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# H1 Squeezer Review

Review Meeting,  
August 19, 2008

ANU, AEI, MIT, CIT and LHO

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Daniel Sigg, Henning Vahlbruch and Stan Whitcomb (so far)

# Motivation

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- ❑ High power operation in future detectors
  - Biggest remaining technical risk (after DC readout)
  - Squeezing allows for lower laser power
- ❑ Squeezer technology now ready
  - 7 dB of squeezing down to 10 Hz
  - Has been demonstrated on a bench and on interferometers (40M)

**Missing: Low frequency noise demonstration**

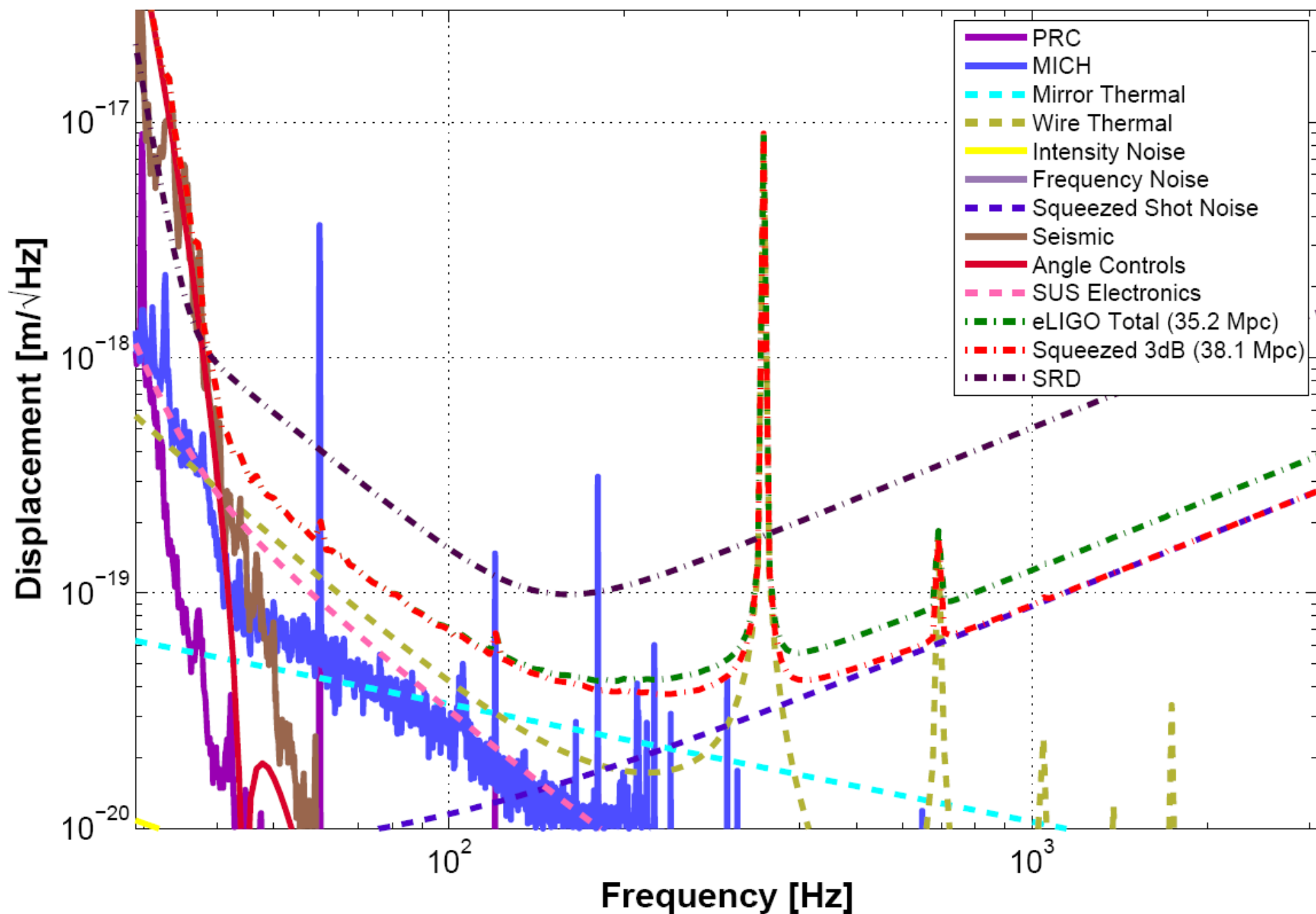
- ❑ Planned Experiments
  - GEO600: prototype for long baseline interferometers
  - Hanford H1: low noise at low frequency

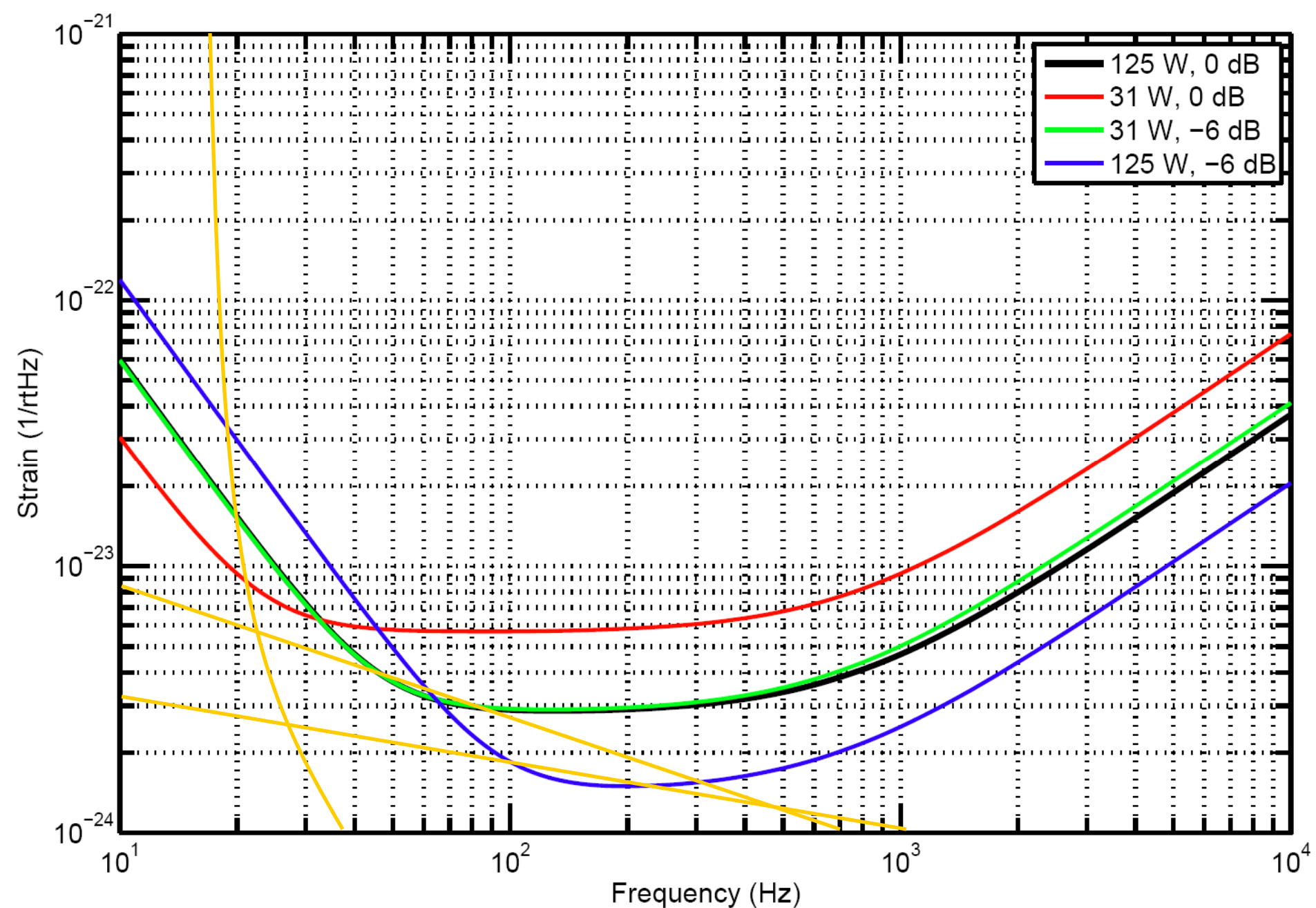
# Goal of the H1 Squeezer Experiment

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- ❑ Demonstrate squeezing at low frequency with a high sensitive long baseline interferometer
  - Demonstrate 3 dB of squeezing at frequencies where we are shot noise limited
  - Do not introduce noise at other frequencies!
- ❑ Build a squeezer which could be readily turned into an advanced LIGO upgrade
  - Fully engineered optical breadboard
  - Use LIGO type electronics and controls
  - Prepare for long-term reliability investigations
- ❑ Be ready for a test on H1 after S6

