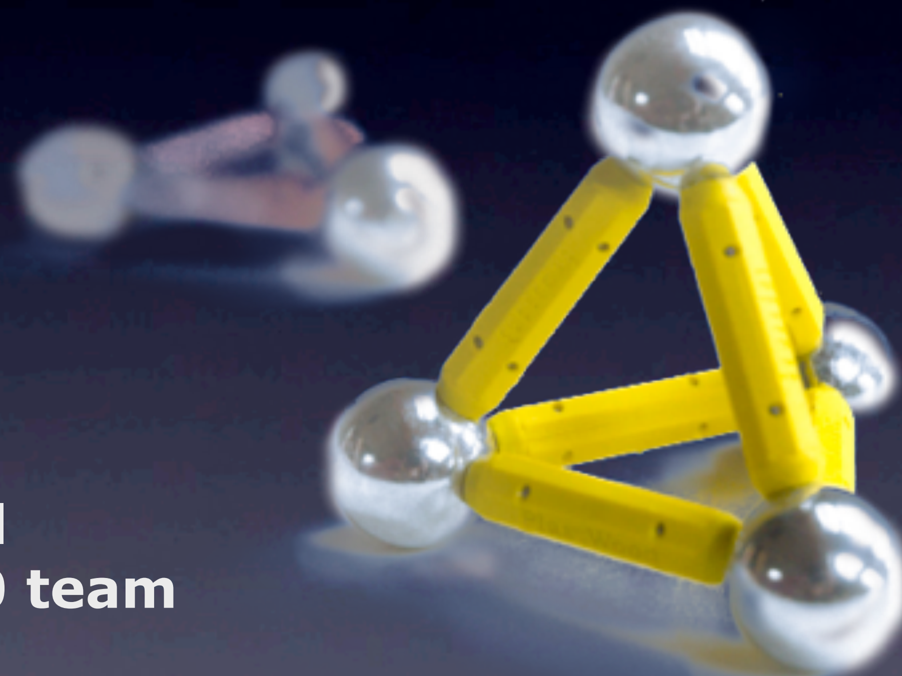
Experiences and lessons learned from interferometer simulations at GEO



Andreas Freise for
Hartmut Grote, Holger Wittel
and the rest of the **GEO 600 team**

GWADW, 22.05.2013

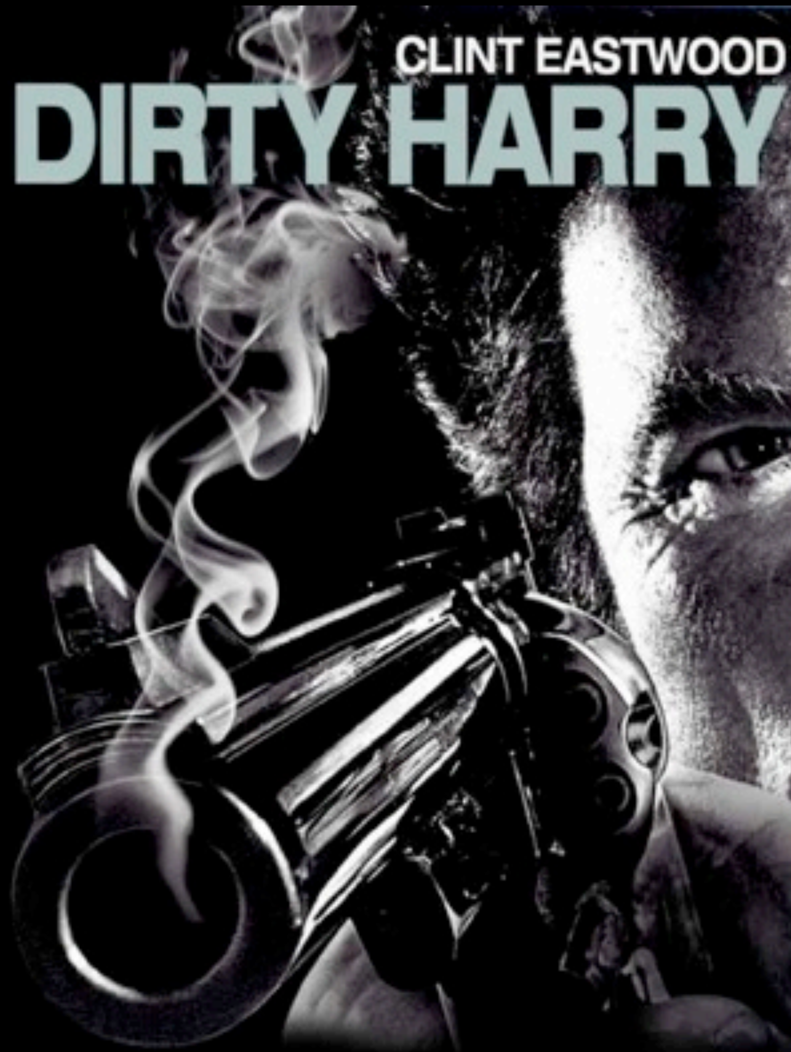
Quick + Dirty Simulations

Quick!

- Quick means:
  - You can do the simulation
  - The simulation and the right input file are ready on your computer
  - results are fast, first tests take seconds
- Motivation:
  - Commissioning is a fast-paced, high-pressure activity
  - Related simulations are an iterative process

Dirty?

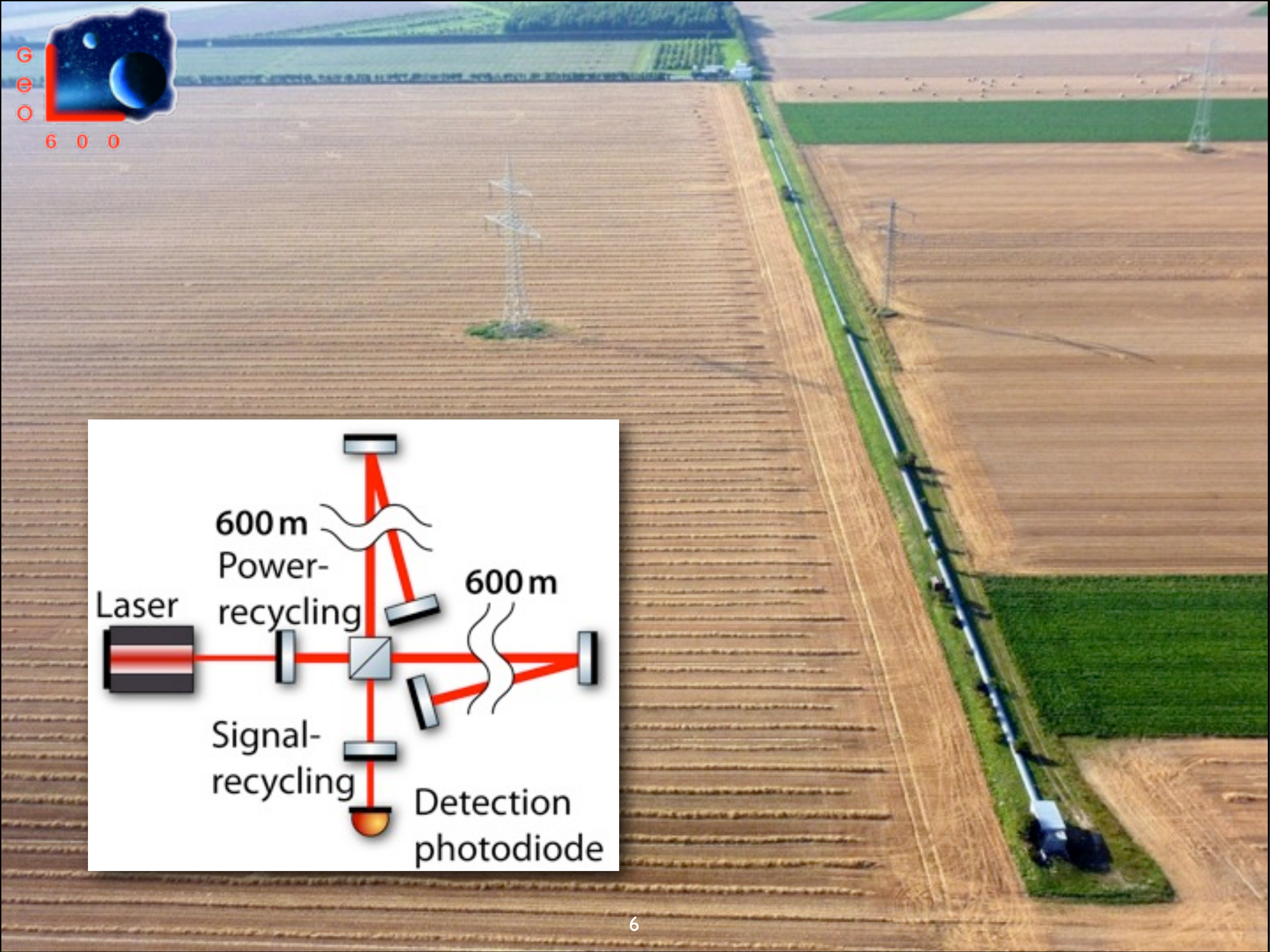
- Commissioning is the art of dealing with the unexpected
- Your interferometer does not work, your previous models are wrong! (or rather: incomplete)
- Make your model dirty, i.e. include all kinds of small defect, detunings and aberrations



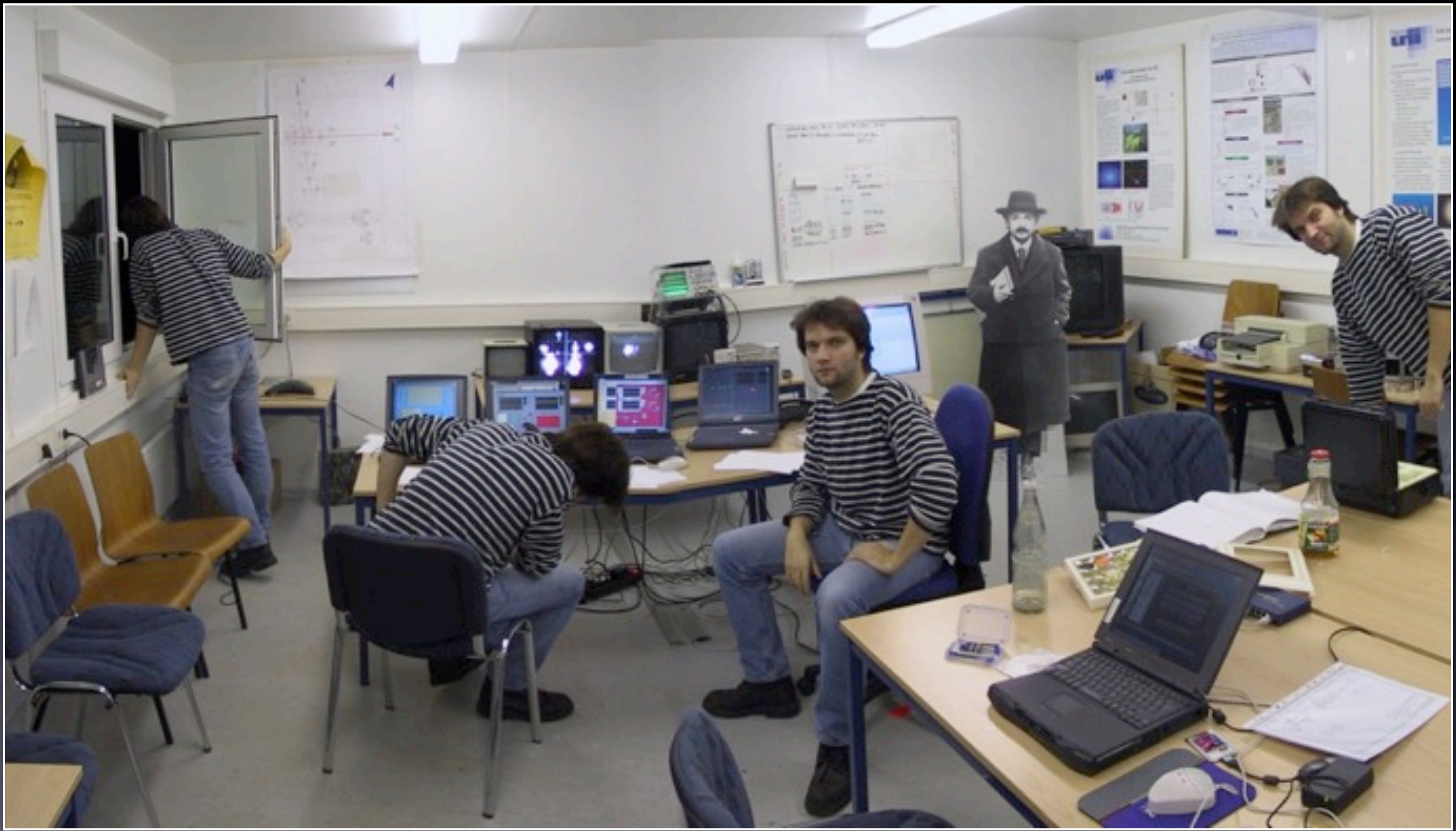
Overview

- Snippets from the GEO logbook
- From more than a decade of commissioning
- Recurring topic: beam shapes and modes
- Our standard tool: FINESSE

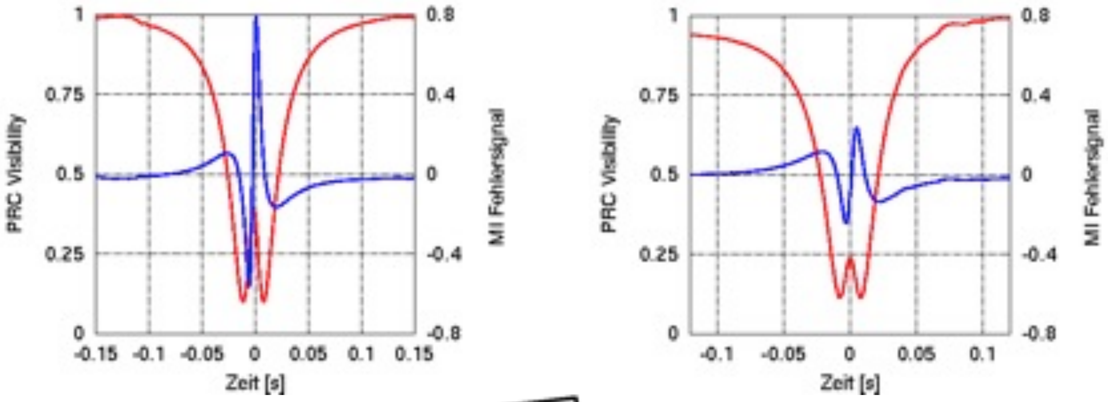

Geo
600

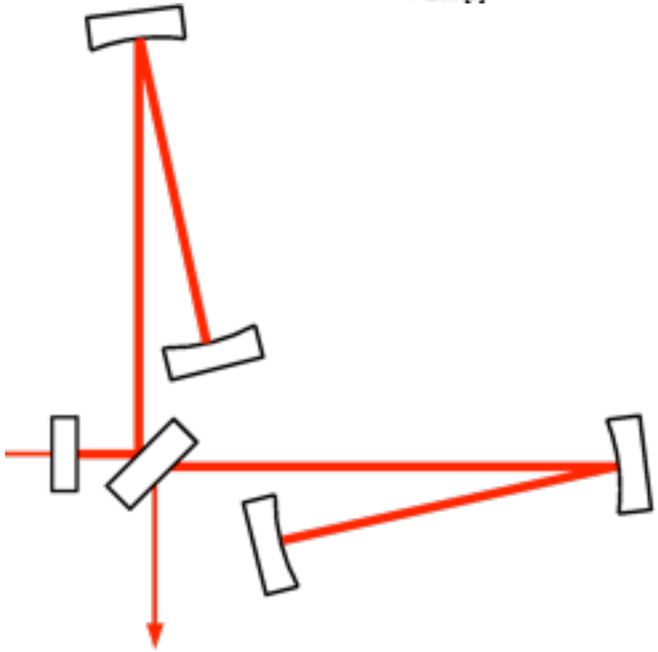

GEO
600
600 m
Power-
recycling
Laser
600 m
Signal-
recycling
Detection
photodiode

A long time ago,
in a control room far away ...



