise might be a stronger problem.

Optical gain of tuned DC and 1kHz DC

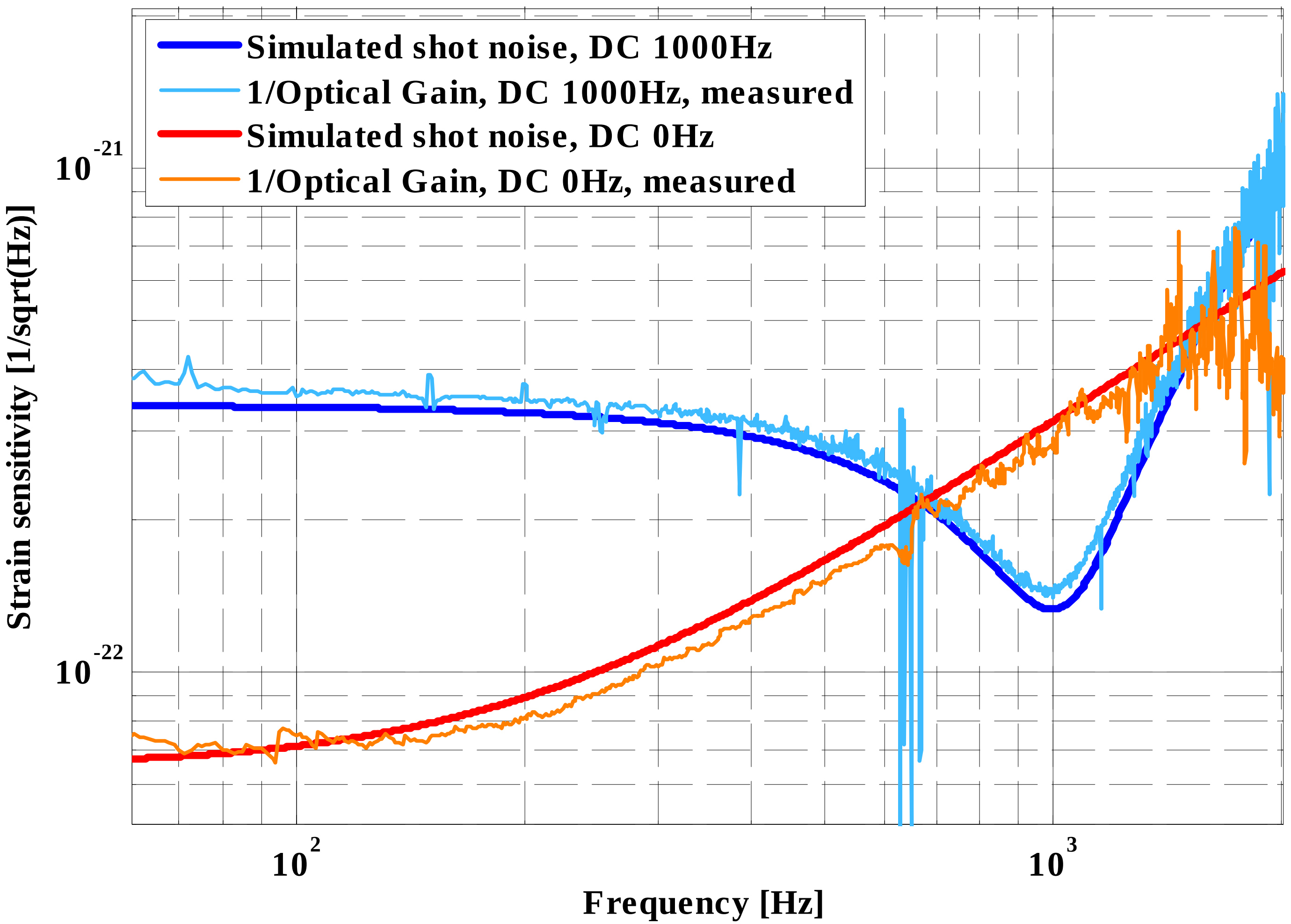
Finally we were able to realize tuned SR with DC-readout.