# Squeezed Enhanced LIGO, 30 W

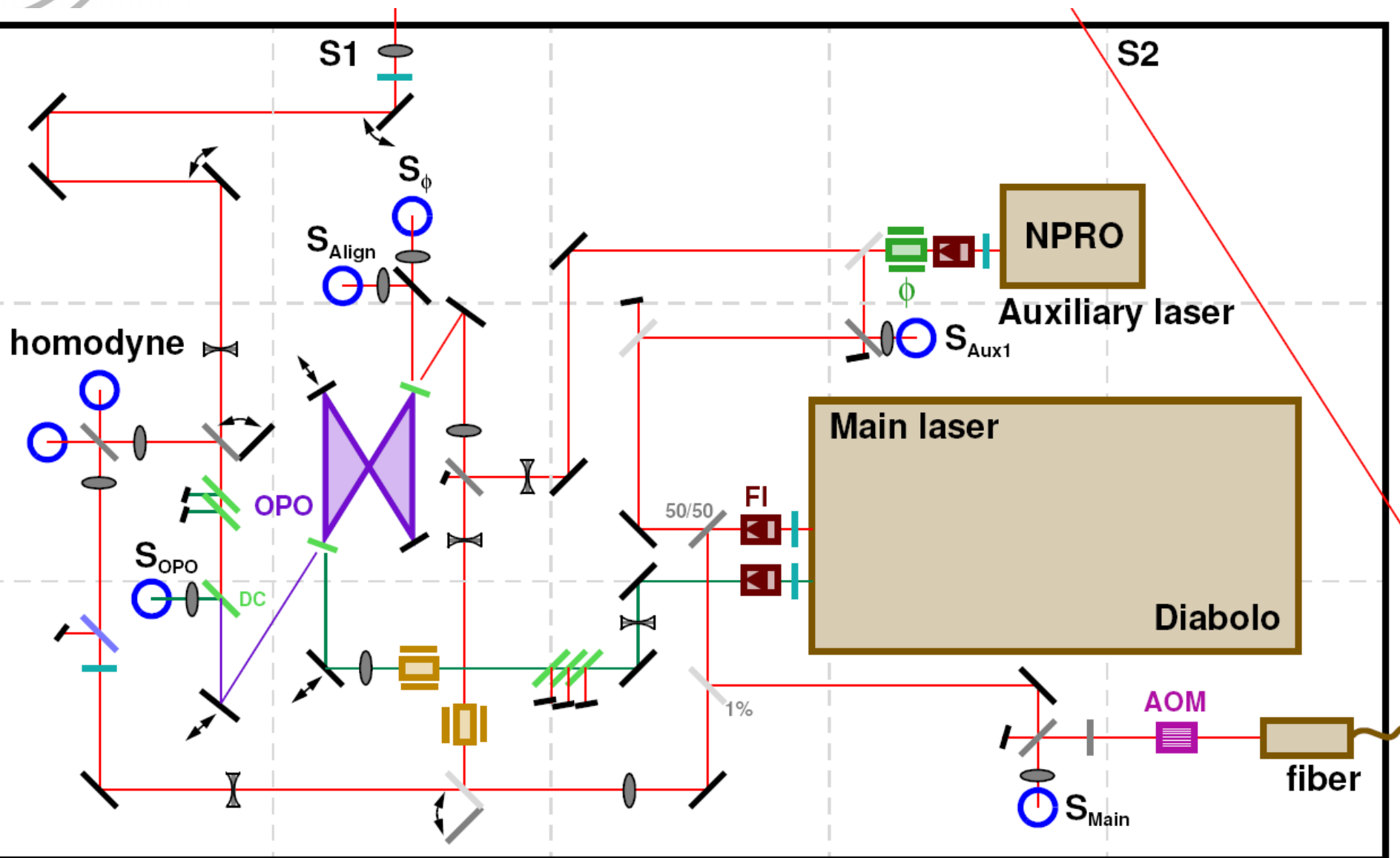




# Baseline Design

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- ❑ Inject into HAM4
  - SQT4 opposite of ISCT4
  - New advanced LIGO Faraday design
- ❑ Optical breadboard 5' x 3'
- ❑ 1W frequency double Nd:YAG laser
  - Locked to interferometer laser by fiber
- ❑ Auxiliary laser for frequency shifted subcarrier
- ❑ Optical parametric oscillator (OPO)
  - Doubly resonant
  - Bowtie configuration
  - Non-linear crystal: PPKTP



# Servos

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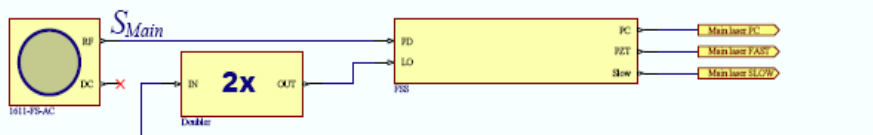
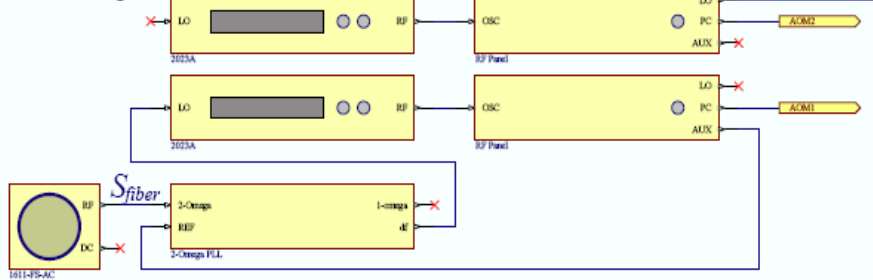
- ❑ Fiber stabilization: Feed forward
- ❑ Main laser offset-locked to probe beam
  - Use initial LIGO FSS
  - Pockels cell & PZT & thermal actuator
- ❑ Auxiliary laser offset-locked to main laser
- ❑ OPO: PDH on green light
  - PDH on probe beam at carrier frequency for alignment
- ❑ Squeezer phase & LO phase
  - Subcarrier sensing
  - Feedback to PZT mirror in green and squeezed light paths
- ❑ Homodyne detector for verifying squeezing

# Electronics Setup

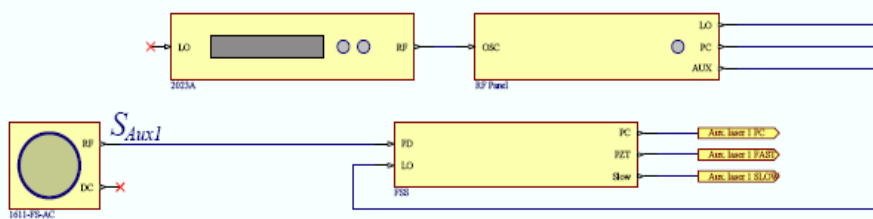
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- ❑ Compensation networks too fast for digital servos
  - Look-and-feel of a PSL system
- ❑ Remote controls: EtherCat from Beckhoff
  - Same as in Advanced LIGO laser
  - EPICS interface through OPC server
  - Can be used stand-alone with a PC or control panel
- ❑ LIGO electronics wherever possible
  - FSS, CM/MC board, RF distribution, demodulator, phase shifter, ...
  - PZT actuators from Physik Instrumente
  - No WFSs!

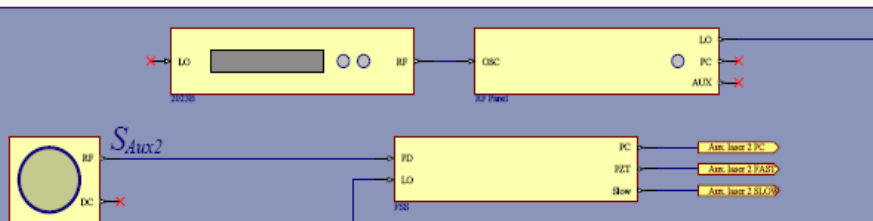
### Fiber Locking



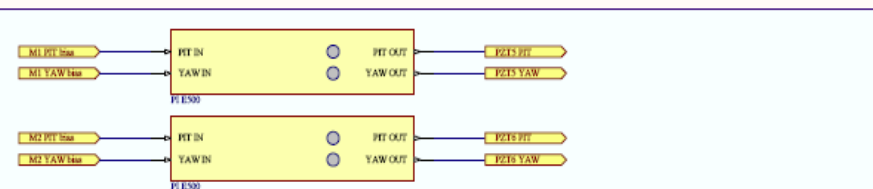
### Main Laser Locking



### Auxiliary Laser 1 Locking

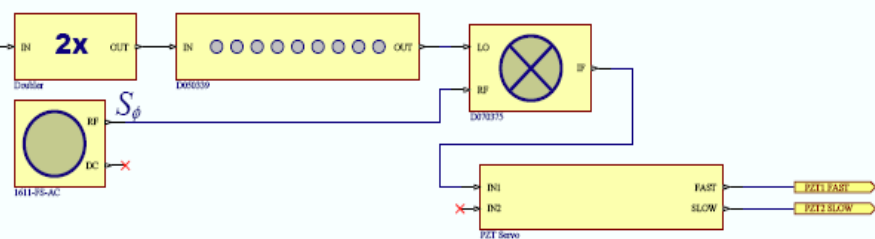
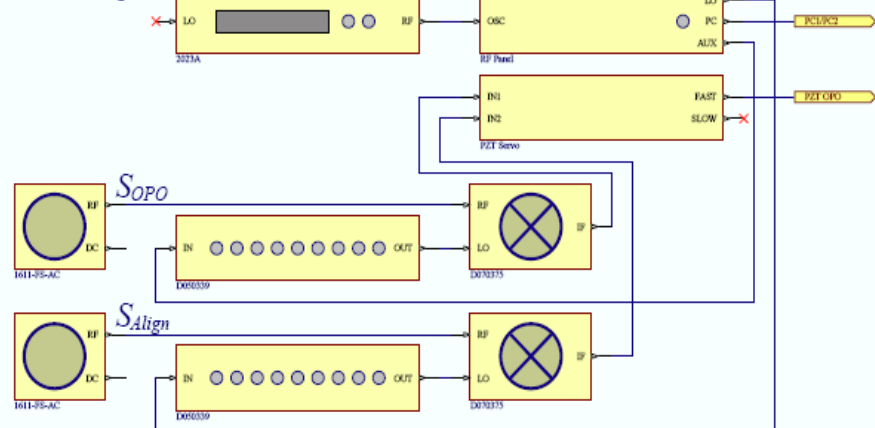