Power Recycling Control (2003)





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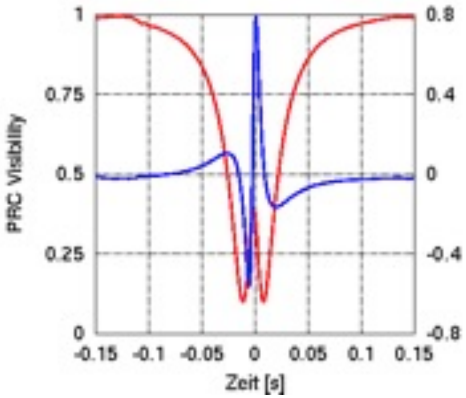
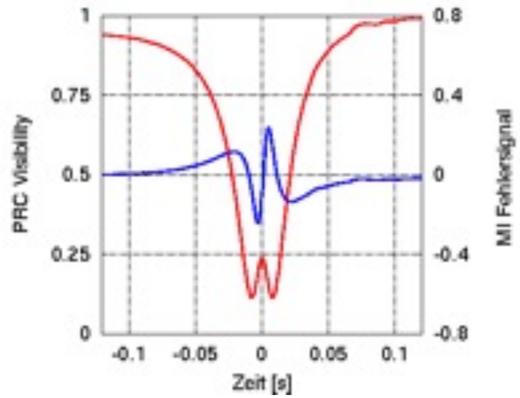
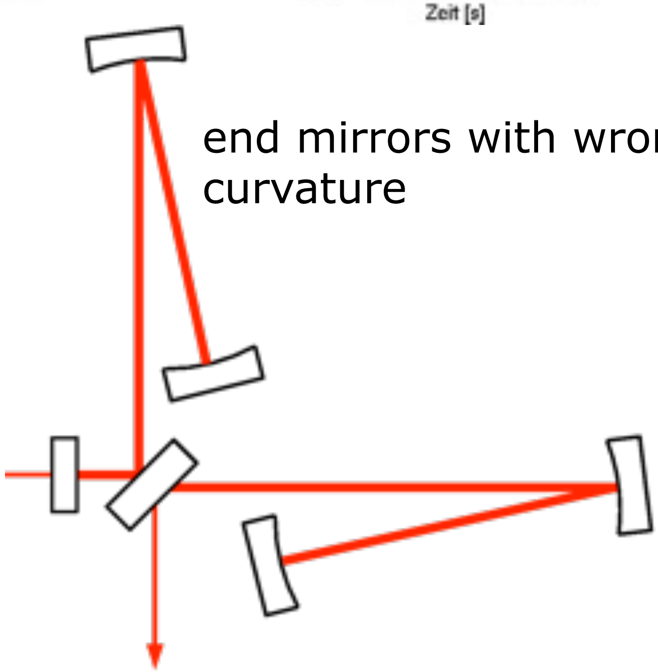
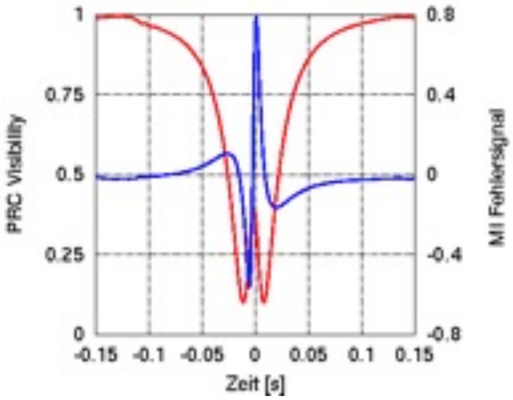


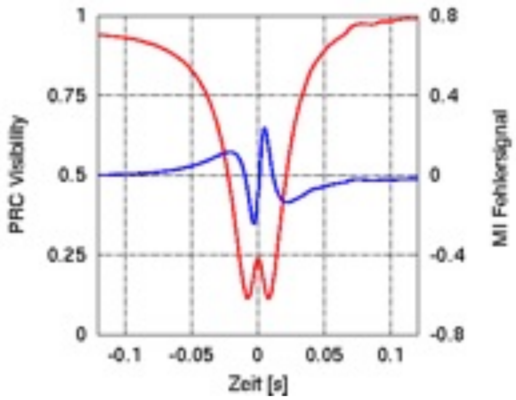


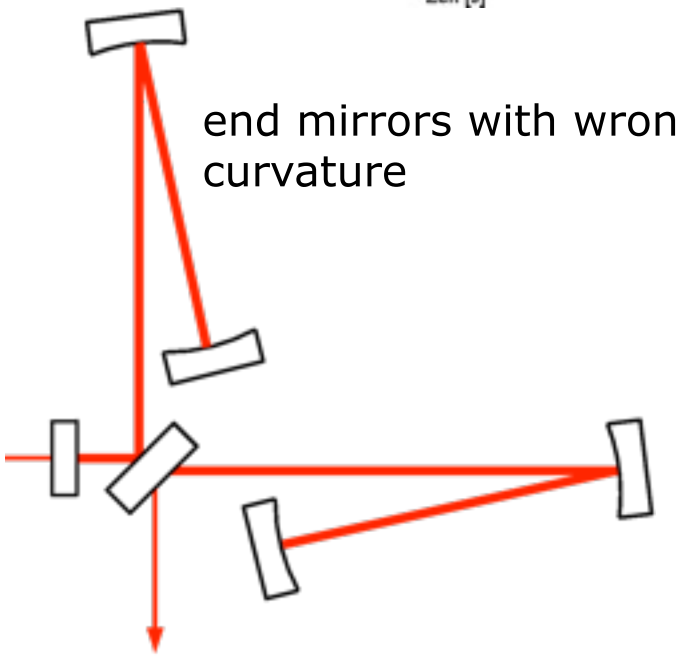


end mirrors with wrong curvature

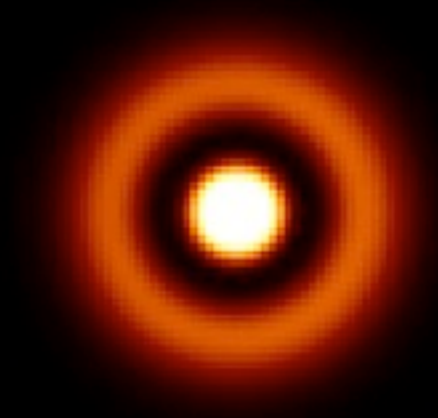
Power Recycling Control (2003)



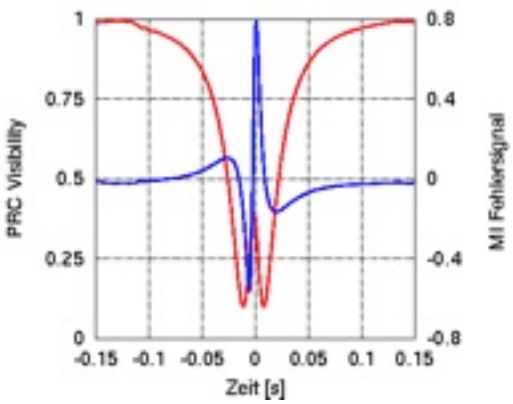


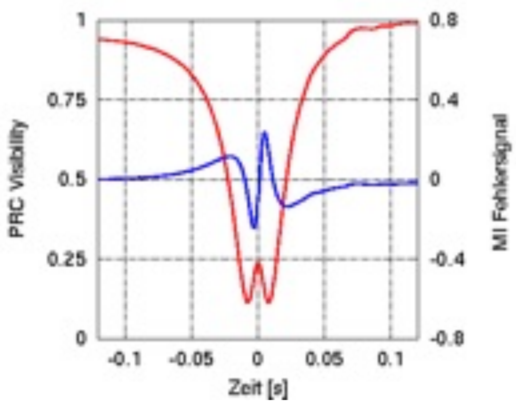


end mirrors with wrong curvature



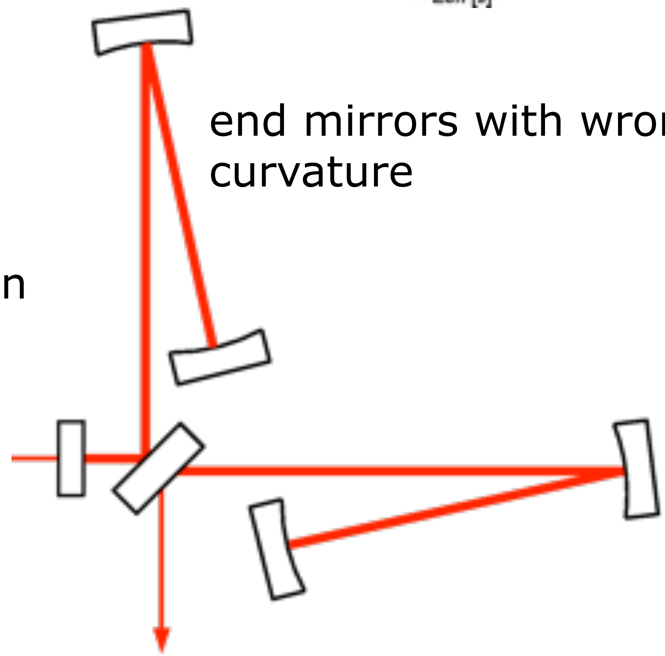
Power Recycling Control (2003)

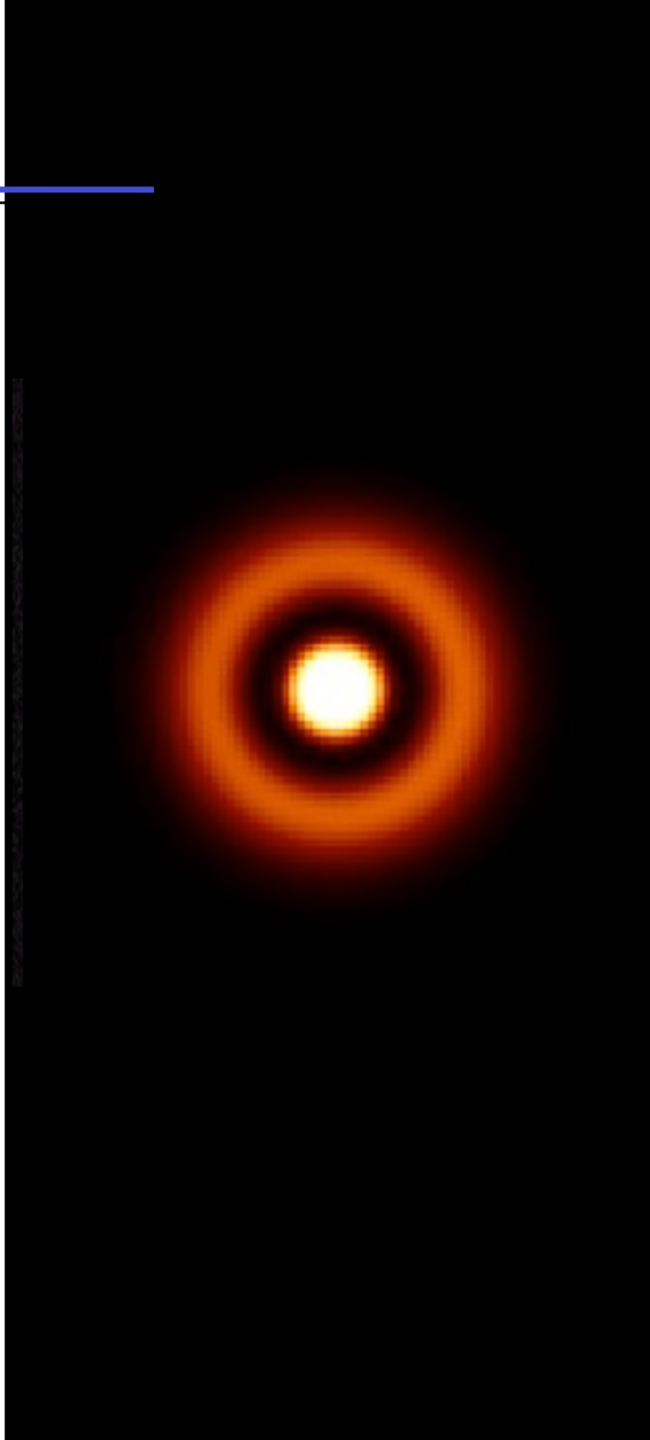




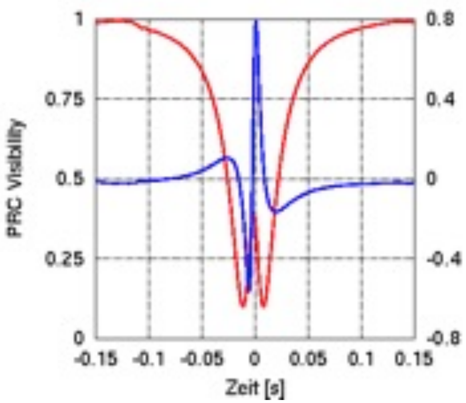
end mirrors with wrong curvature

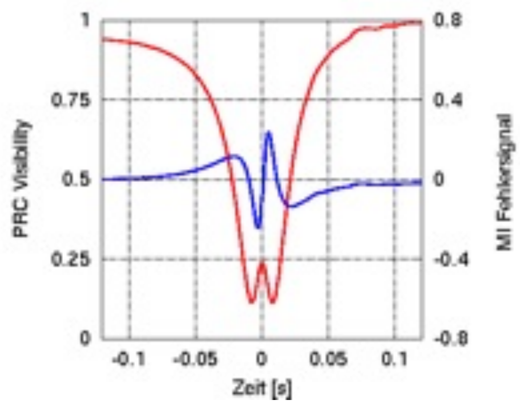
BS `tilt' motion excited





Power Recycling Control (2003)