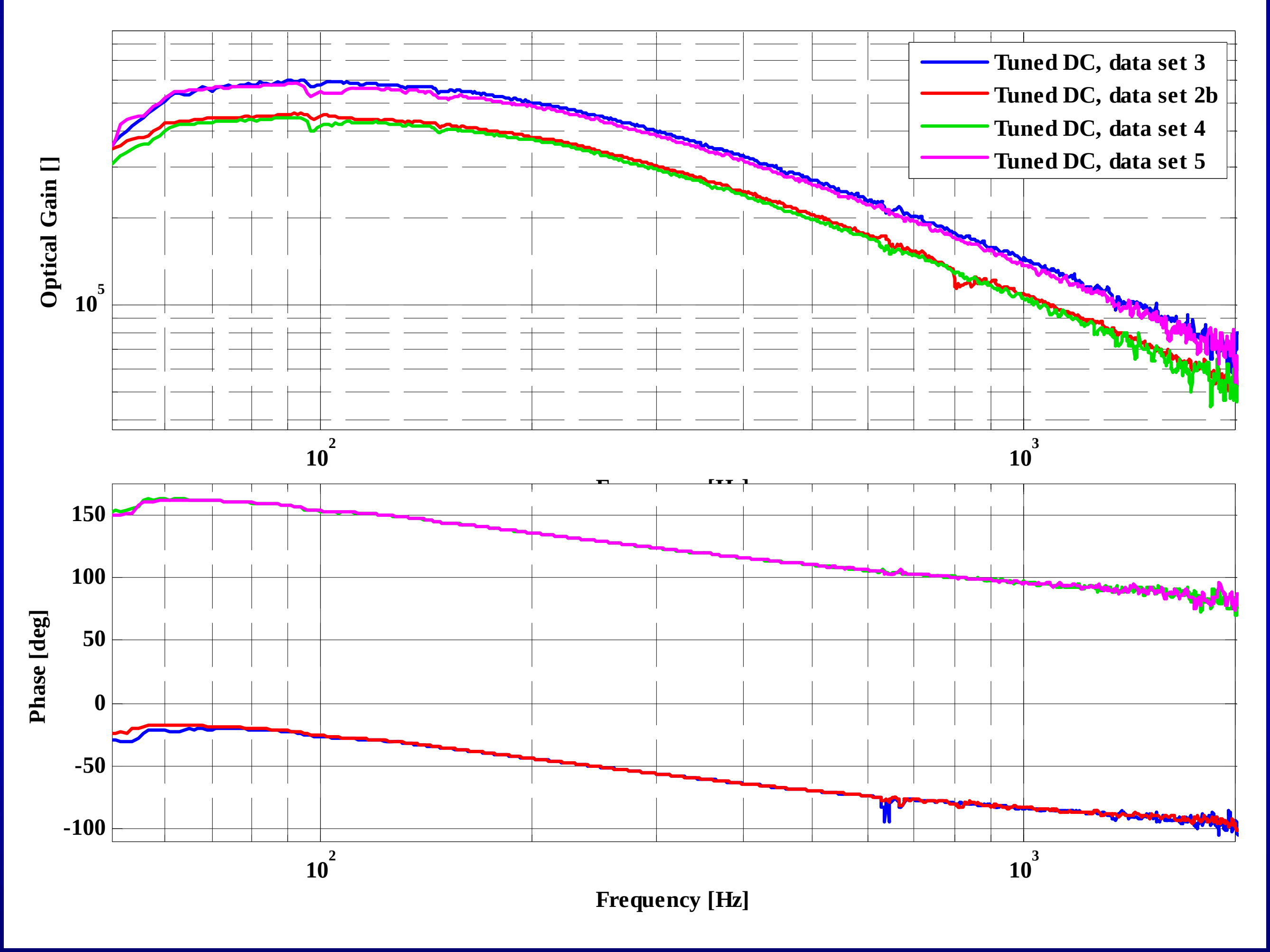


The optical gain for tuned DC looks like expected.