### Auxiliary Laser 2 Locking

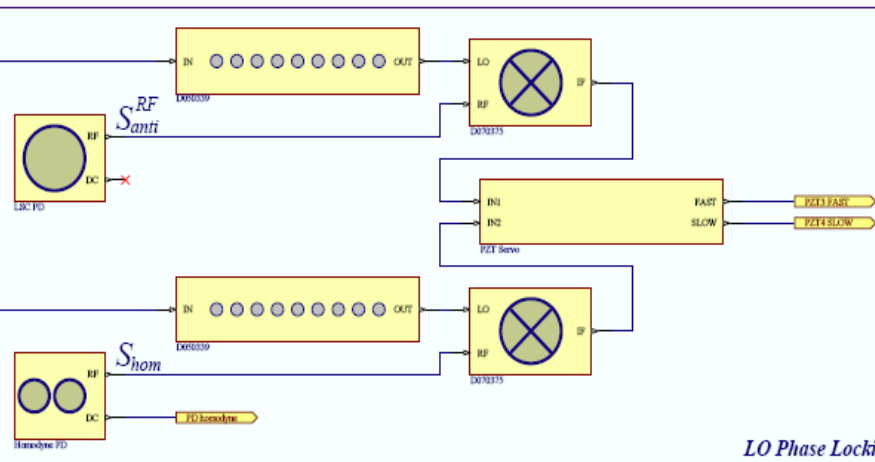


### Angular Control

### *OPO Locking*



### Squeezer Phase Locking



### LO Phase Locking

# Technical Issues (1)

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- ❑ OPO: see ANU presentation
- ❑ SHG
  - Diabolo laser system comes with an integrated SHG
  - Need to address internal scattering issues
- ❑ Auxiliary lasers
  - Scattering of AOMs too much trouble
  - Freedom to choose subcarrier frequency
  - A singly-resonant cavity would require a 2<sup>nd</sup> auxiliary laser to lock it
- ❑ Fiber stabilization
- ❑ In-vacuum AS-port Faraday isolator
  - Develop advanced LIGO unit

# Technical Issues (2)

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## ❑ Scattering paths

- Inject opposite ISCT4
- Second in-vacuum Faraday isolator in injection path
- Baffling on the optical breadboard

## ❑ Long-term reliability

- Squeezer will be available after H1 experiment

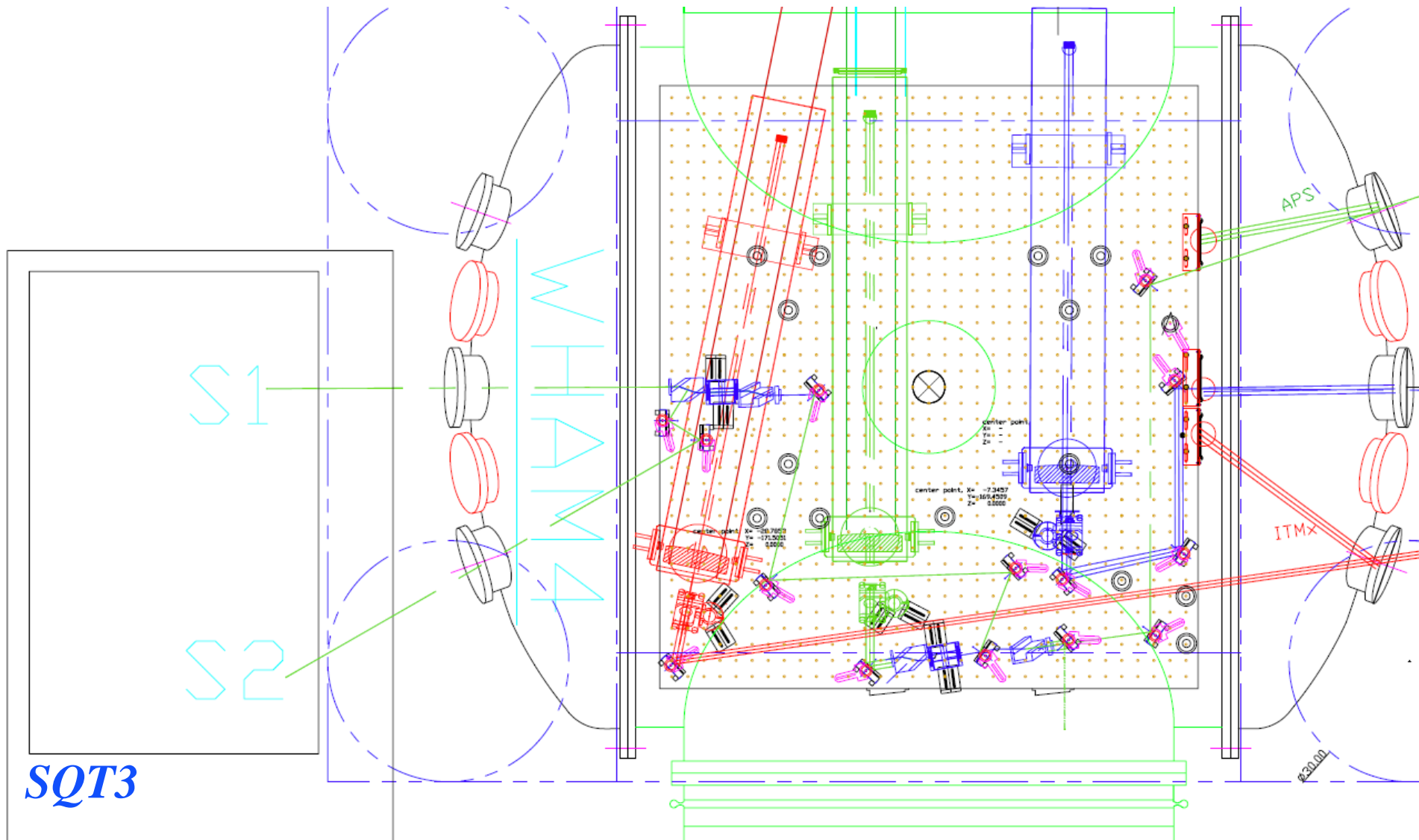
## ❑ SQT4

- Reuse ISCT3
- Mount table high to avoid a periscope

## ❑ Initial Alignment

- Use rejected beam from Faraday in injection path as a fiducial

# HAM4 Layout





# Squeezing GEO600

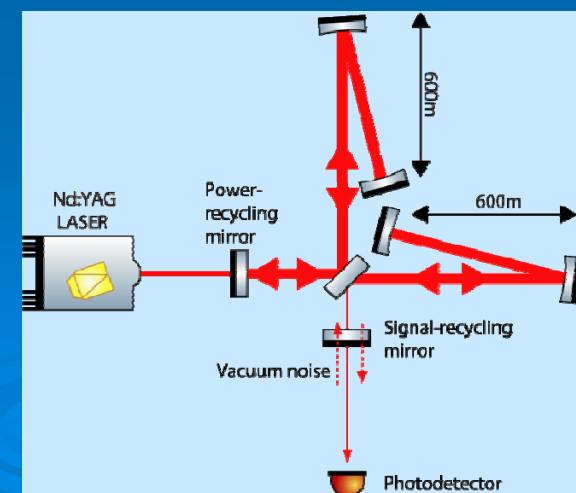
Harald Lück



# Current GEO600 operation mode



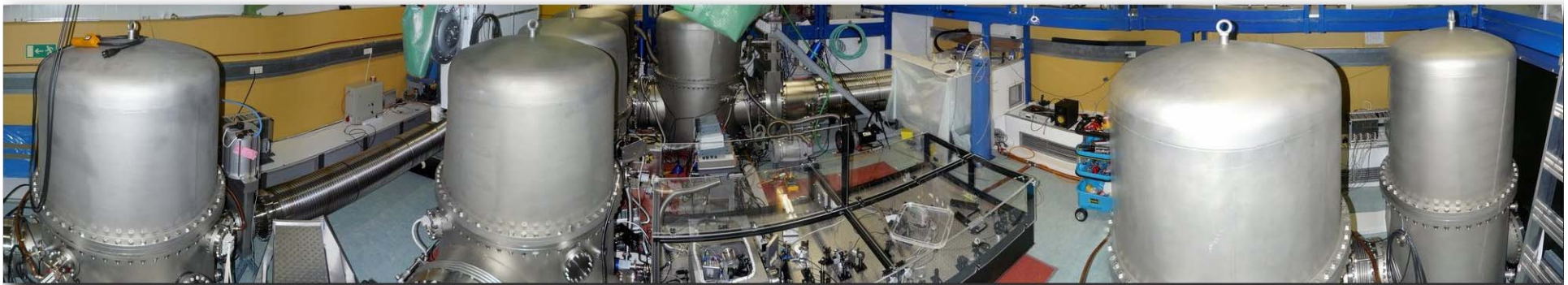
- Dual recycling; detuned to 550Hz
- SR transmission 2%
- Heterodyne read-out 15MHz
- 3 kW inside PR cavity