end mirrors with wrong curvature

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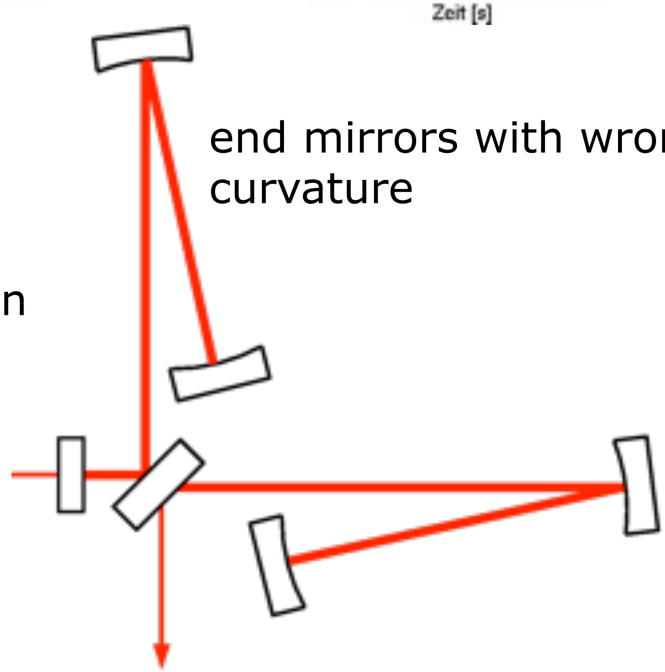
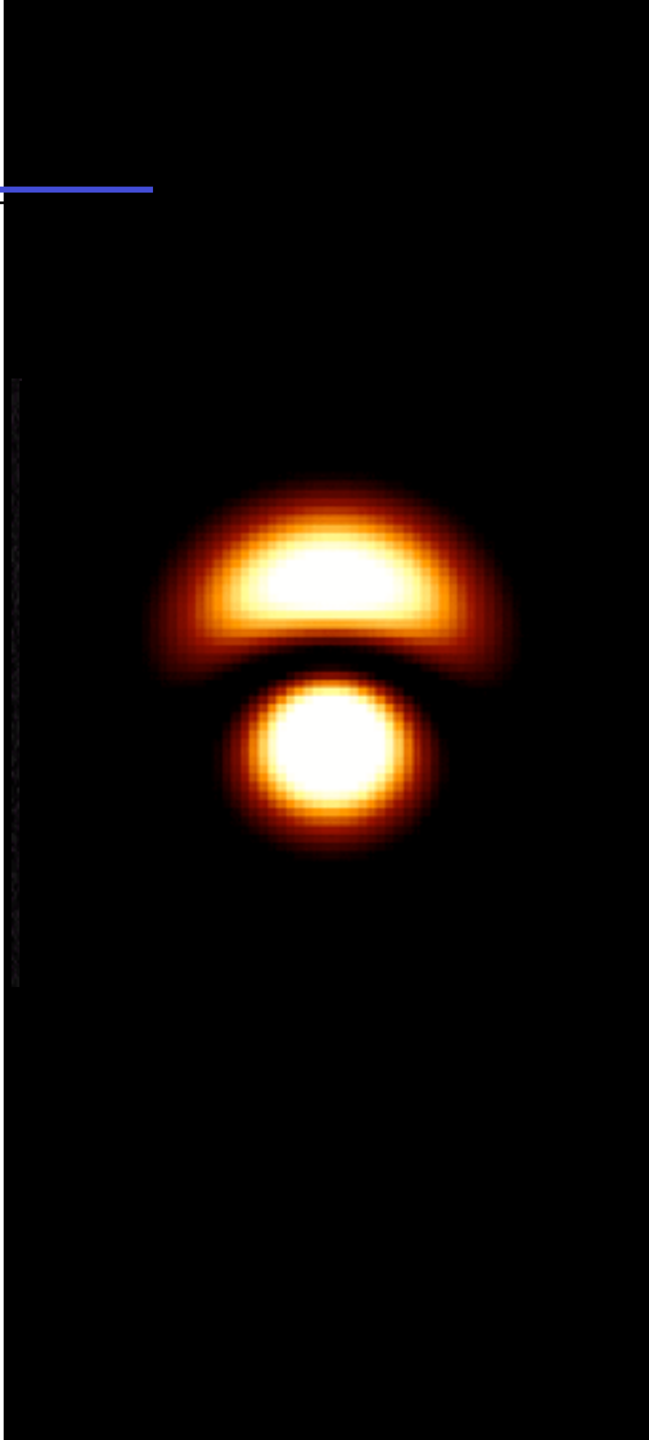
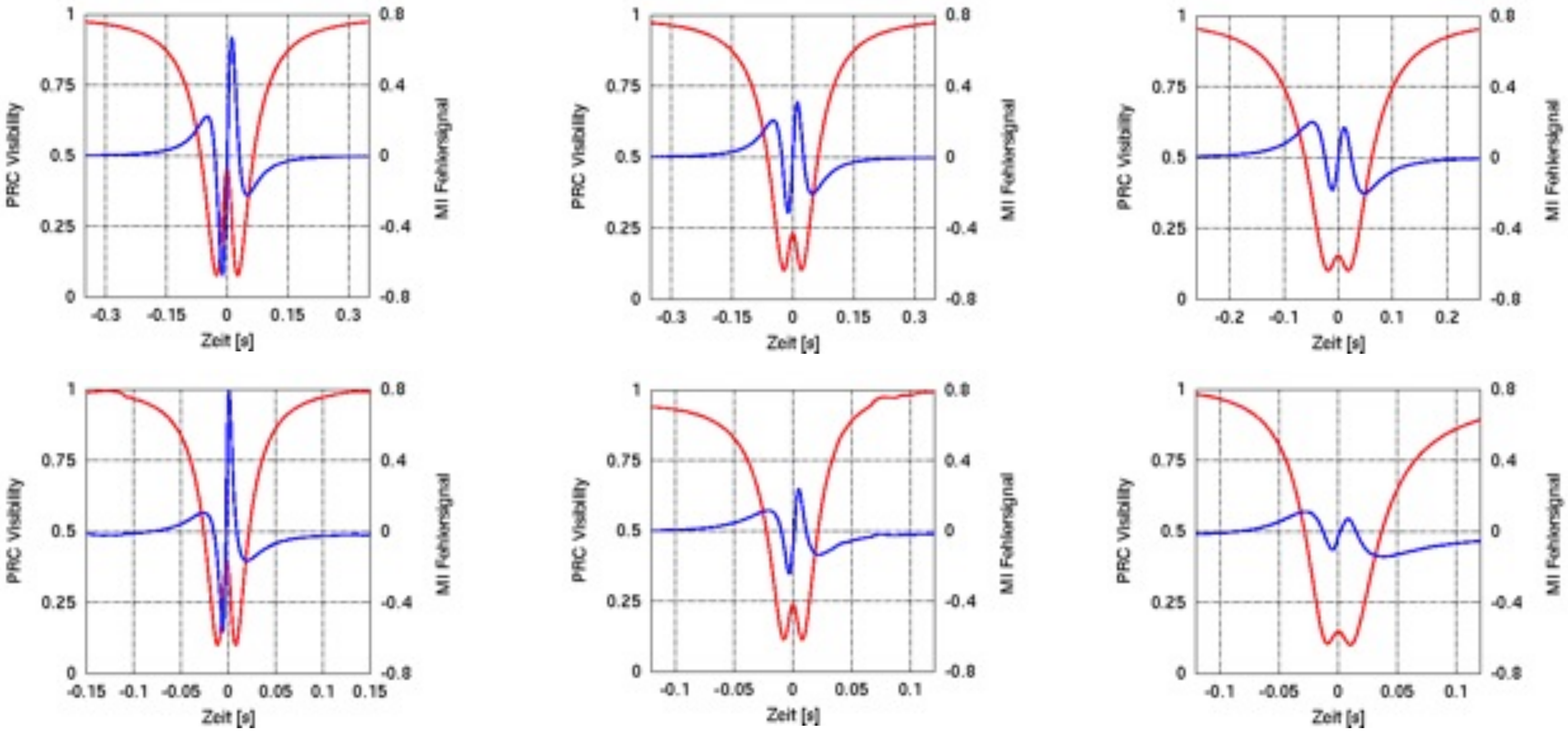
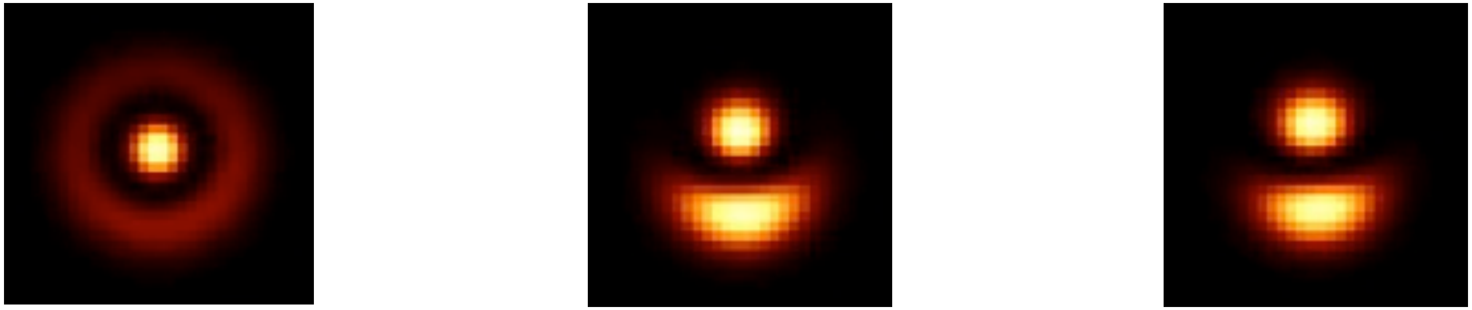




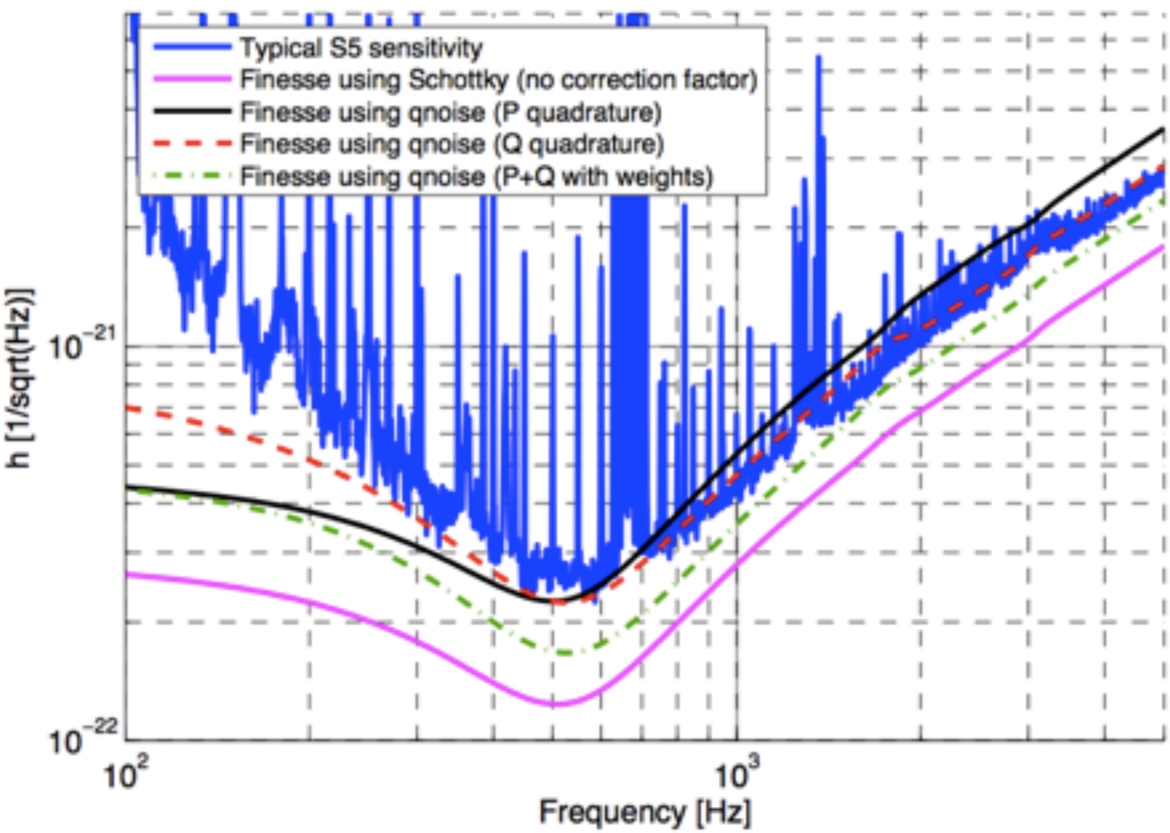
Power Recycling Control (2003)

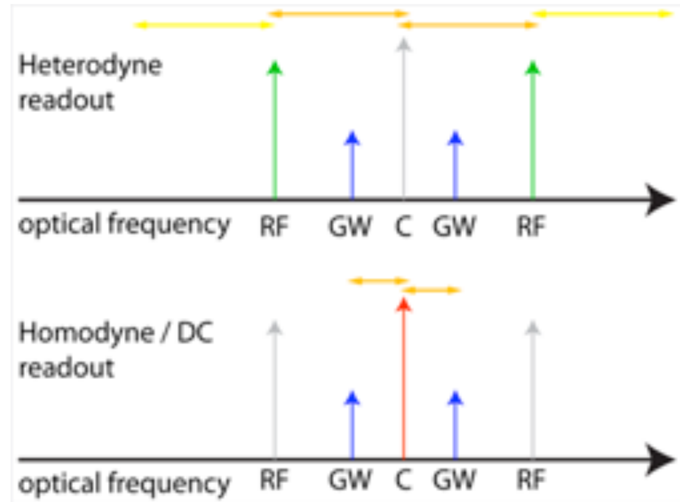


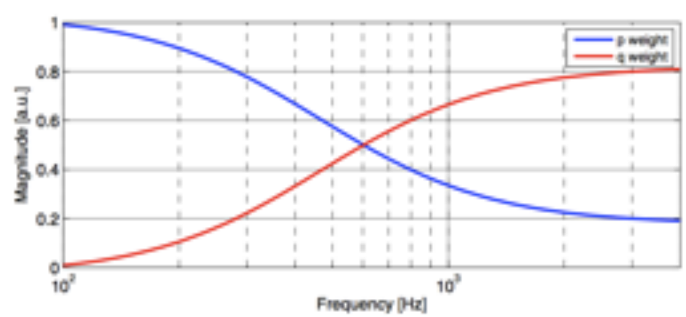


Shotnoise projection (2007)

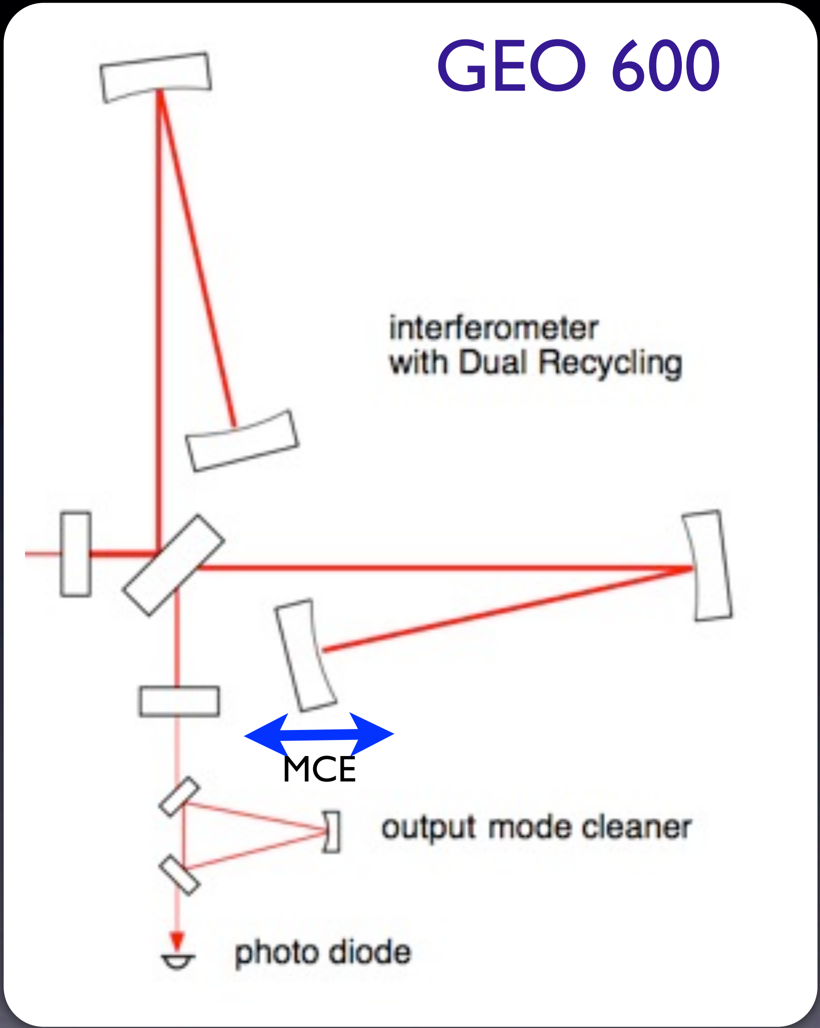
Heterodyne detection and Signal Recycling make for a more complex shot-noise projection