Comparison of measured and simulated optical transfer function



Tuned DC with various dark fringe offsets



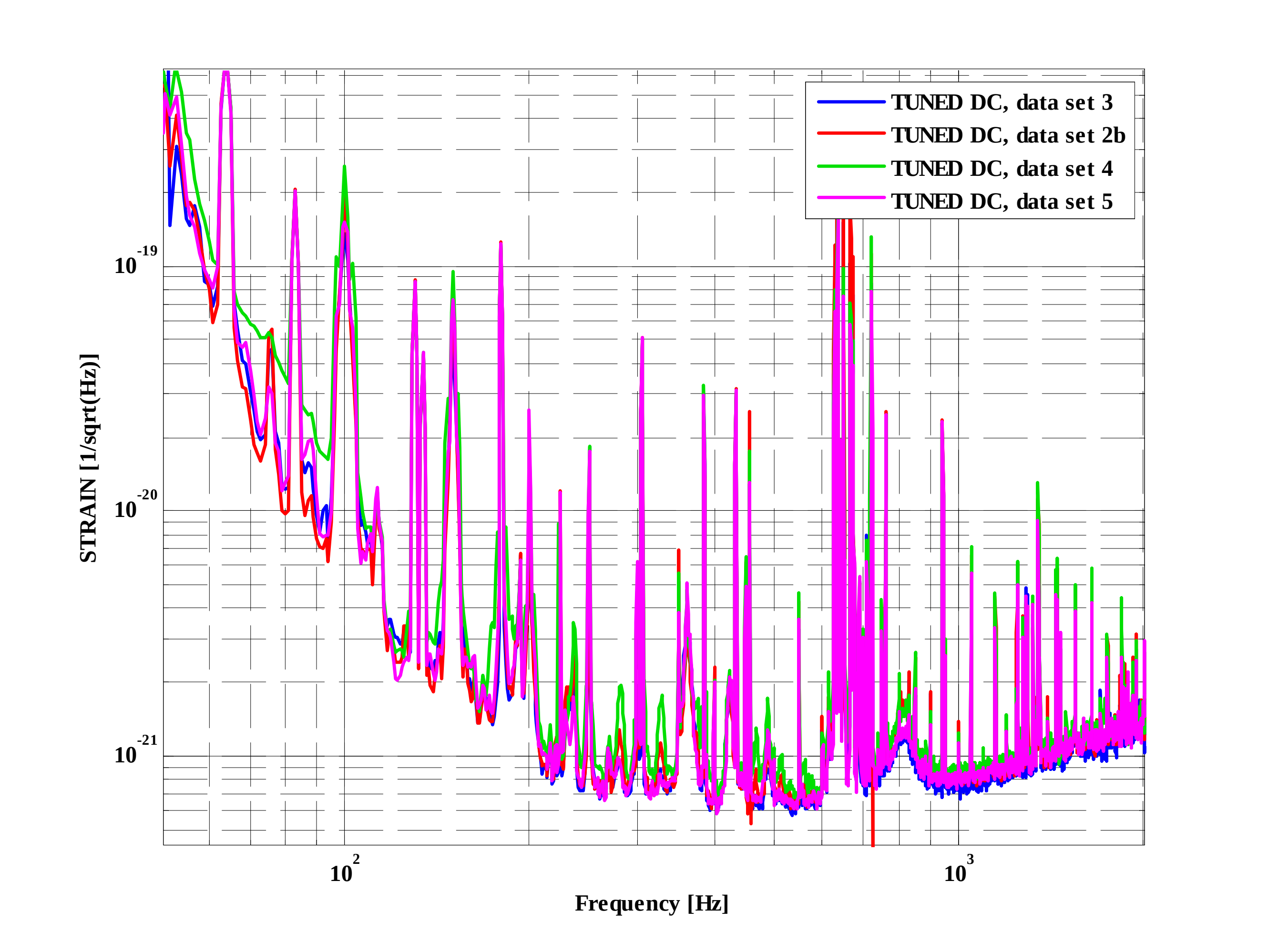
data set **2b:**
small –dfo

data set **3:**