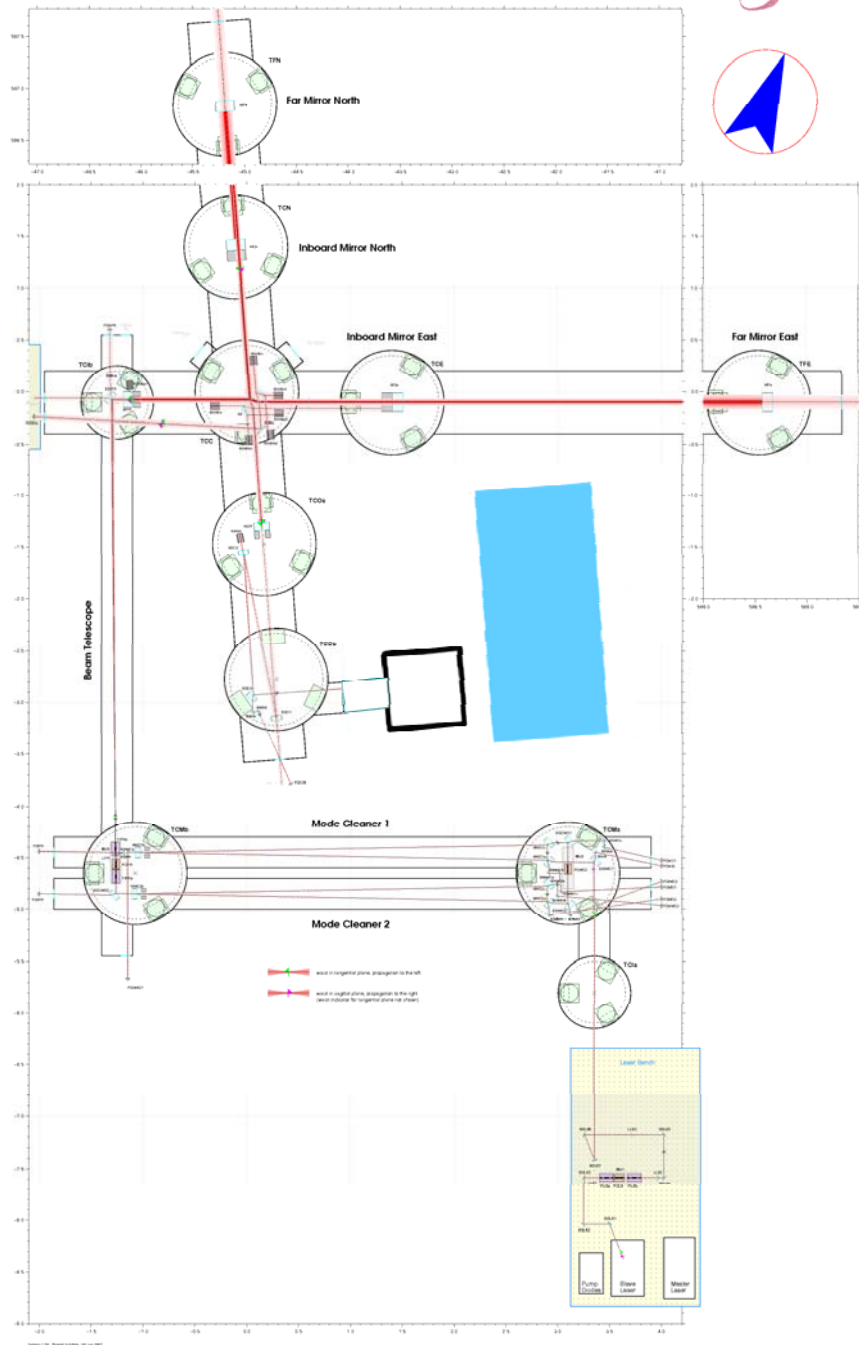
# Plans



- Astrowatch + low-risk commissioning until 'Enhanced' IFOs come online (spring 2009 )
- Keywords: DC readout, squeezing, OMC, higher power, thermal comp., tuned SR, lower SR factor, extended digital control...
- Goal: demonstration of long term stable operation of GEO-HF with squeezed light @ improved sensitivity



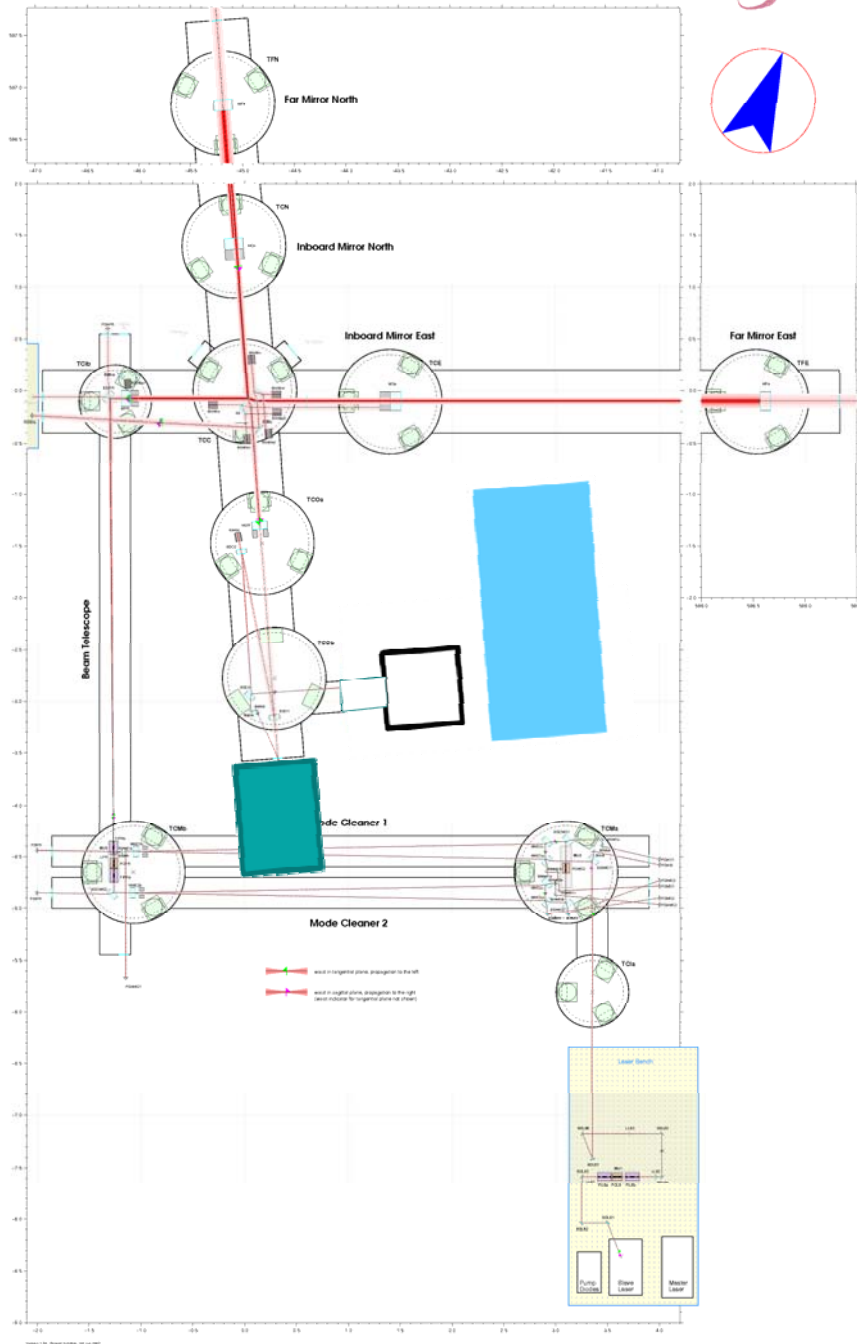
## GEO 600 optical layout



Now:

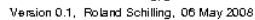
- Auto Alignment on detection bench
- Main photo detector on detection bench outside vacuum system

## GEO 600 optical layout



Then:

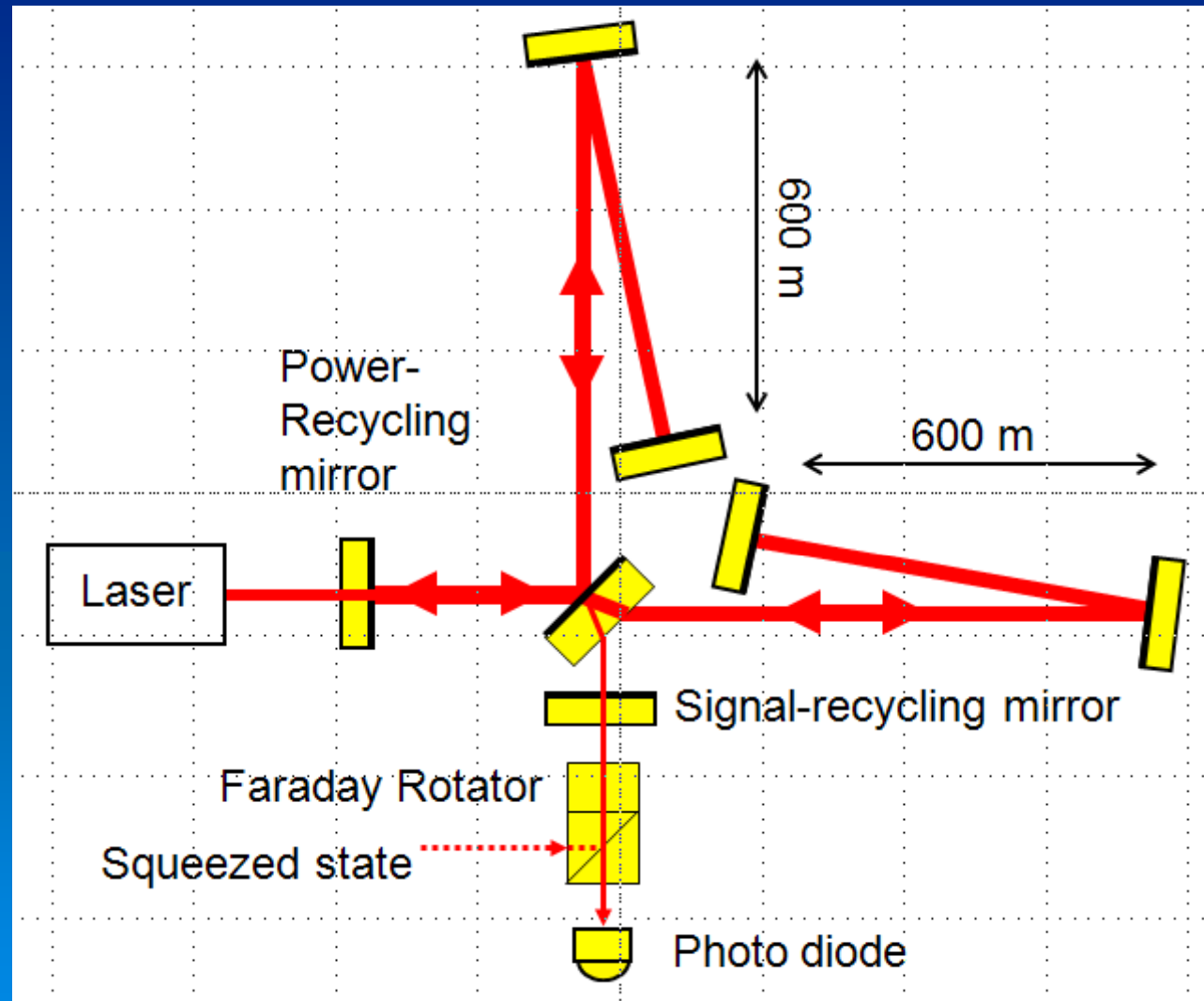
- Auto Alignment on new AA bench
- Main photo detector in additional vacuum tank
- OMC to reduce higher order TEM mode contributions to detected light
- > less technical problems with PD @ higher light levels