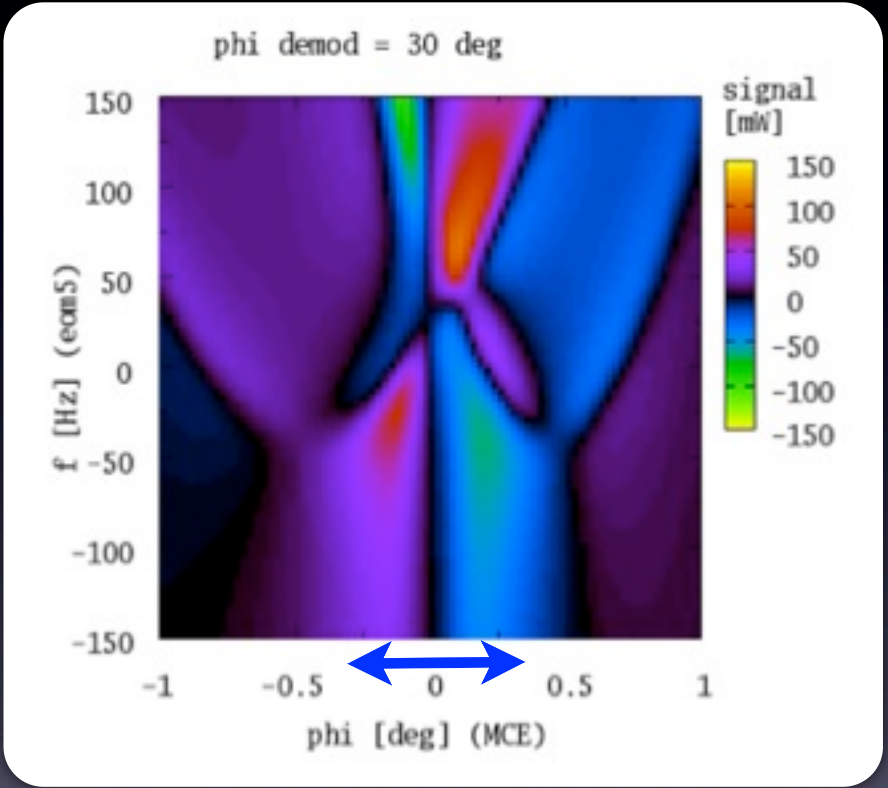






Sensing and Control





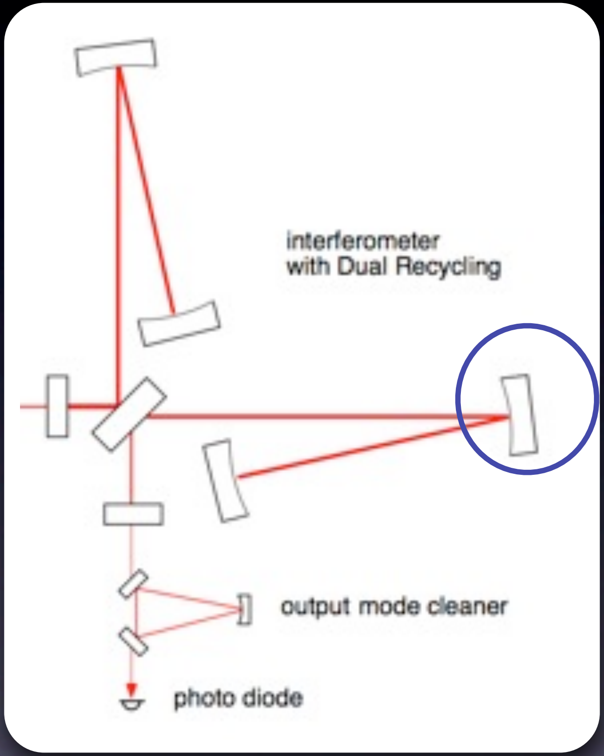
GEO HF upgrade

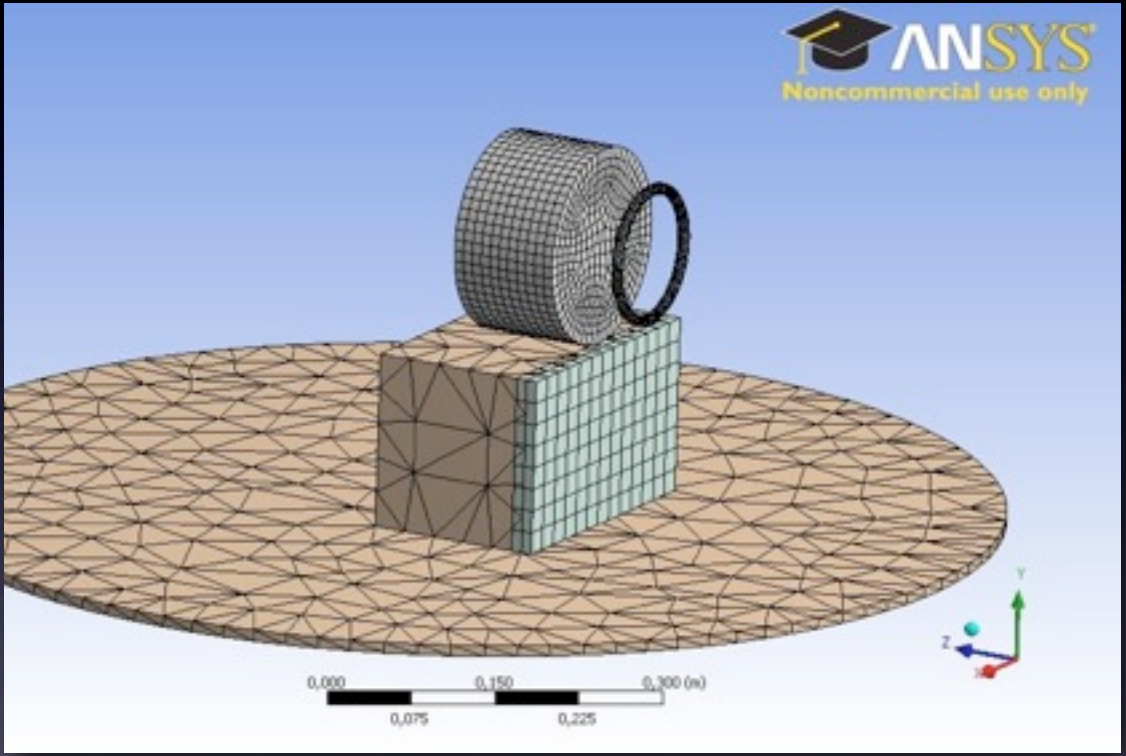
- 07-2009: Tuned signal-recycling
- 09-2009: DC-readout
- 12-2009: OMC installation
- 04-2010: Squeezing installation
- 05-2011: Output optic suspension
- 06-2011: Use 5W input power, routine squeezing
- 06-2011 to 09-2011: Joint GEO - VIRGO run
- 09-2011: Laser upgrade
- 11-2012: IMC upgrade, baffle installation, side heater
- 2013- ... : Input mode cleaner change, TCS, power increase, squeezing integration mid freq. noise hunting, baffle installation

Beam Shape Distortions

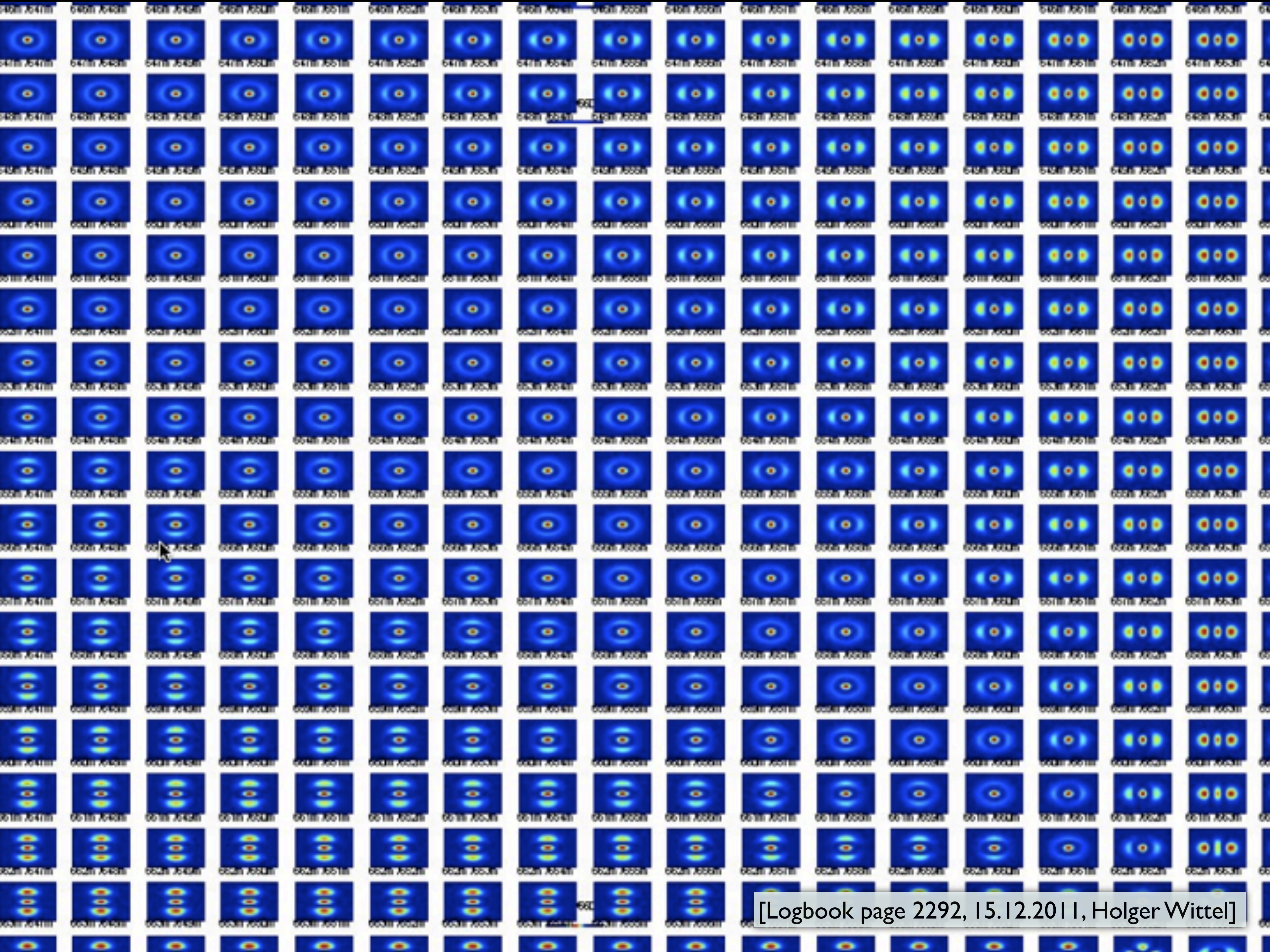
- Asymmetries in beam shape in the interferometer arms create losses (dark fringe contrast)
- Can be caused by mirror distortion of *thermal lens* in central BS
- Partially mitigated by Signal Recycling (mode healing)
- Further mitigated by thermal compensation system (ring- and side-heater)

Ring Heater





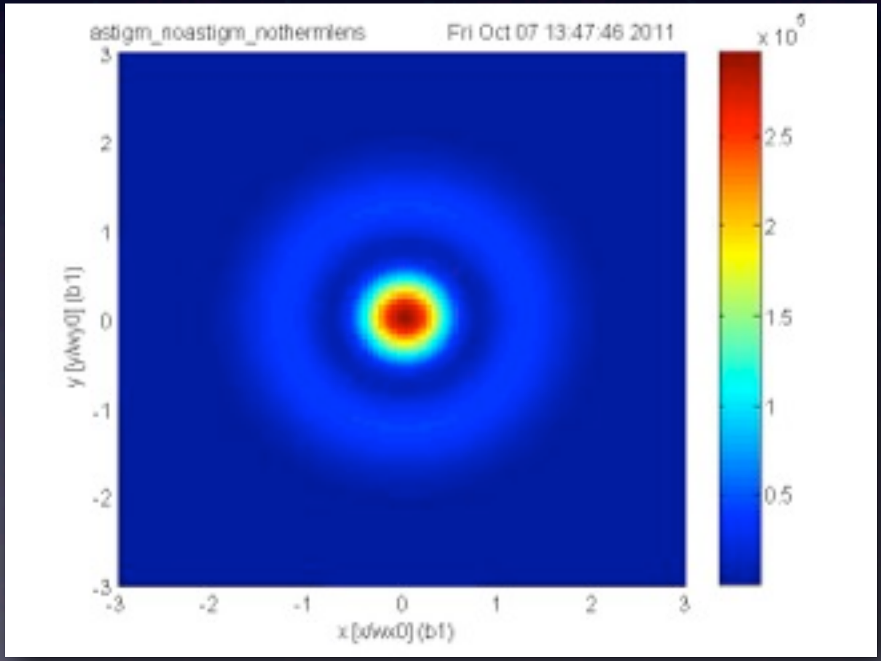
[Logbook page 453, 24.2.2010, Holger Wittel]

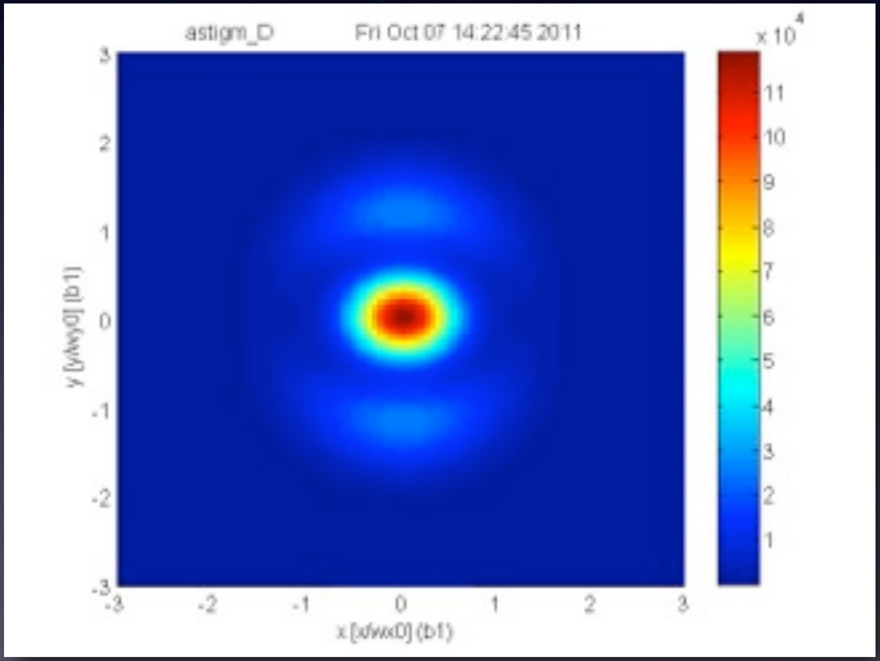


[Logbook page 2292, 15.12.2011, Holger Wittel]

Astigmatism

- The GEO interferometer suffers from two counts of astigmatism:
- thermal lens in the BS
- astigmatic curvature of for end mirror MFE (Rcx 657.4m, Rcy 655.8m at 90W ring heater power)
- Simulating the effect on the dark fringe beam shape:



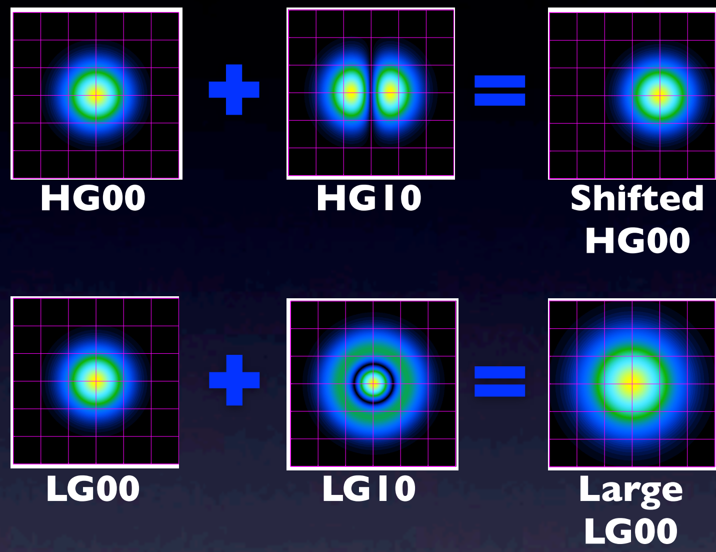


[Logbook page 2049, 07.10.2011, Holger Wittel]

Mode healing

1. Beam shift

small misalignments of the beam



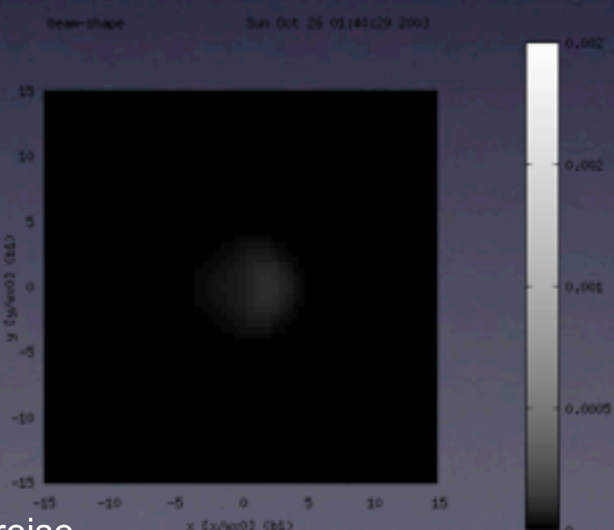
Order 1

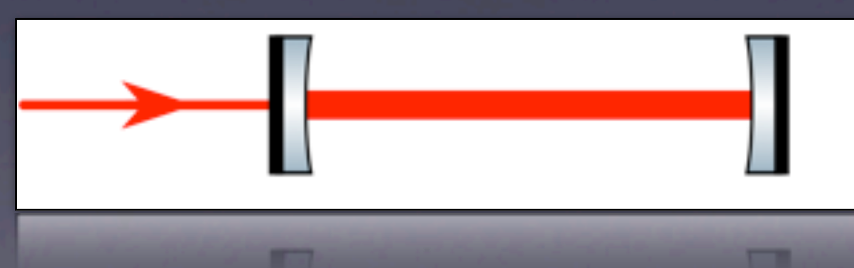
2. Beam size

small size/curvature mismatch between beam and cavity

Order 2

Simple, small effects can be described well with just one HOM.