large –dfo

data set **4:**
small +dfo

data set **5:**
large +dfo

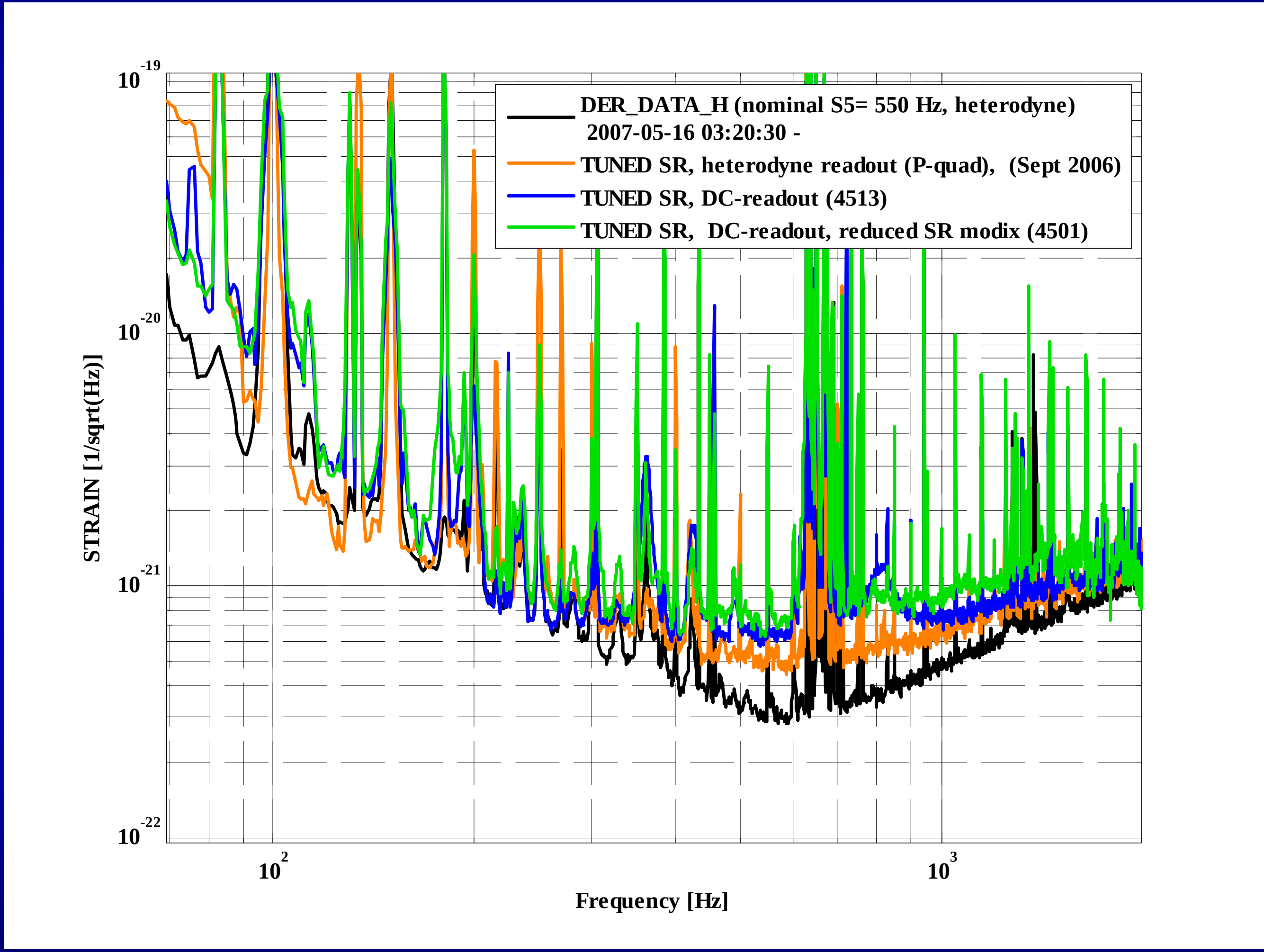
Sensitivity of tuned DC with various dfo



For the dark fringe offsets that were tested:

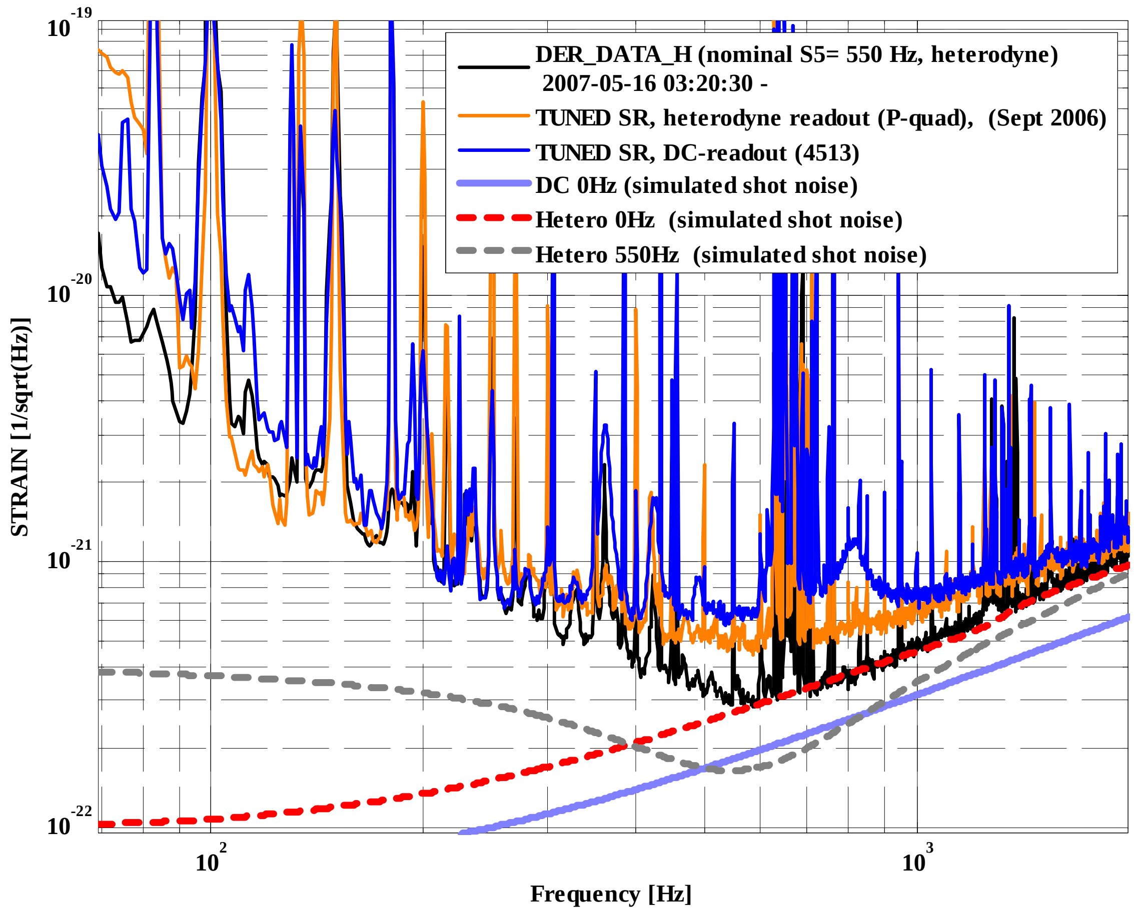
The sensitivity seems to be independent from size and sign of the dark fringe offset.

Sensitivity comparison for tuned DC



- Reducing the SR modulation index reduces the peak at 800 Hz, but also increases the noisefloor at high freqs.
- Tuned with heterodyne (with not optimized demod phase) seems to be better than tuned DC.