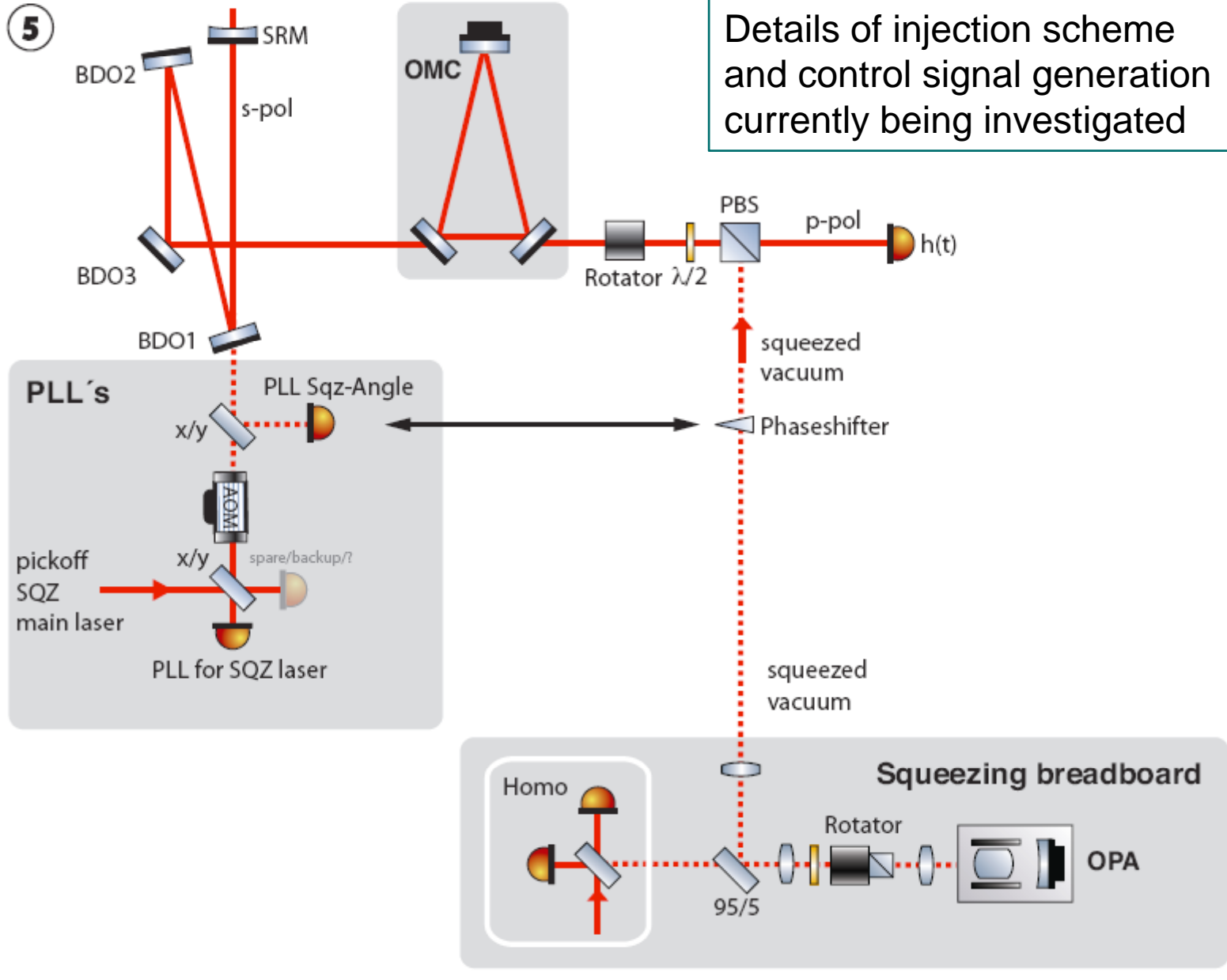
AA

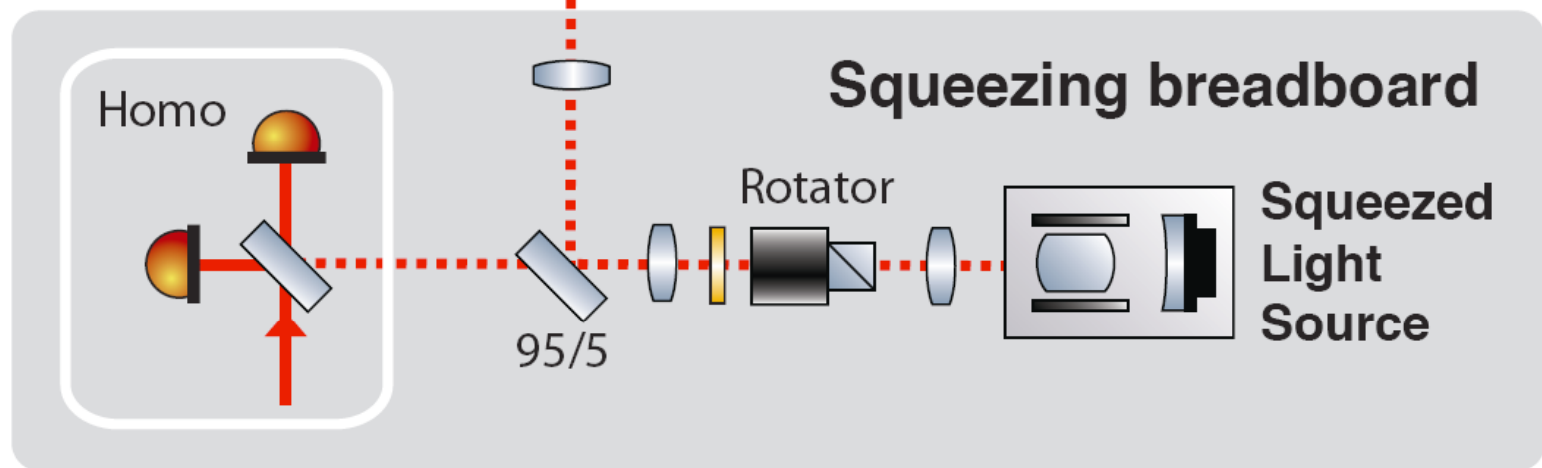
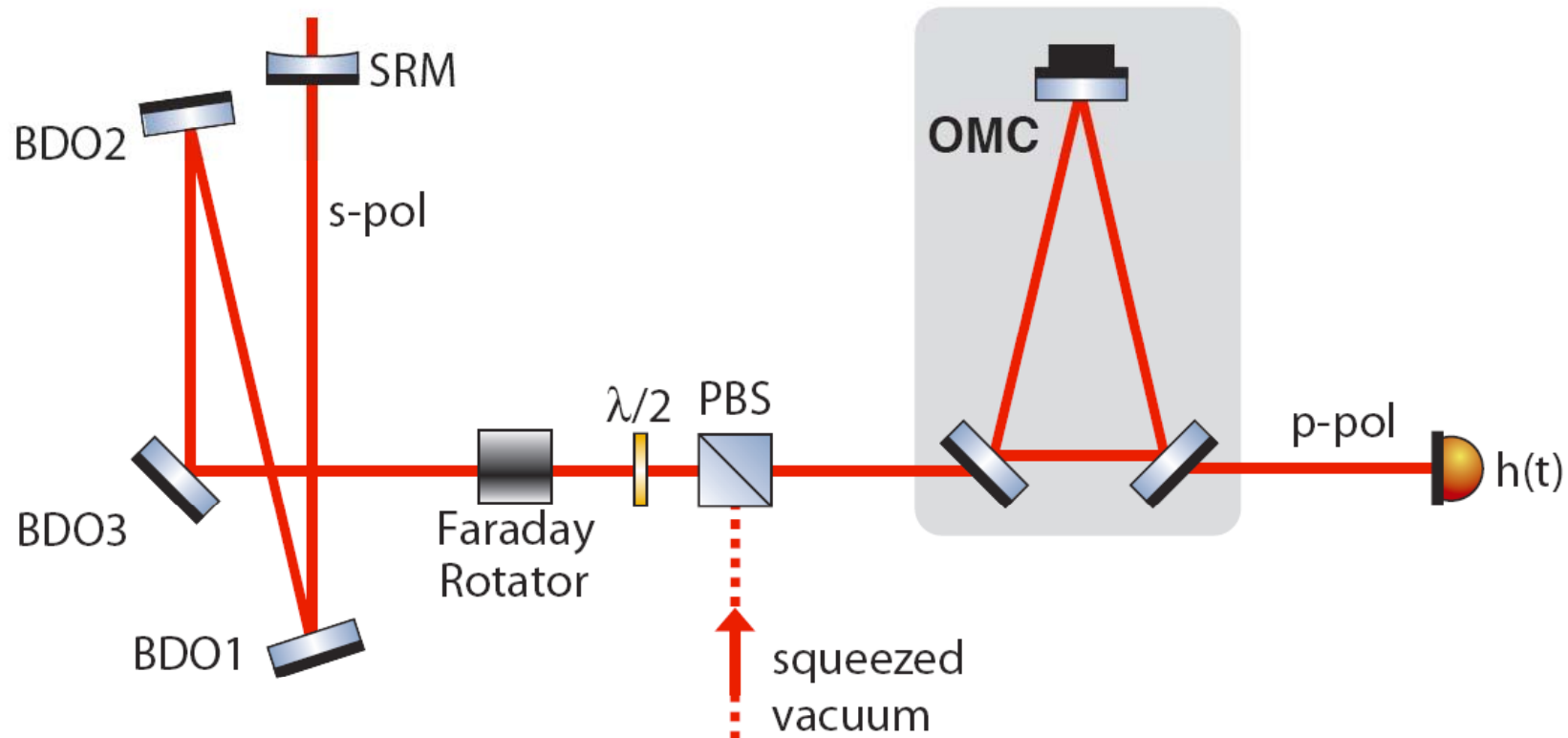
## The Cleaner 1