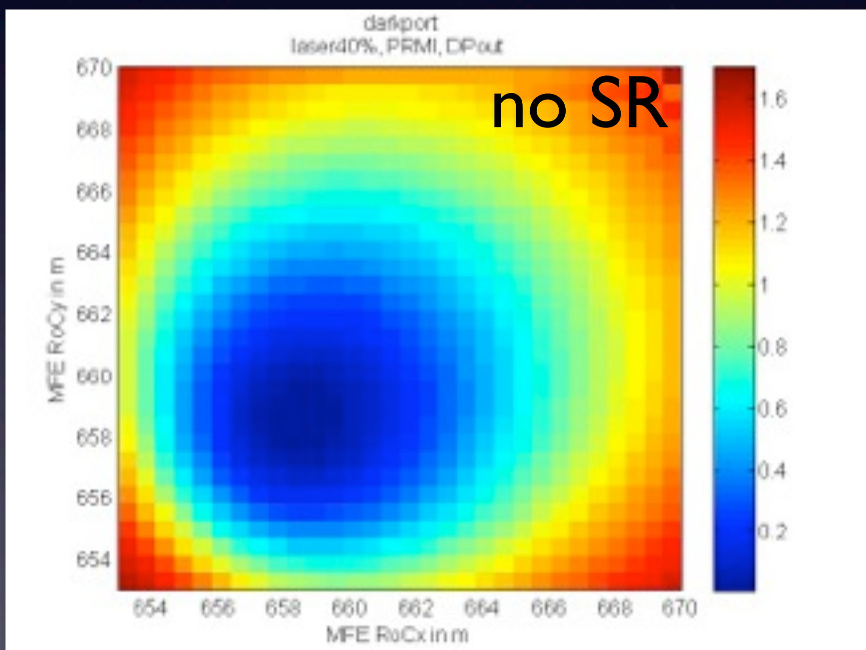


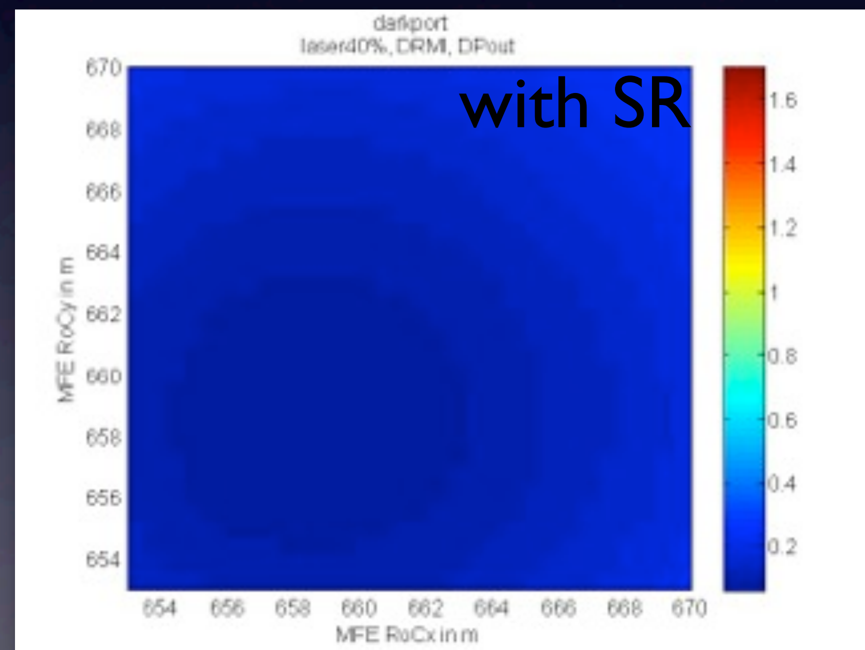


Mode healing

FINESSE simulation of the optical losses through the dark fringe for different radii of curvature of th (far east) end mirror Rx, Ry.

Plots show mode healing due to Signal Recylcing!

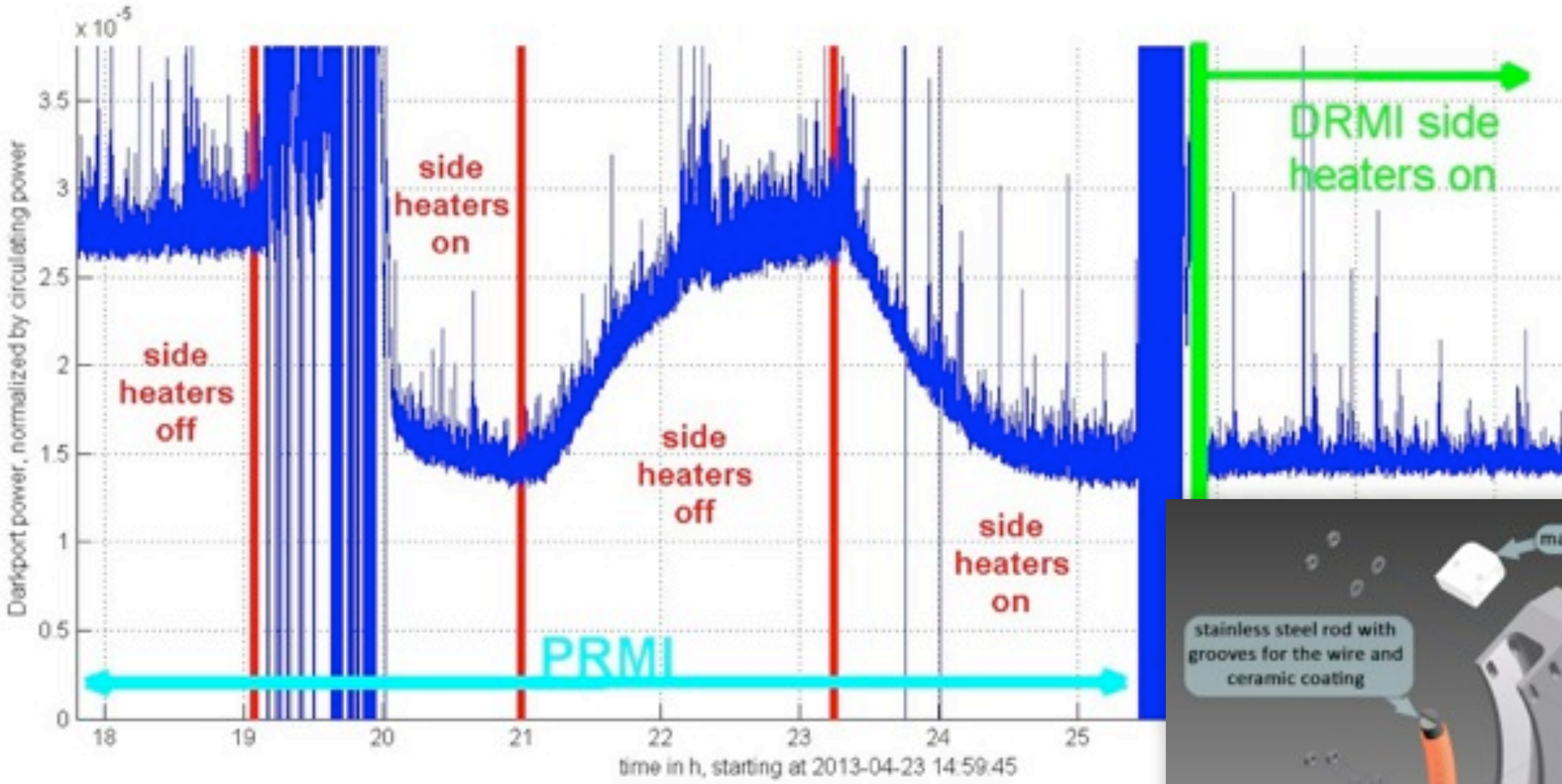


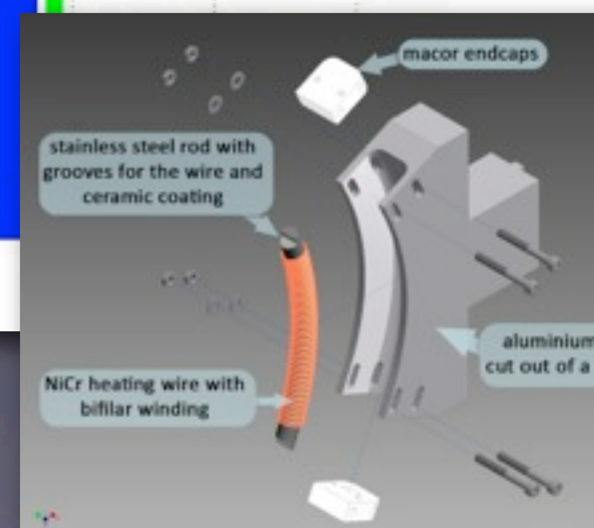


[Logbook page 3818, 1.2.2013, Holger Wittel]

Side heater

[Logbook 4158, 24.04.2013, Holger Wittel]

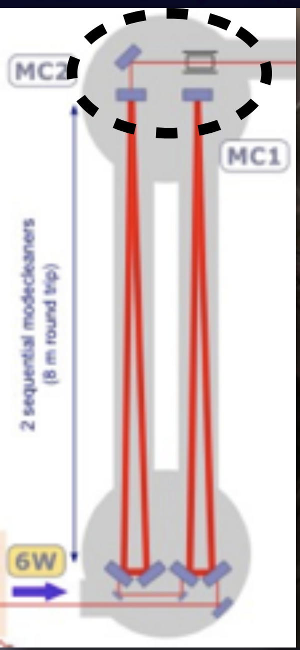


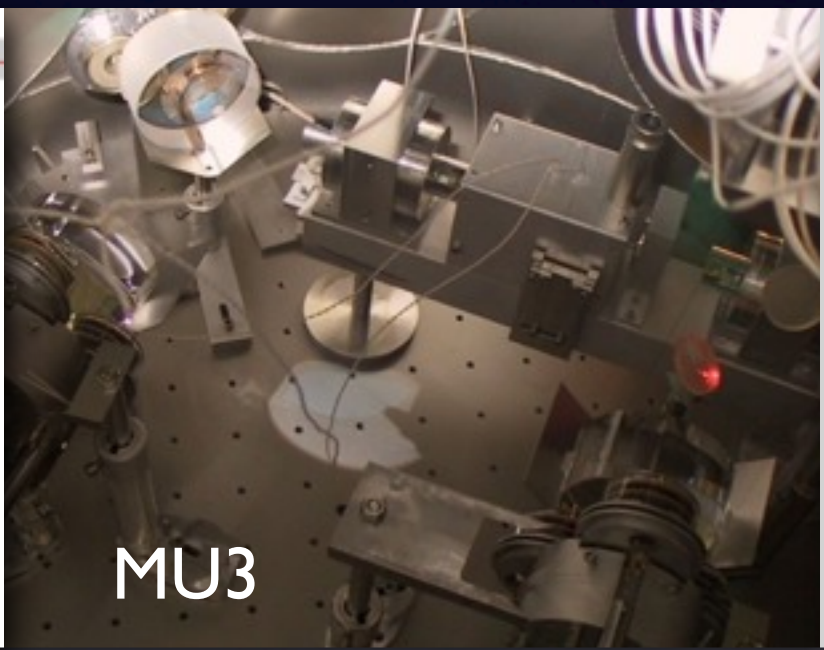


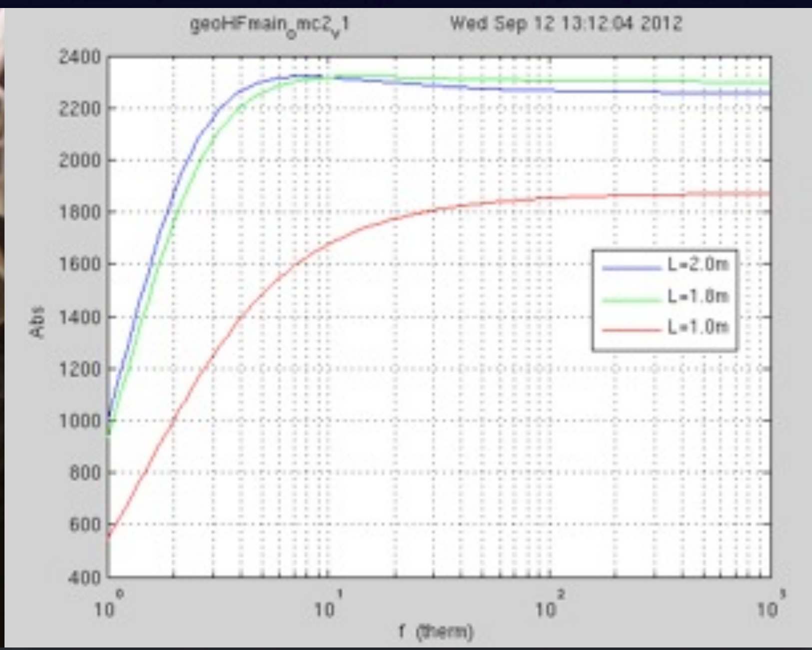
Another Thermal Lens

Mounting unit 3 (MU3) houses Faraday isolators, two modulators and a lens. The lens and any thermal lensing in the unit is critical for mode matching into the PR cavity.

Hartmut: ‘a really quick Finesse simulation of the effects of the thermal lens on MU3 on the PR cavity power. This is just to confirm the order of magnitude of expected effect.’