Comapsrison of heterodyne 550 Hz, tuned heterodyne and tuned DC



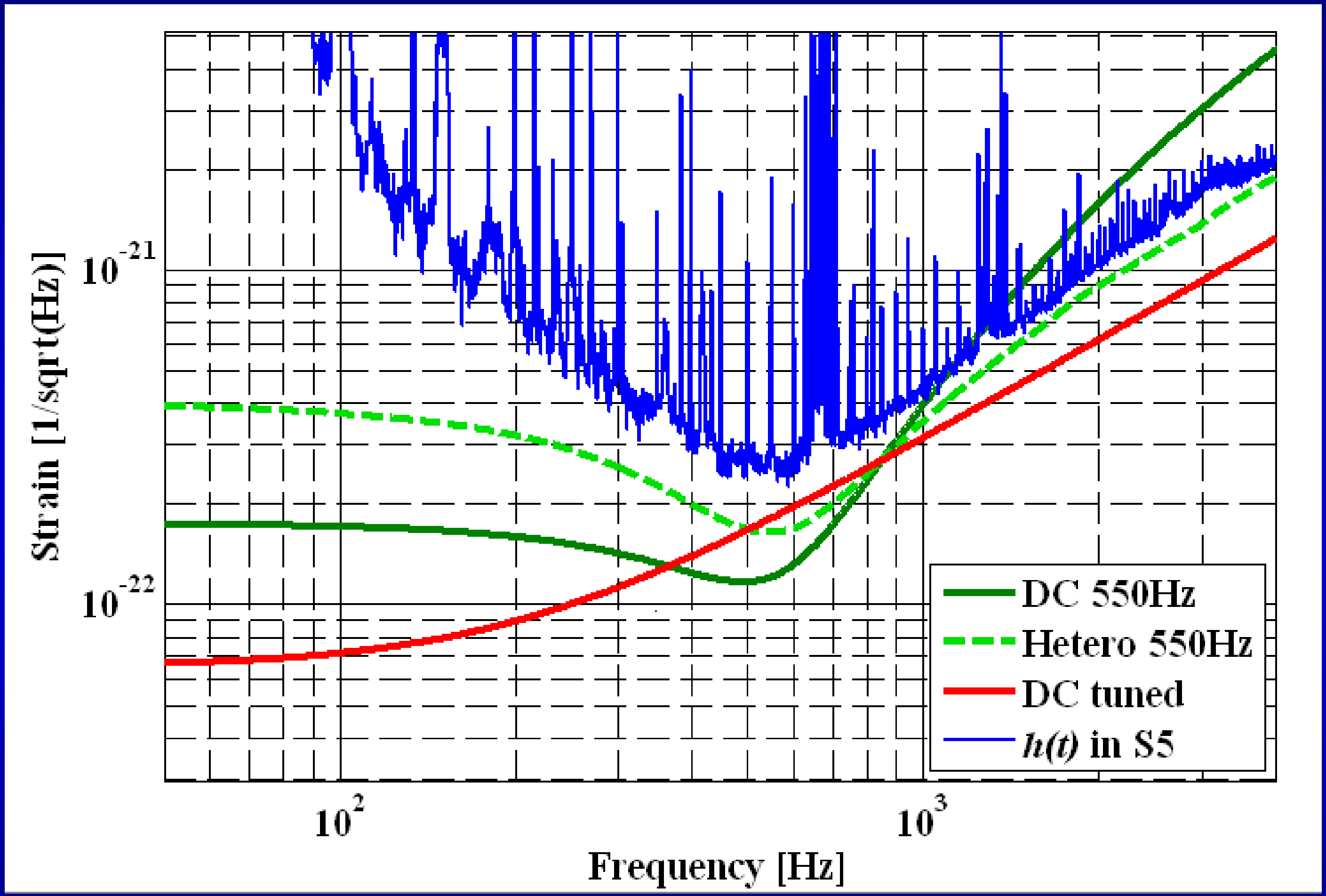
While in the two heterodyne cases the sensitivity is close to simulated shot noise at 2 kHz, this is not the case for tuned DC.

Summary

- DC-readout without OMC is possible !!
- Stable operation with DC-readout and DC-lock in tuned and detuned Signal-Recycling.
- Best achieved DC-readout sensitivity about 2e-19m/sqrt(Hz).
- At high frequency sensitivity achieved in DC-readout is not completely understood. => Ongoing investigations.

Future

What might be gained from DC-readout



Tuned DC-readout might be a useful precursor for GEO-HF
(option for squeeezed light input => no filter cavity necessary)

Combination of tuned SR and squeezing– an option for GEO HF?