# Schematics of injecting squeezed light

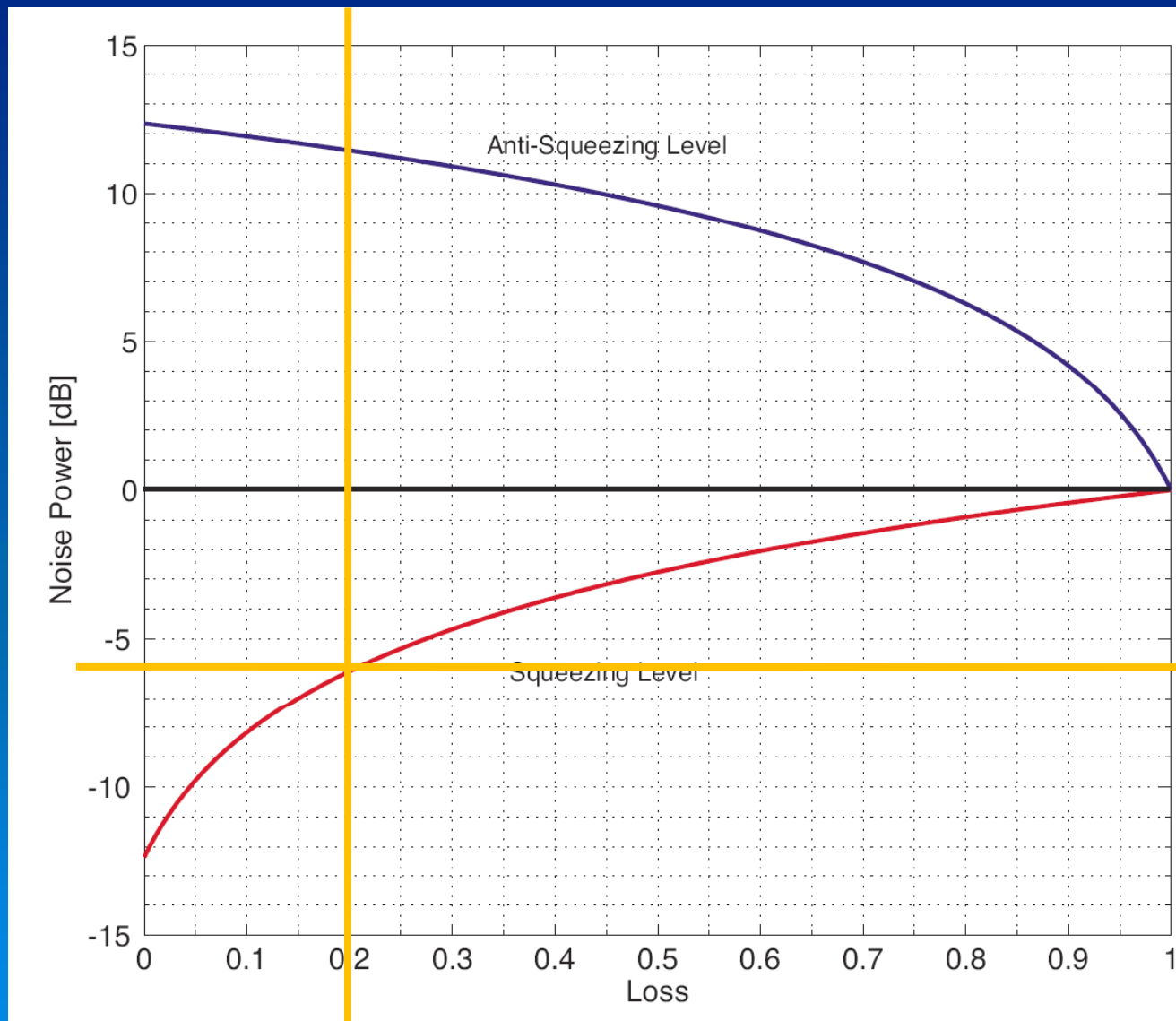


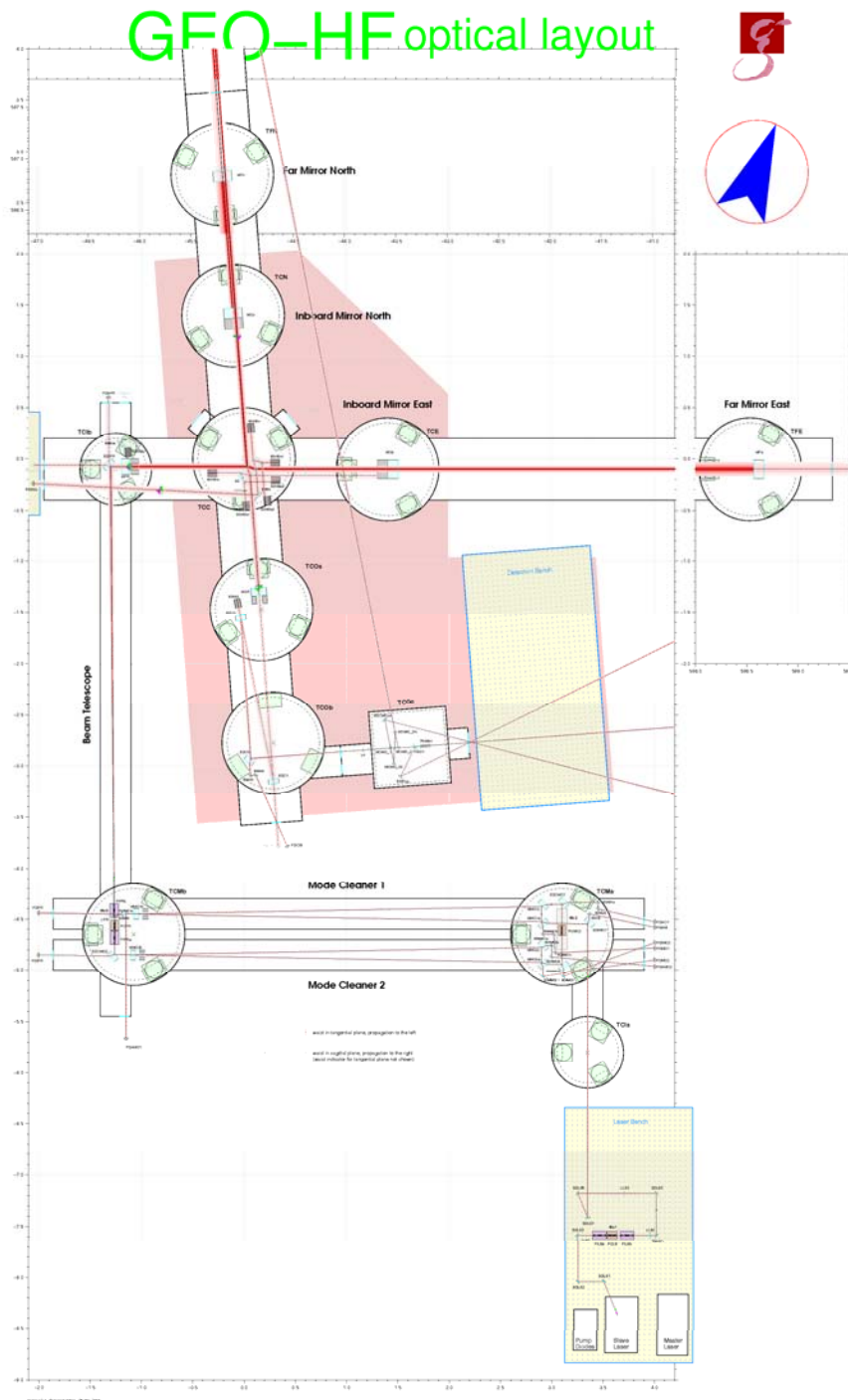
5





# Squeezed light and optical losses

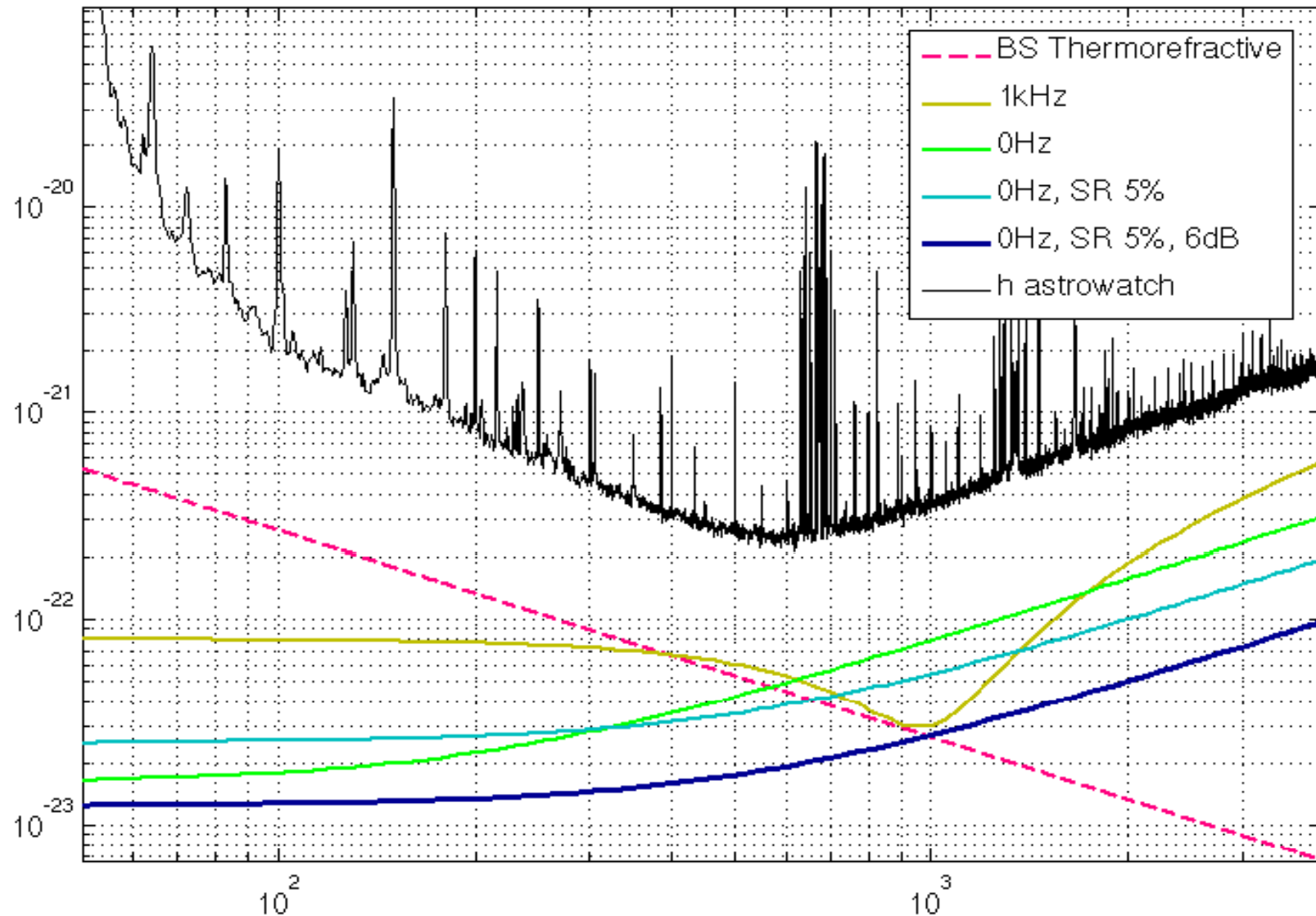