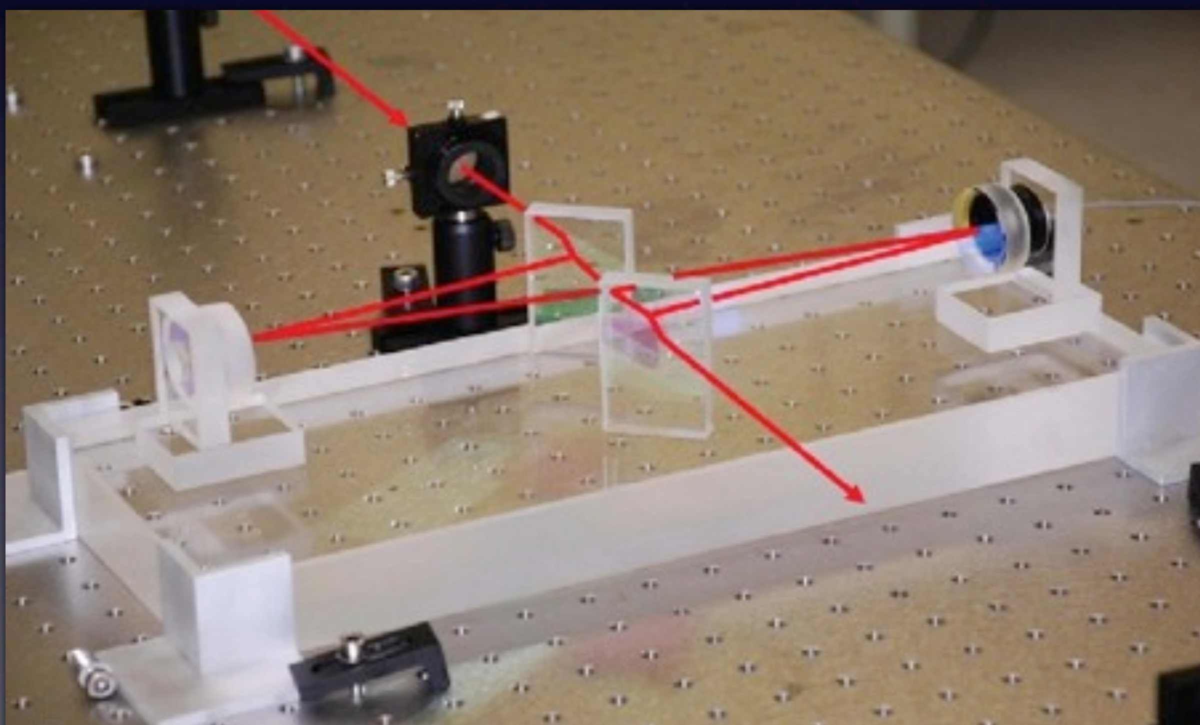


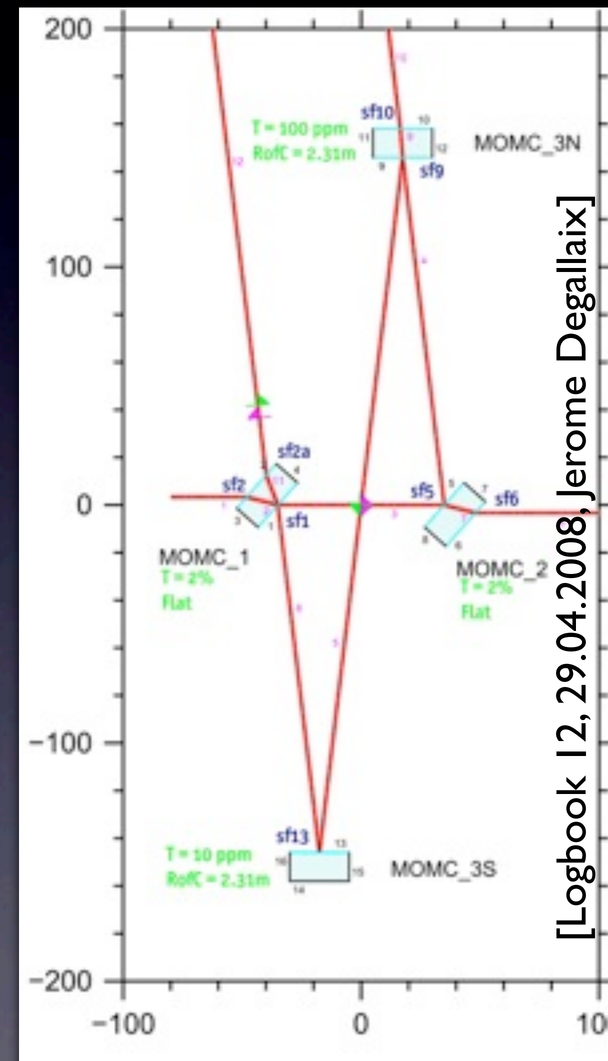


[Logbook 687, 03.06.2010 Stefan Hild, Ken Strain] [Logbook 3318, 29.08.2012, Hartmut Grote]

Output Mode Cleaner (OMC)

- Design parameters generated with OptoCad and available in auto-generated FINESSE file.





[Logbook 12, 29.04.2008, Jerome Degallaix]

Consistent Data Container

FINESSE simulation input files represents a consistent collection of the best measured and estimated parameters:

- file with all parameters produces correct results for standard signals (DC light power, noise coupling)
- all parameters are given and stored in the same format

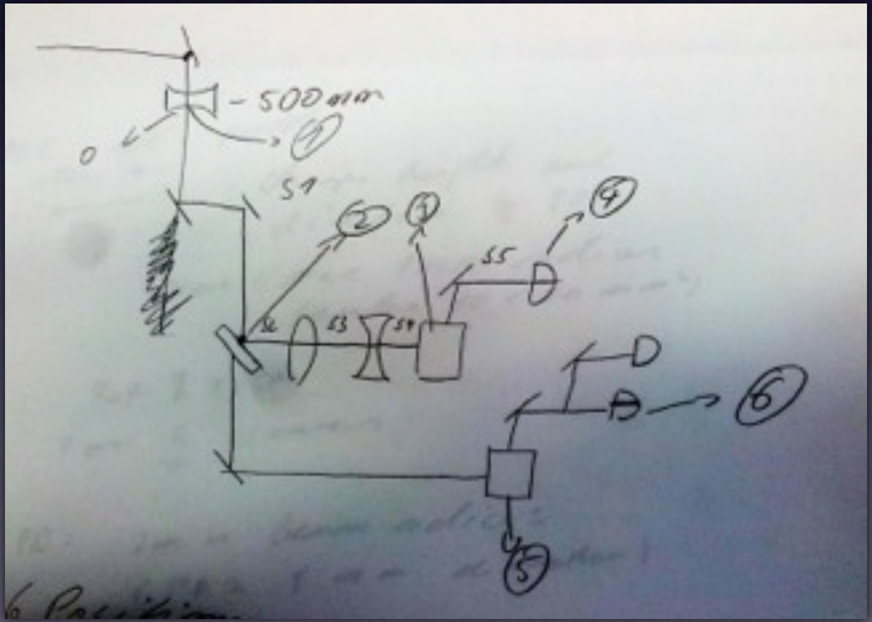
```
# This file should NOT be used as is. It serves as a data
# container. For every simulation task only a subsystem
# should be copied out of this file. Please take care that
# you check the "operating" point of the subsystem properly
# before doing any complex analysis!
```

Telescopes for wavefront sensors

- Telescope in reflection of OMC
- first design ideas, using optical parameter from FINESSE file as reference

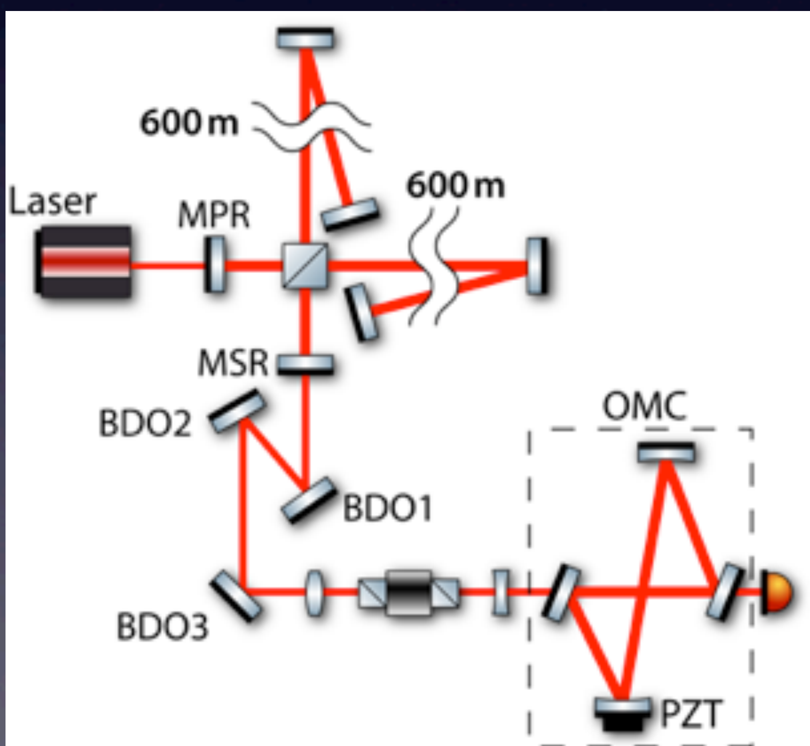
[Logbook 3698, 09.01.2013, Mirko Prijatelj]

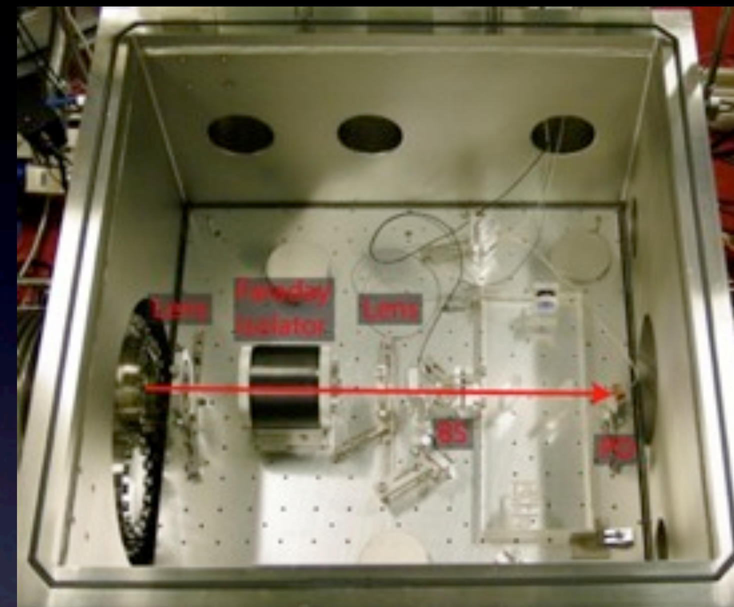
- 105: node nLens1(166); todefoc(105), defoc(116);
  n=1 (todefoc --> nLens1)
  x: w0=424.07649um w=573.68632um
  z=483.77806mm z_R=531.00258mm
  q=(0.483778 + 0.531003i) gamma=798.63357urad
  y: w0=465.94371um w=674.72883um
  z=671.38552mm z_R=641.02527mm
  q=(0.671386 + 0.641025i) gamma=726.87261ura

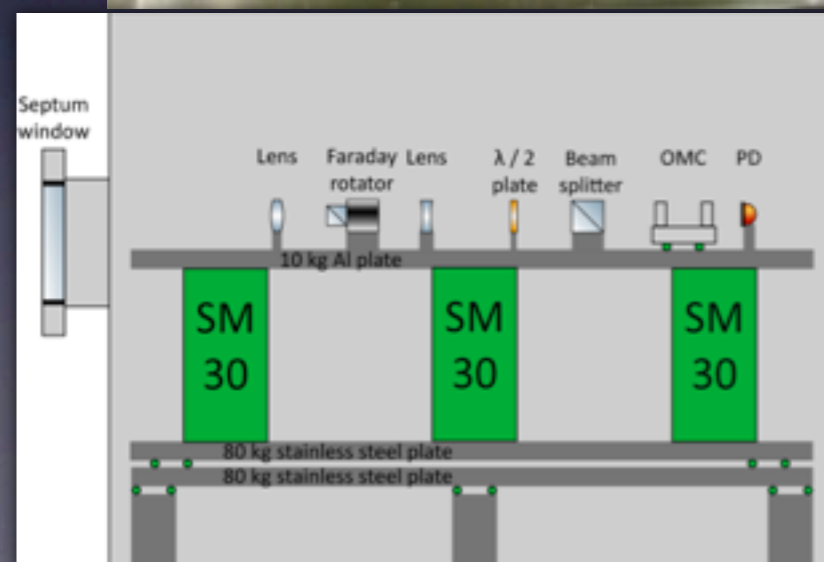


Output Mode Cleaner (OMC)

- OMC housed in vacuum tank
- Multi-stage seismic isolation starting at 1 Hz

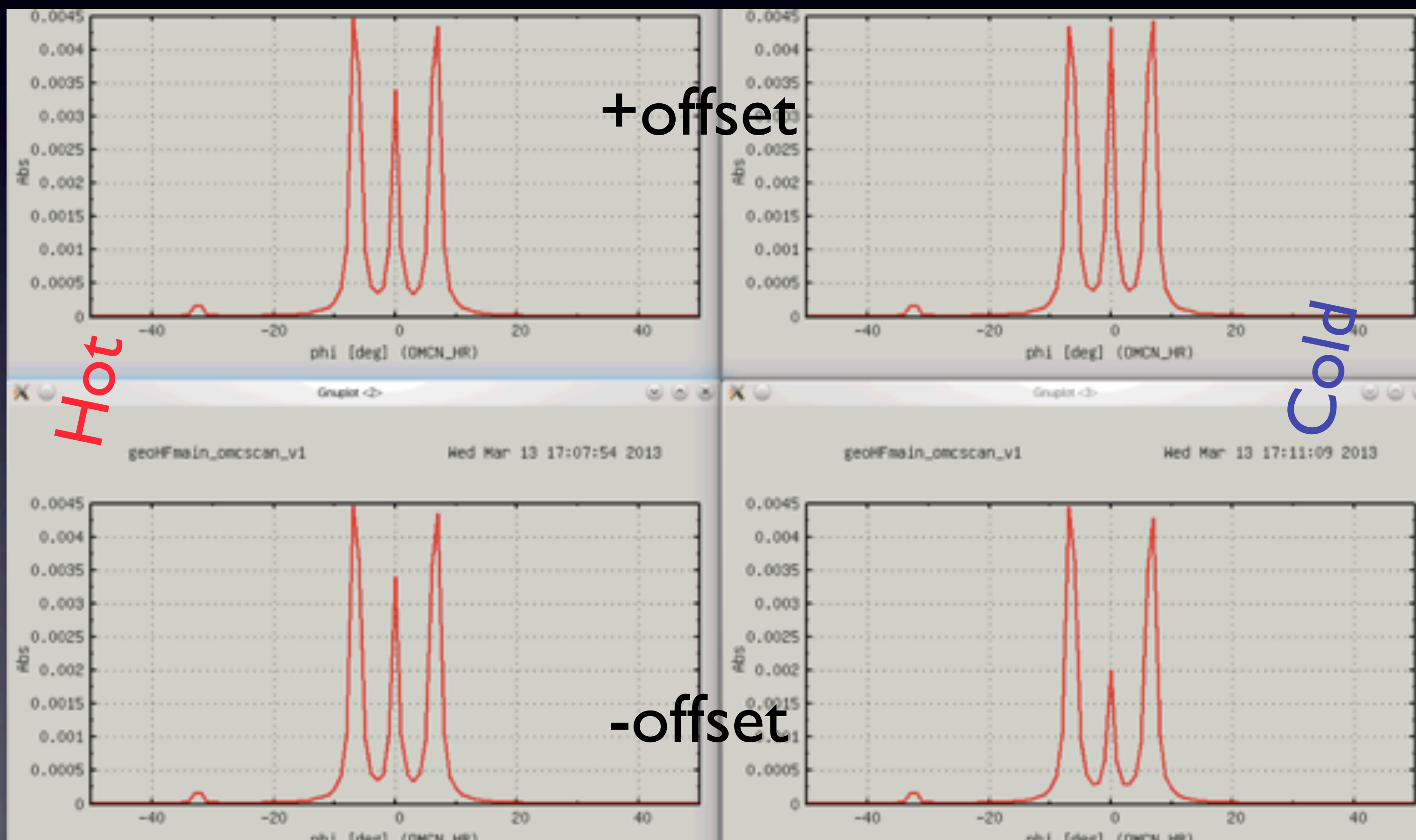






OMC, hot and cold

- Hartmut: `We confirmed today that the carrier peak on the other side of the dark fringe offsetis _larger_ than usual in the cold locking state.'
- Recreate effect with FINESSE (below), then study model to understand the effect



[Logbook 3988, 13.03.2013, Hartmut Grote]

Simulation Tools

- `Quick and Dirty' simulations require carefully curated simulation tools
- Something that `just works' for you needs more work and care


Finesse

FINESSE
Frequency domain INterfErometer Simulation SotfwarE

- Started in 1997 as a PhD side project
- Used extensively worldwide

  [http://www.gwoptics.org/finesse/impact.php]
- Open sourced in 2012

  [http://kvasir.sr.bham.ac.uk/redmine/projects/finesse]
- Ten Simple Rules for the Open Development of Scientific Software

  [http://www.ploscompbiol.org/article/info%3Adoi%2F10.1371%2Fjournal.pcbi.1002802]