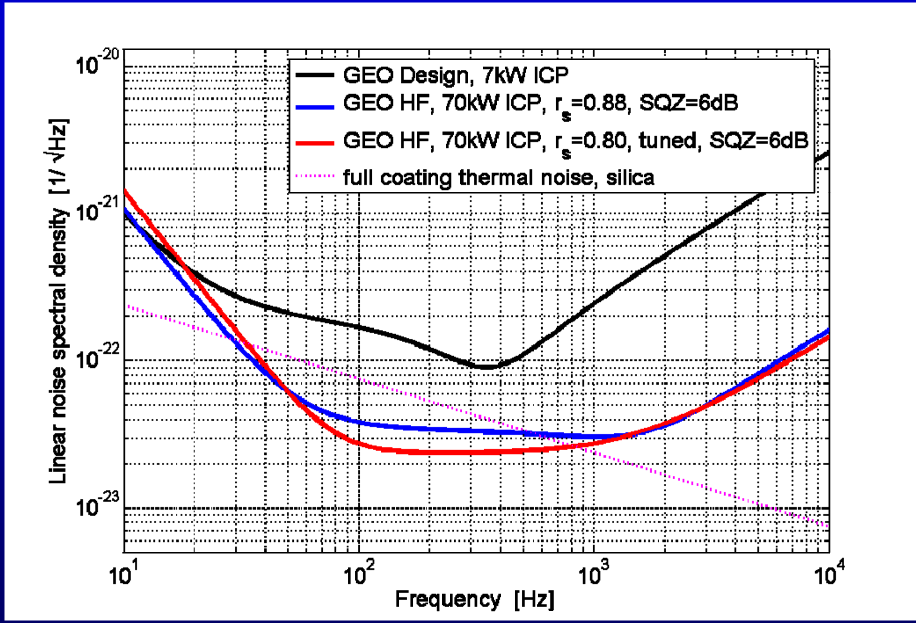
- Squeezed light is available for injection

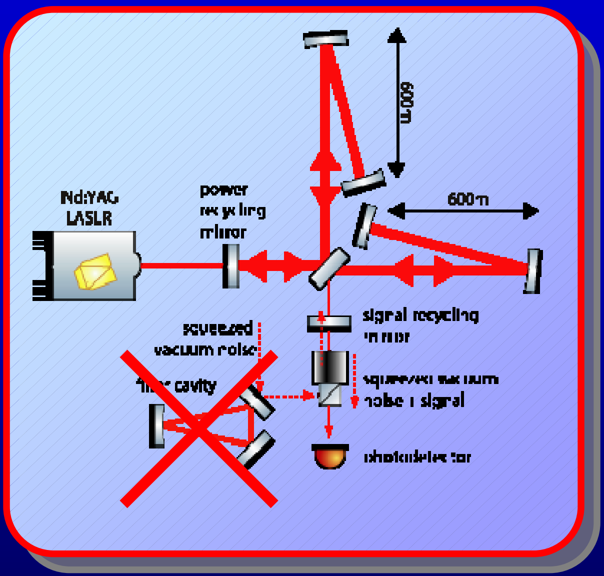
“Coherent Control of Vacuum Squeezing in the Gravitational-Wave Detection Band“, Vahlbruch et al, PRL 97, 011101 (2006)

- Tuned Signal-Recycling operation was demonstrated

„Demonstration and comparison of tuned and detuned Signal-Recycling in a large scale gravitational wave detector“ , S Hild et al, CQG. ***24*** *No 6, 1513-1523.*

⇒ No need for long filter cavity !





Plans for the near future

- Noise projections for tuned DC
- Intensive noise hunting in tuned DC
- Figure out whether we miss signal amplitude
- Try a larger photodiode (5mm InGAs)