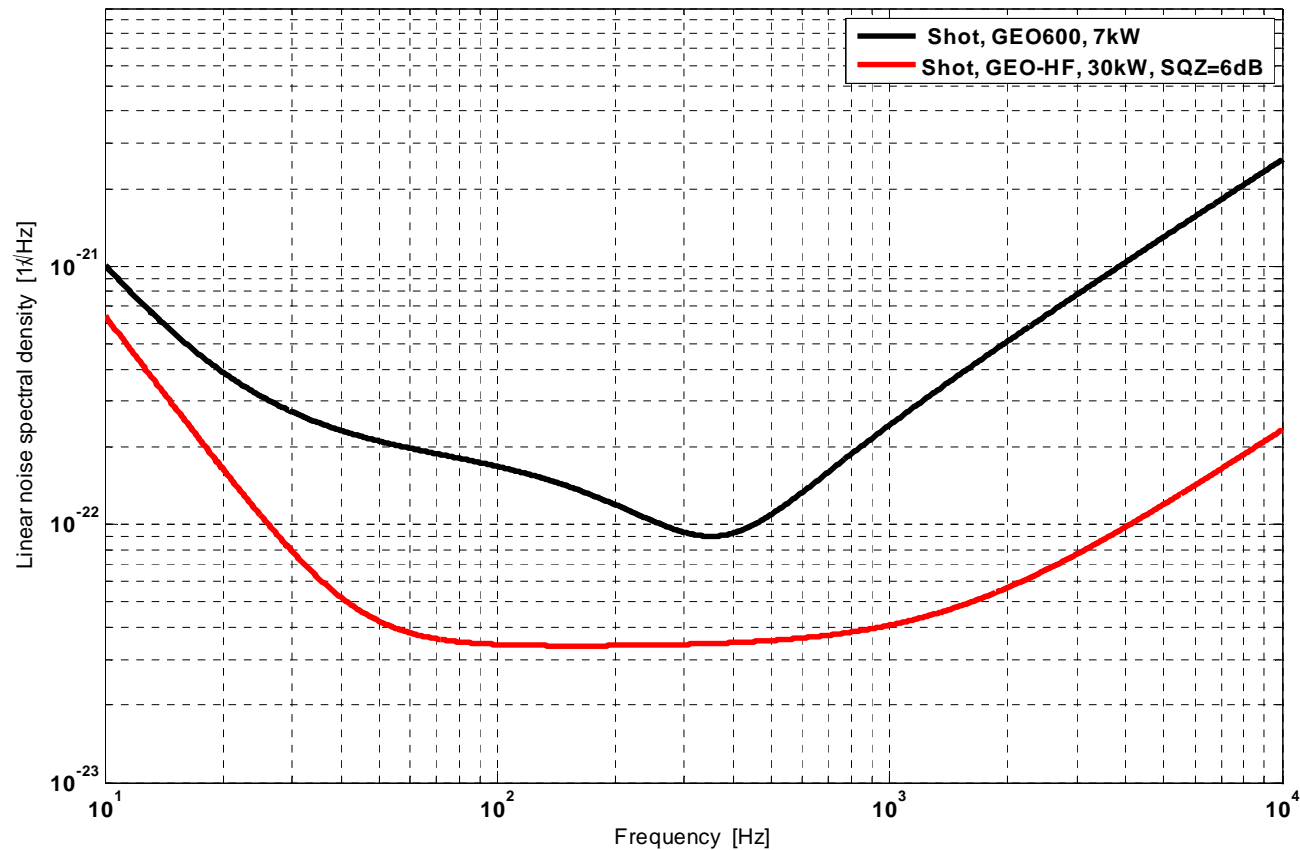
# Power increase

- Currently **3.5kW @ MPR**
- Increase laser power  
10 W (6 W) -> 35 W
- Exchange MC mirrors  
-> increase throughput 2x  
**-> 30kW @ MPR**