Rule 1: Don't Reinvent the Wheel

Rule 2: Code Well

Rule 3: Be Your Own User

Rule 4: Be Transparent

Rule 5: Be Simple

Rule 6: Don't Be a Perfectionist

Rule 7: Nurture and Grow Your Community

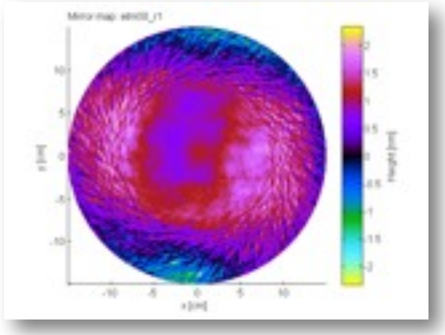
Rule 8: Promote Your Project

Rule 9: Find Sponsors

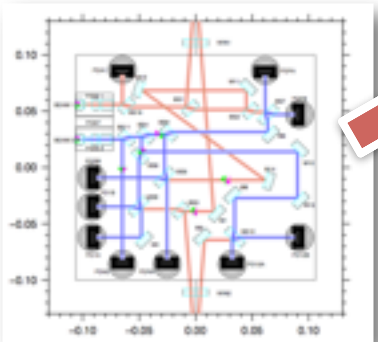
Rule 10: Science Counts

The FINESSE Ecosystem

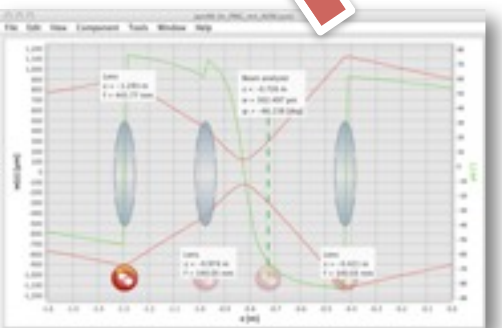
Luxor
www.gwoptics.org/finesse/luxor.php



SimTools
www.gwoptics.org/simtools/



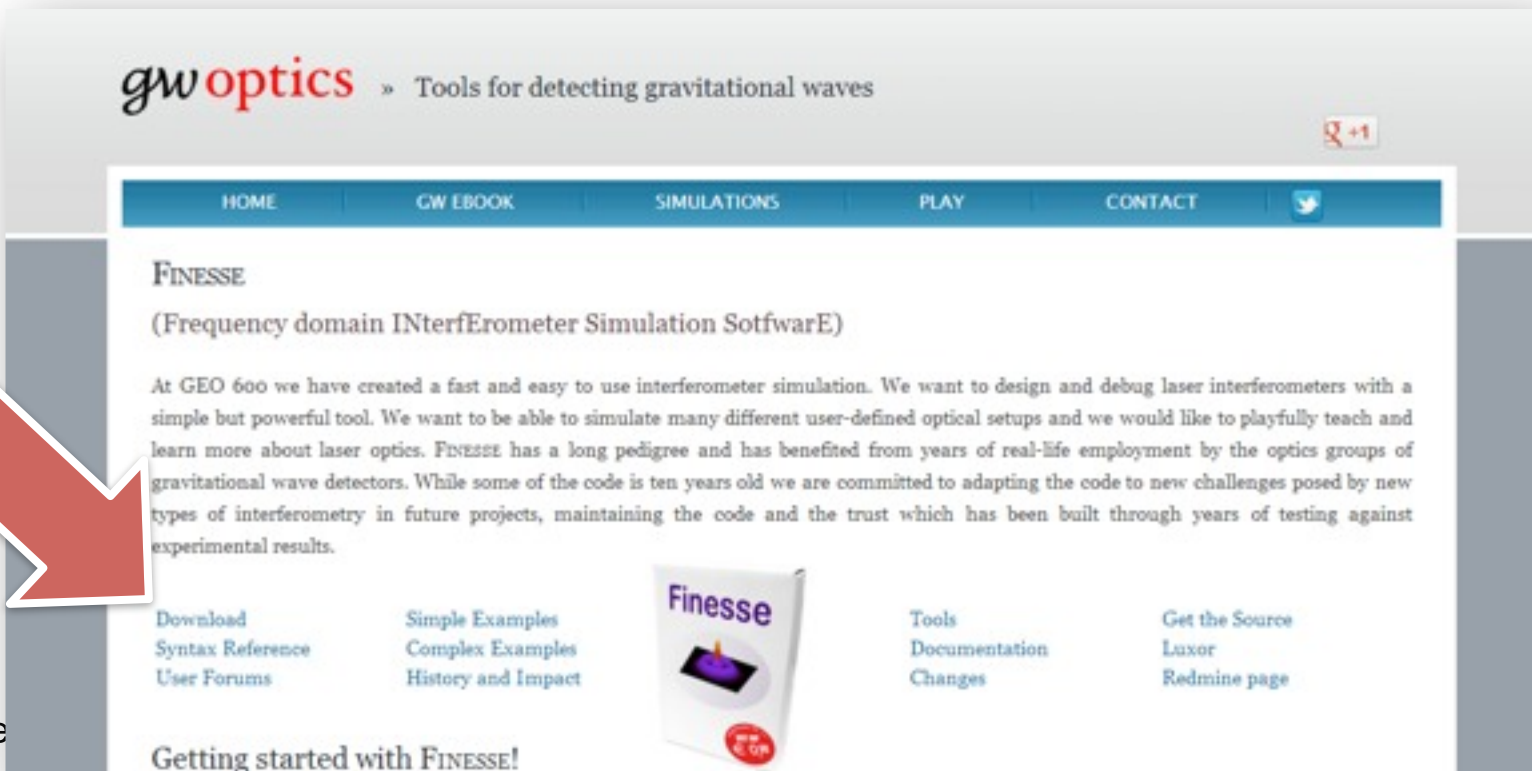
OptoCad
home.rzg.mpg.de/~ros/



JamMT
http://www.sr.bham.ac.uk/dokuwiki/doku.php?id=geosim:jammt

FINESSE: How do I get it?

- Go to www.gwoptics.org/finesse
- Versions available for Windows, Linux and Mac OSX



Summary

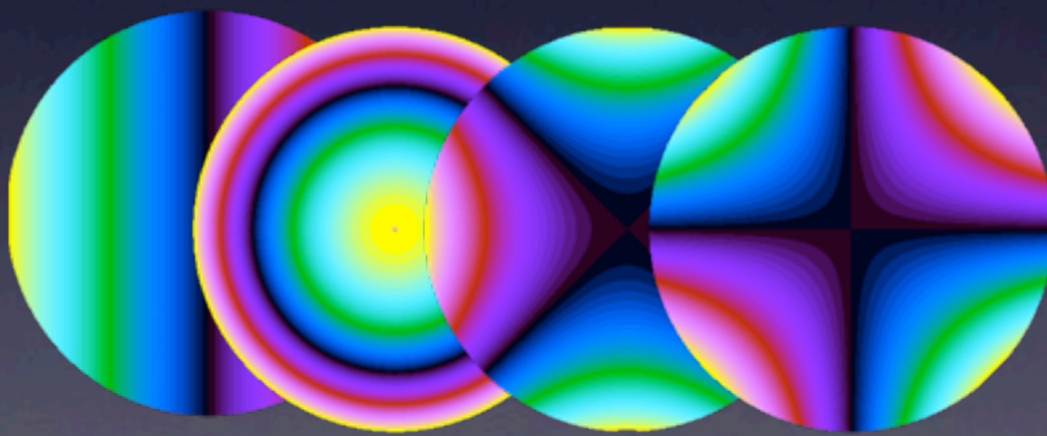
- Quick and Dirty simulations for commissioning, very successful concept at GEO 600
- Hot topic for advanced detectors: SR, beam shape distortions, complex noise projections, >10 years of experience encoded in simulation tools and models

Understand your detector

Design new solutions

Coherent storage of knowledge

...end



Finesse Manual

- 185 pages, mixes background optics, numerical algorithms, simulation examples

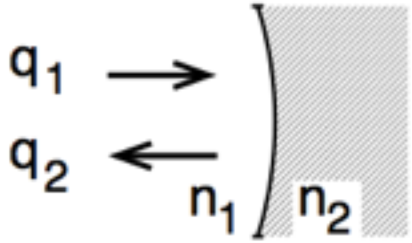
```
// setting reflection matrix
if (NOT node1.gnd_node) {
    n1 = *(node1.n);
    if (mirror->Rcx == 0) {
        mirror->qqr1t = Unity;
    } else {
        mirror->qqr1t = make_ABCD(1.0, 0.0, -2.0 * n1 / mirror->Rcx, 1.0);
    }

    if (mirror->Rcy == 0) {
        mirror->qqr1s = Unity;
    } else {
        mirror->qqr1s = make_
    }
}
```

Code

Reflection at a mirror: The matrix for reflection is given by:

$$M = \begin{pmatrix} 1 & 0 \\ -\frac{2n_1}{R_C} & 1 \end{pmatrix}$$

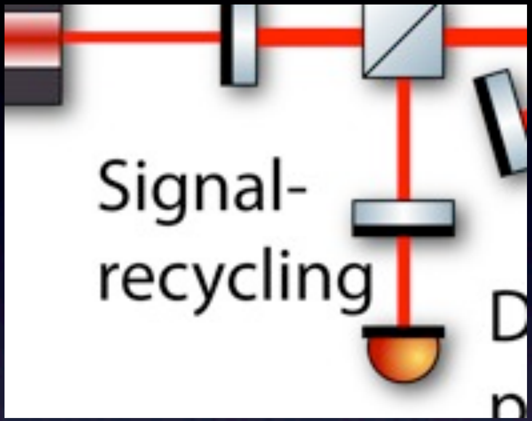


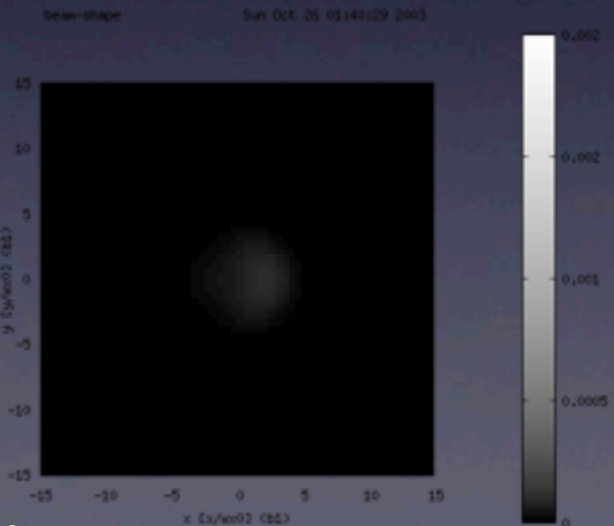
Manual

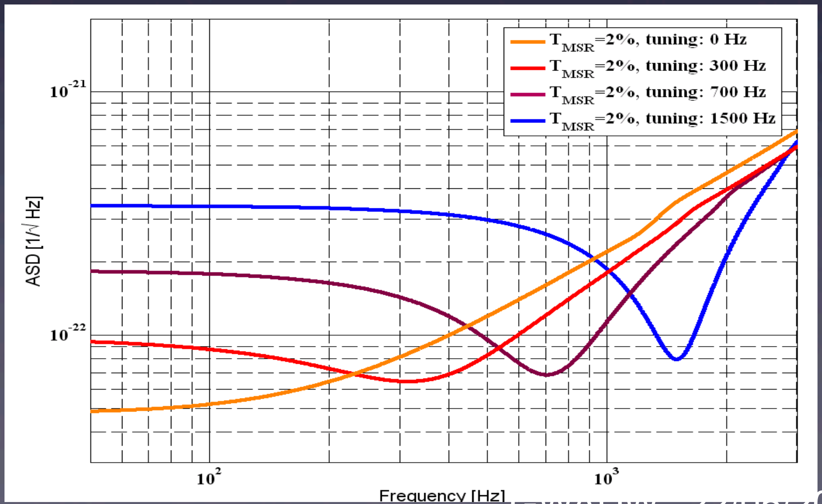
Signal Recycling

Signal Recycling:

- makes GEO resonant to GWs
- Allows shaping of the shot noise
- Influences higher-order modes in the dark fringe

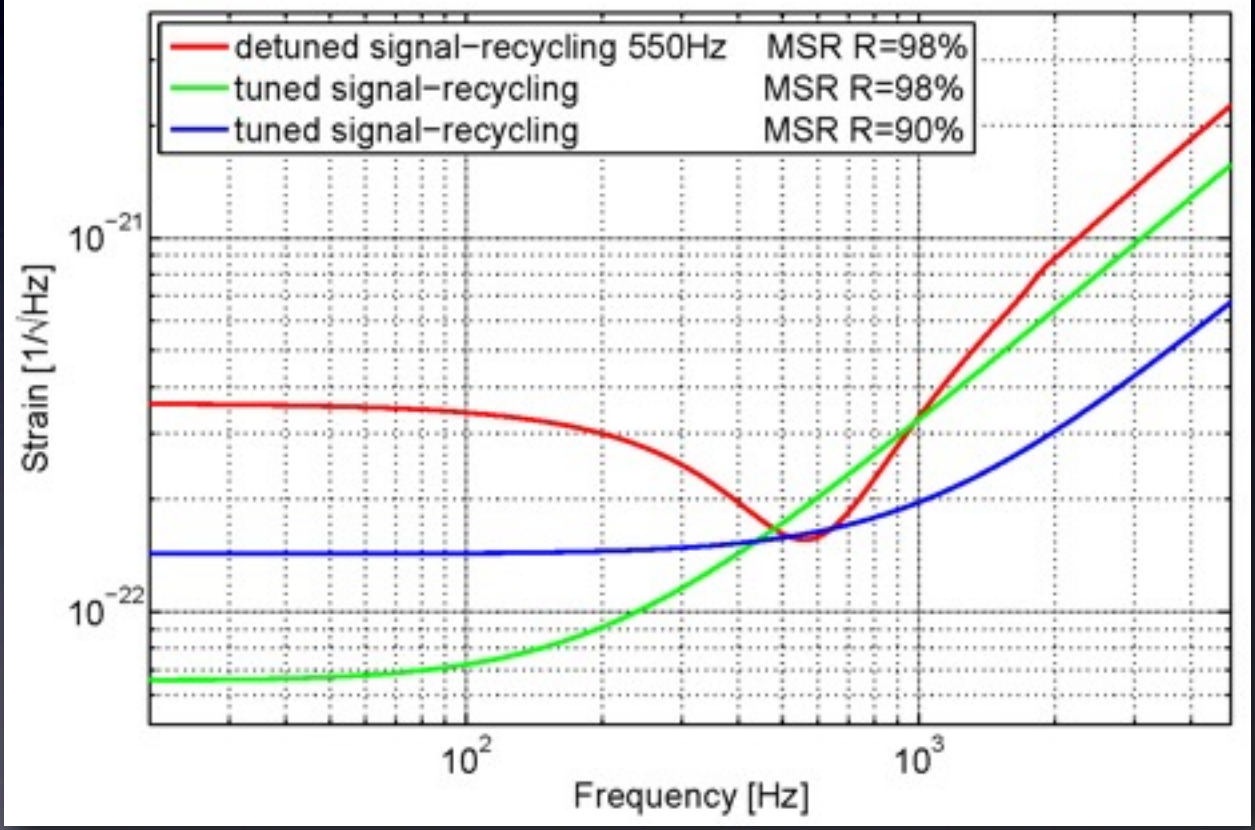






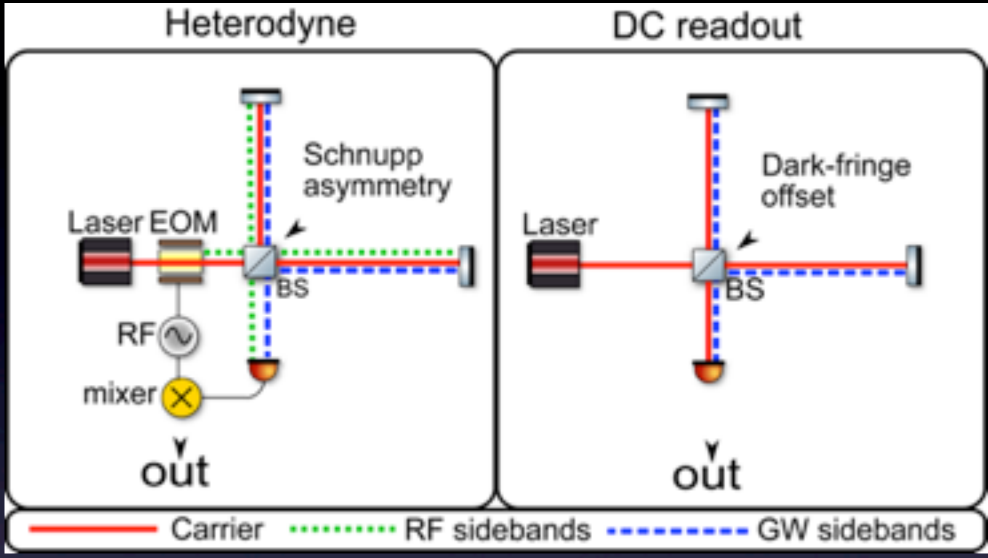
Signal Recycling Change (2010)