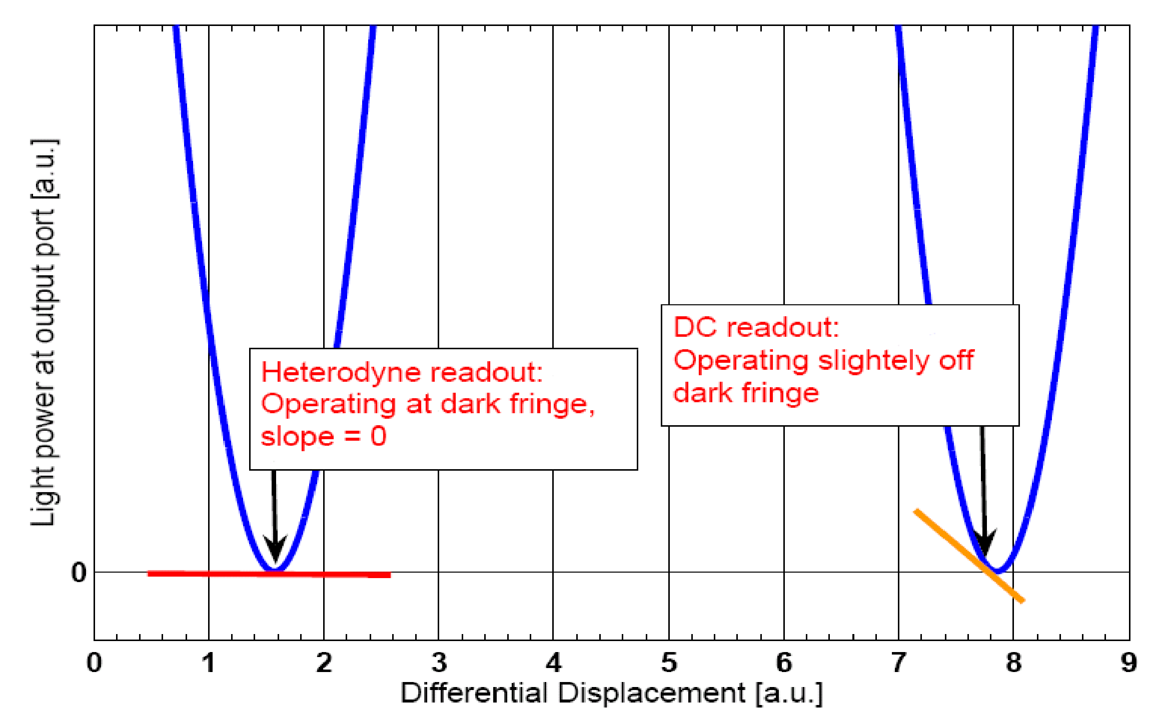
- Find/decide optimal detector configuration for 2008

Heterodyne
detuned SR
tuned SR
DC-readout

E n d

Heterodyne vs DC-readout

- Local oscillator for heterodyne: RF sidebands (Schnupp modulation).
- Local oscillator for DC-readout: Carrier light from dark fringe offset.



It is a noteworthy fact, that in recent times the relative stability of the light in the IFO is better than the relative phase noise achievable with excellent RF technique.

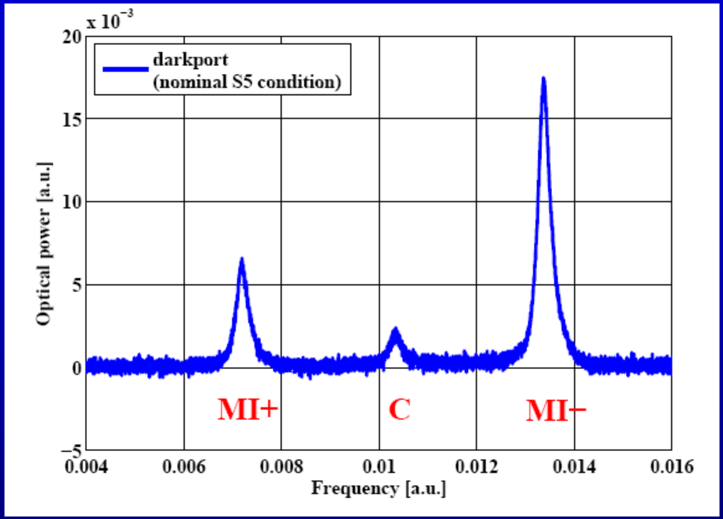
Shot noise improvement from DC_readout

[Buonanno03] *"Quantum noise in laser-interferometer gravitational-wave detectors with a heterodyne readout scheme"*, A Buonanno, Y Chen, and N Mavalvala, Phys. Rev. D **67**, 122005, (2003)

[Harms06] *"Shot Noise and Heterodyne Detectors"*, J Harms, internal document, 2006

When going to DC-readout the signal to shotnoise ratio will be increased by a factor between sqrt(1.5) for balanced sidebands and sqrt(2) for completely unbalanced sidebands.

Measurements of the dark port light field of GEO (TEM00) using a scanning Fabry-Perot cavity.



We expect an increase roughly in the middle between balanced and unbalanced.