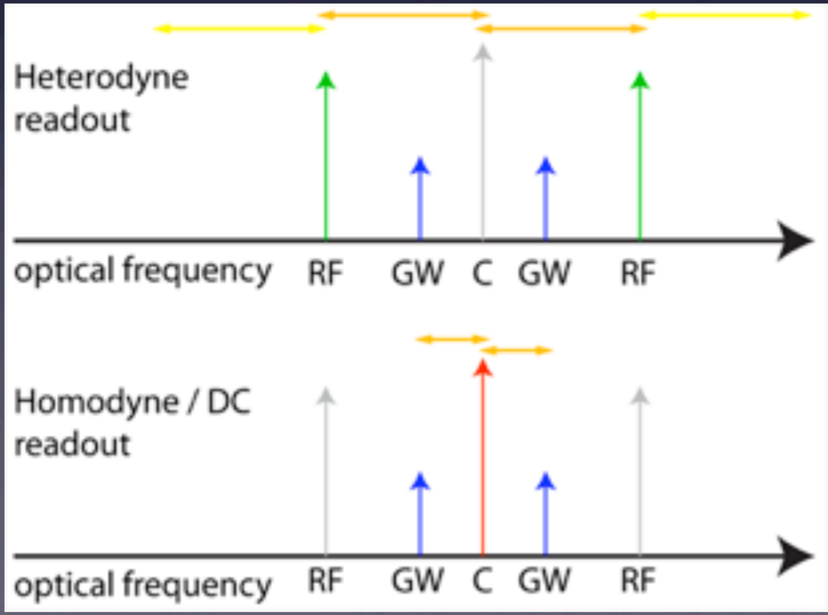
Increase transmission of Signal Recycling mirror to reduce shot noise at high frequencies



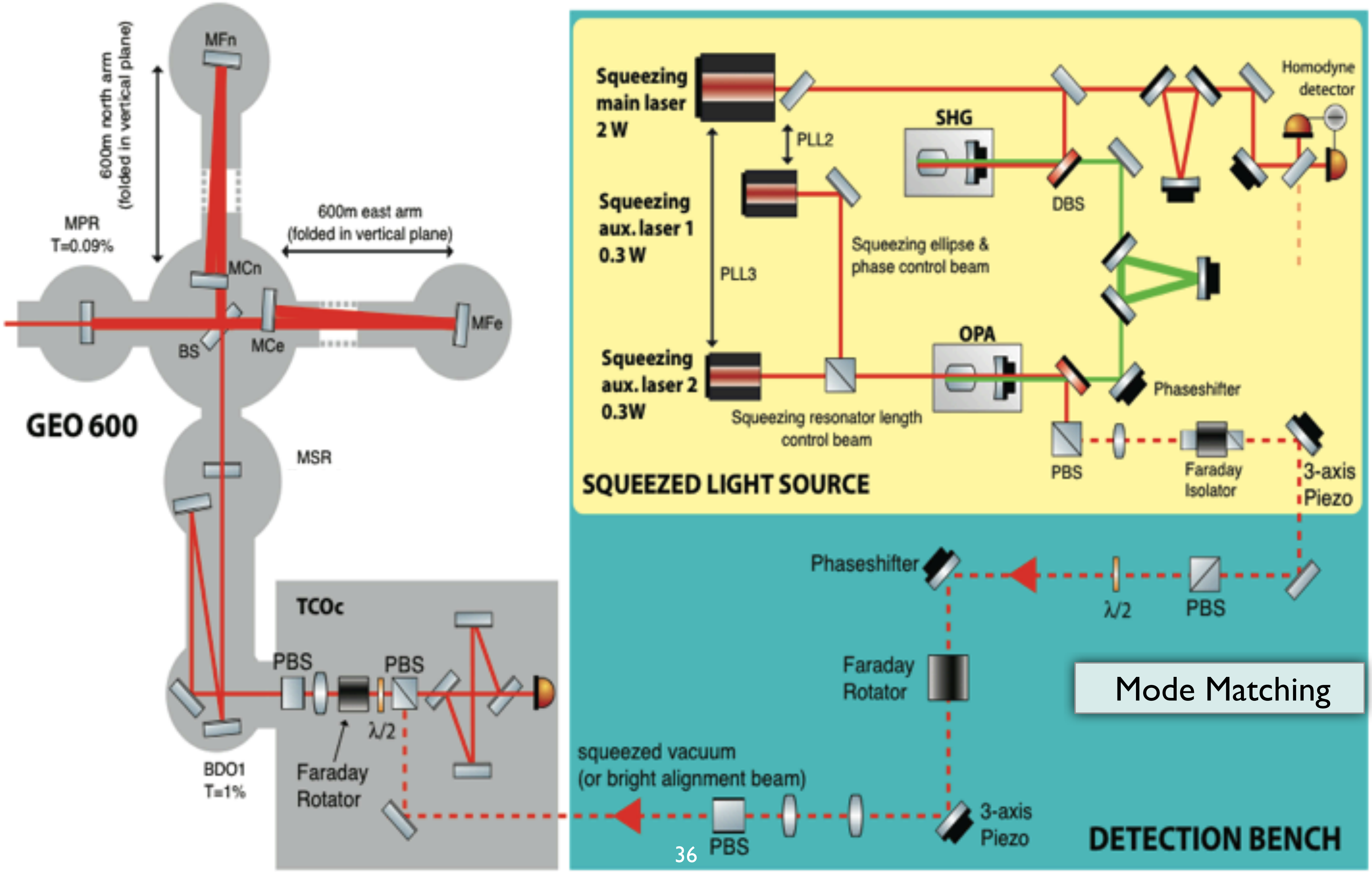
Heterodyne vs DC readout

- Heterodyne readout
  - GW information in beat of GW-SBs ↔ RF-SBs
  - (Almost) no carrier at IFO output
- DC readout
  - GW information in beat of GW-SBs ↔ carrier
  - Some carrier light at the output required
  - GW signal directly in detected power

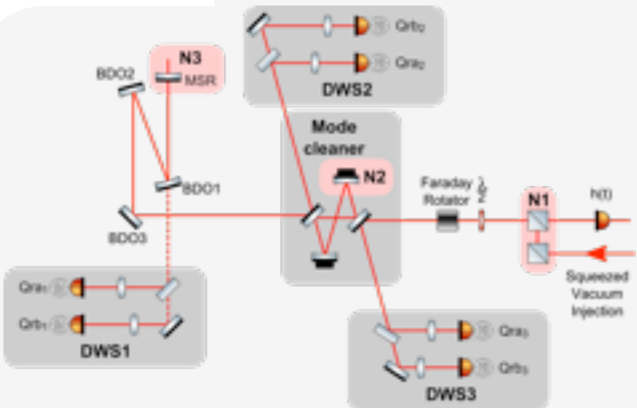




GEO 600 and Squeezed Light



GEO Squeezer Alignment



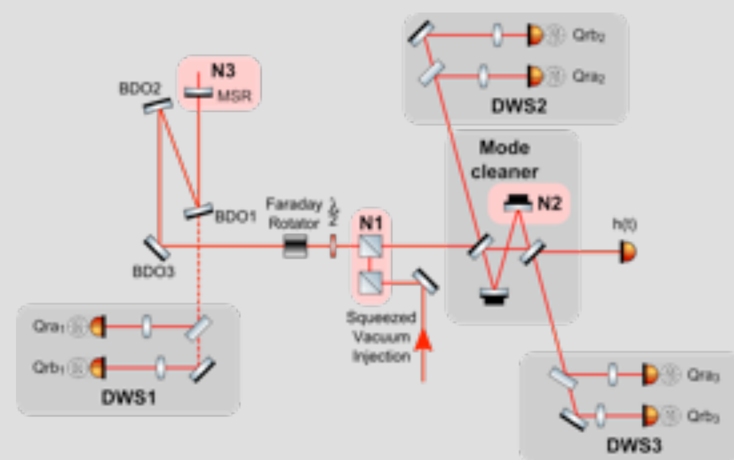
$$
C_{\mathrm{config-1}} = \begin{array}{c} \\ \mathrm{N1\text{-}BS1} \\ \mathrm{N1\text{-}BS2} \\ \mathrm{N2} \\ \mathrm{N3} \\ \mathrm{BDO2} \end{array}
\begin{array}{cccccc} \mathrm{Qr1a} & \mathrm{Qr1b} & \mathrm{Qr2a} & \mathrm{Qr2b} & \mathrm{Qr3a} & \mathrm{Qr3b} \end{array}
\left(\begin{array}{cccccc}
+4.498e^{-3} & +4.539e^{-3} & -4.508e^{-1} & -4.263e^{-1} & 0 & 0 \\
-3.169e^{-3} & -2.074e^{-3} & +3.161e^{-1} & +1.899e^{-1} & 0 & 0 \\
-5.448e^{-4} & -1.119e^{-3} & +5.441e^{-2} & +1.090e^{-1} & 0 & 0 \\
-3.100e^{-2} & +1.068e^{-2} & +3.013e^{+0} & -1.249e^{+0} & 0 & 0 \\
-6.767e^{-3} & +3.175e^{-3} & -1.323e^{-1} & +5.950e^{-1} & 0 & 0
\end{array}\right)
$$

$$
\mathrm{S.N.}_{\mathrm{crossing-c1-1f}} = \begin{array}{c} \\ \mathrm{N1\text{-}BS1} \\ \mathrm{N1\text{-}BS2} \\ \mathrm{N2} \\ \mathrm{N3} \\ \mathrm{BDO2} \end{array}
\begin{array}{cccccc} \mathrm{Qr1a} & \mathrm{Qr1b} & \mathrm{Qr2a} & \mathrm{Qr2b} & \mathrm{Qr3a} & \mathrm{Qr3b} \end{array}
\left(\begin{array}{cccccc}
+1.0e^{-8} & +1.0e^{-8} & -9.9e^{-10} & +1.0e^{-9} & X & X \\
-1.5e^{-8} & -2.2e^{-8} & -1.4e^{-9} & +2.3e^{-9} & X & X \\
-8.5e^{-8} & -4.1e^{-8} & +8.8e^{-9} & +4.1e^{-9} & X & X \\
-1.5e^{-9} & +4.5e^{-9} & +1.5e^{-10} & -3.7e^{-10} & X & X \\
-6.9e^{-9} & +1.4e^{-8} & -3.5e^{-9} & +7.7e^{-10} & X & X
\end{array}\right)
$$

[S. Chelkowski, J. DiGuglielmo 2009]

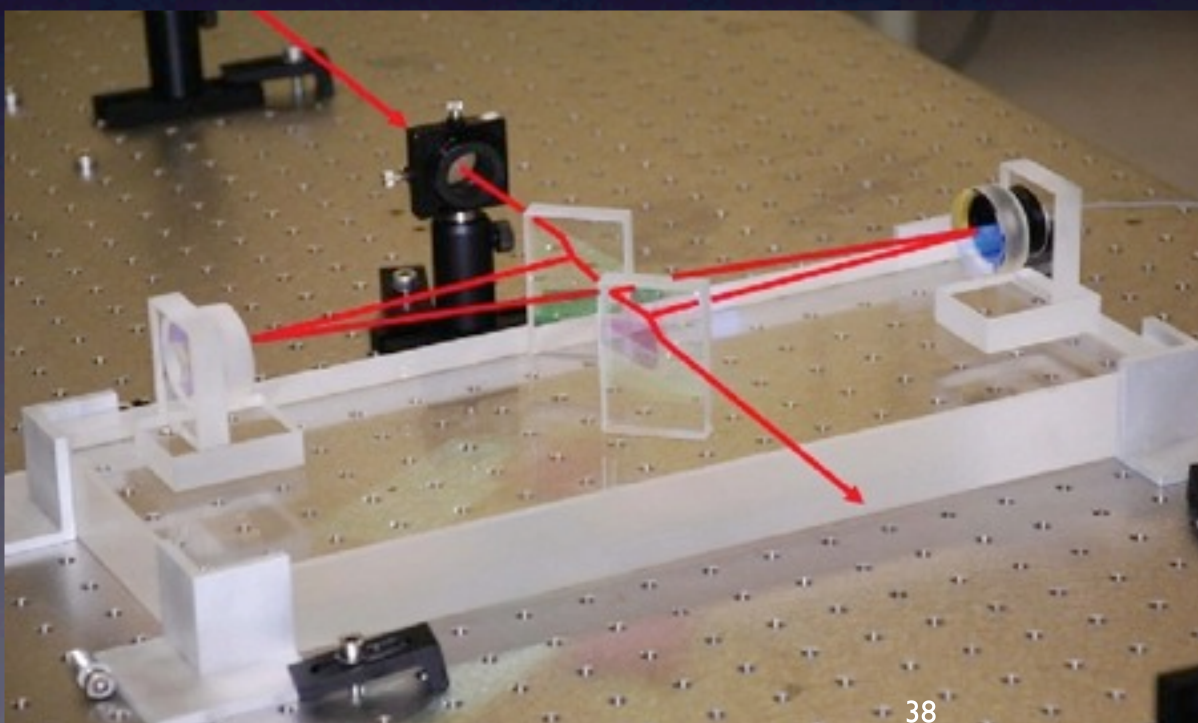
$$
C_{\mathrm{config-2}} = \begin{array}{c} \\ \mathrm{N1\text{-}BS1} \\ \mathrm{N1\text{-}BS2} \\ \mathrm{N2} \\ \mathrm{N3} \\ \mathrm{BDO2} \end{array}
\begin{array}{cccccc} \mathrm{Qr1a} & \mathrm{Qr1b} & \mathrm{Qr2a} & \mathrm{Qr2b} & \mathrm{Qr3a} & \mathrm{Qr3b} \end{array}
\left(\begin{array}{cccccc}
+4.006e^{-2} & -3.874e^{-2} & -4.528e^{-1} & -4.633e^{-1} & 0 & 0 \\
+1.434e^{-1} & -8.255e^{-2} & -1.688e^{+0} & -9.009e^{-1} & 0 & 0 \\
0 & 0 & +1.636e^{+0} & -2.242e^{+0} & 0 & 0 \\
+9.488e^{-1} & -1.535e^{+0} & -1.070e^{+2} & +1.826e^{+1} & 0 & 0 \\
+4.919e^{-1} & -3.130e^{-1} & -5.018e^{+1} & -4.101e^{+1} & 0 & 0
\end{array}\right)
$$

$$
\mathrm{S.N.}_{\mathrm{crossing-c2-1f}} = \begin{array}{c} \\ \mathrm{N1\text{-}BS1} \\ \mathrm{N1\text{-}BS2} \\ \mathrm{N2} \\ \mathrm{N3} \\ \mathrm{BDO2} \end{array}
\begin{array}{cccccc} \mathrm{Qr1a} & \mathrm{Qr1b} & \mathrm{Qr2a} & \mathrm{Qr2b} & \mathrm{Qr3a} & \mathrm{Qr3b} \end{array}
\left(\begin{array}{cccccc}
+1.3e^{-9} & -1.3e^{-9} & -7.1e^{-10} & -7.1e^{-10} & X & X \\
+3.8e^{-10} & -6.1e^{-10} & -1.9e^{-10} & -3.5e^{-10} & X & X \\
X & X & -2.0e^{-10} & -1.5e^{-10} & X & X \\
+5.4e^{-11} & -3.2e^{-11} & -3.9e^{-12} & +1.9e^{-11} & X & X \\
+1.3e^{-10} & -1.5e^{-10} & -6.1e^{-12} & +7.3e^{-12} & X & X
\end{array}\right)
$$

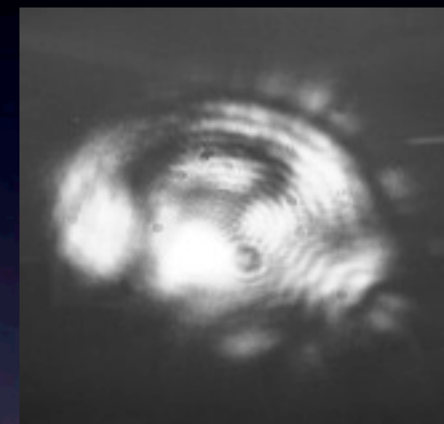


Output Mode Cleaner (OMC)

- Design: (optimised for DC readout)
  - Quasi-monolithic
  - Four mirror cavity
  - Length actuation via PZT



Before OMC (≈60 mW):



After OMC (≈6 mW):