# Options Towards GEO-HF

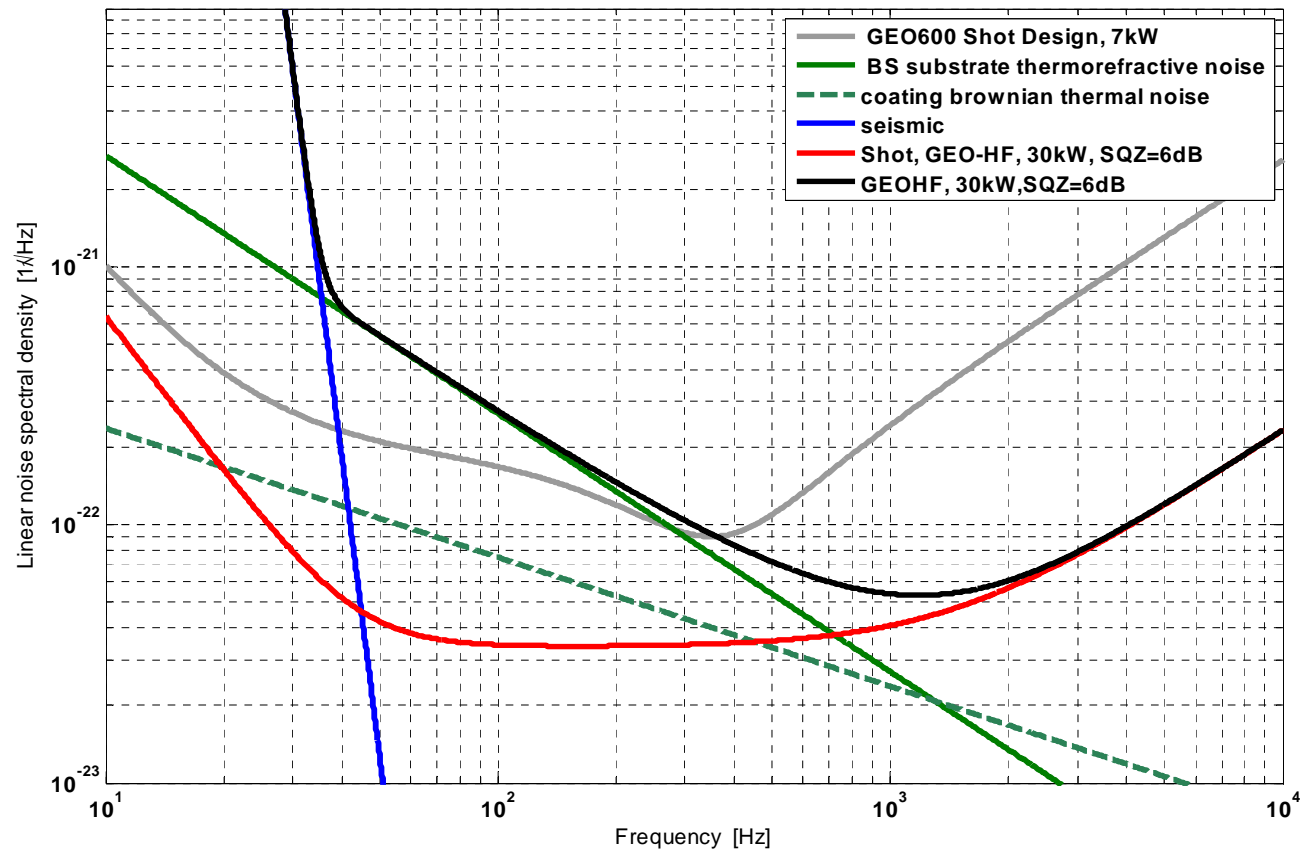


# Quantum Noise GEO600 vs. GEO-HF



GEO600: 7kW, Schnupp Modulation, 550Hz detuning  
GEO-HF: 30kW, DC Readout, OMC, Tuned, broadband

# GEO HF Noises



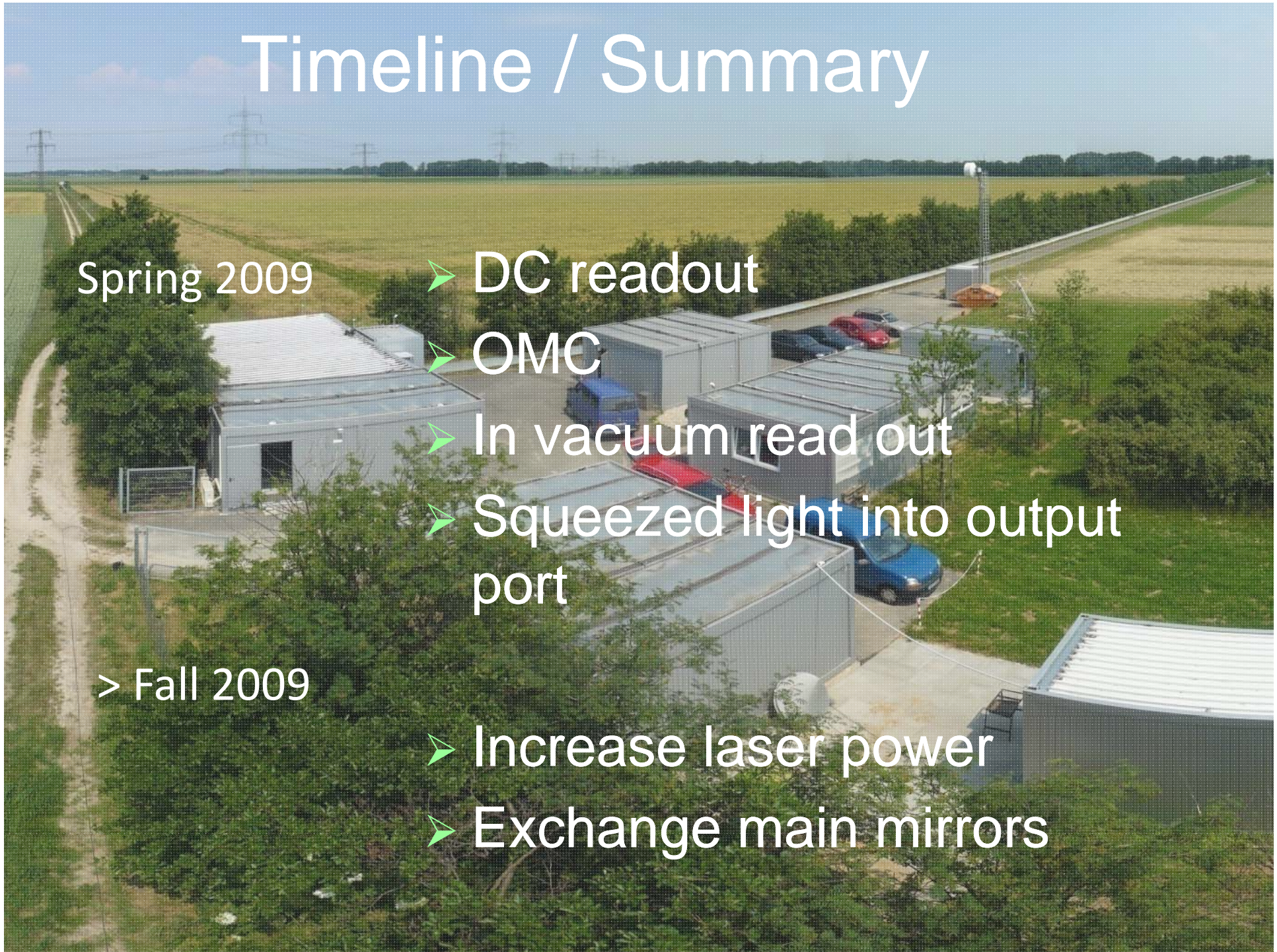
# Timeline / Summary

Spring 2009

- DC readout
- OMC
- In vacuum read out
- Squeezed light into output port

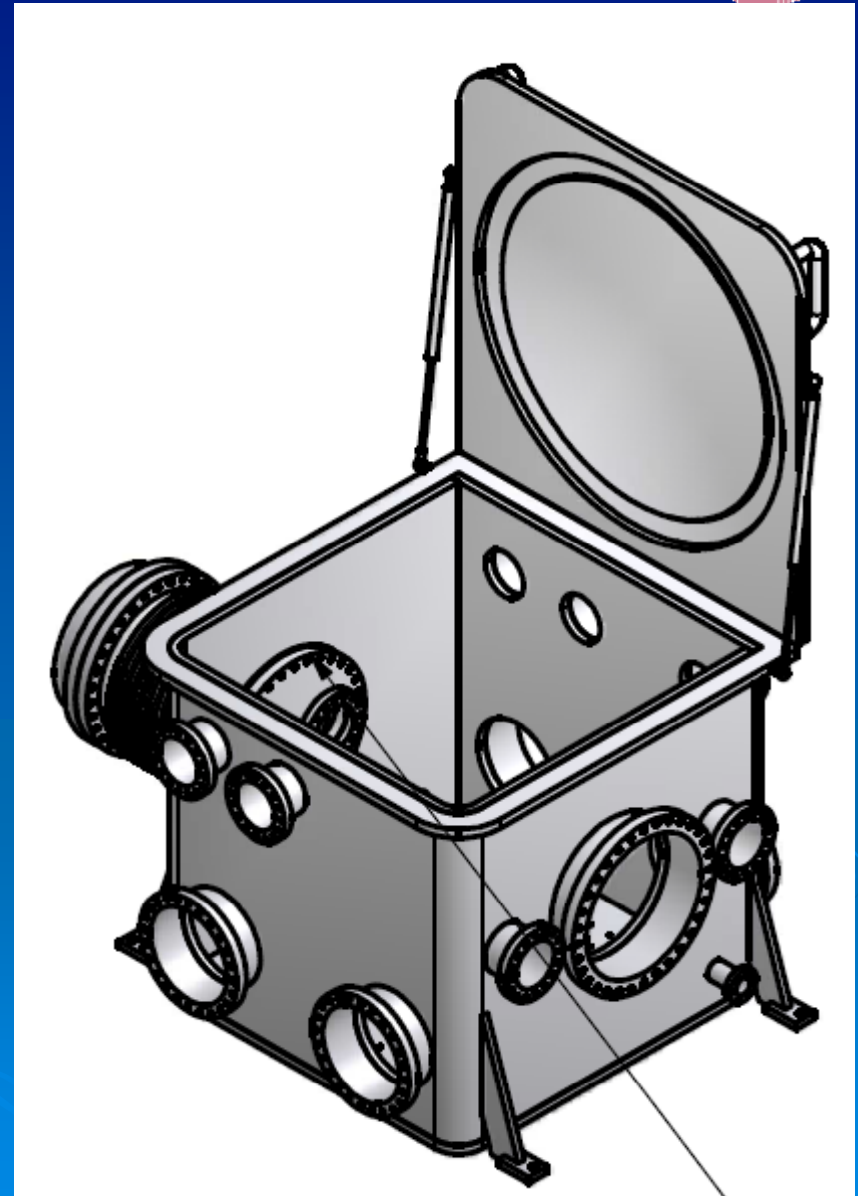
> Fall 2009

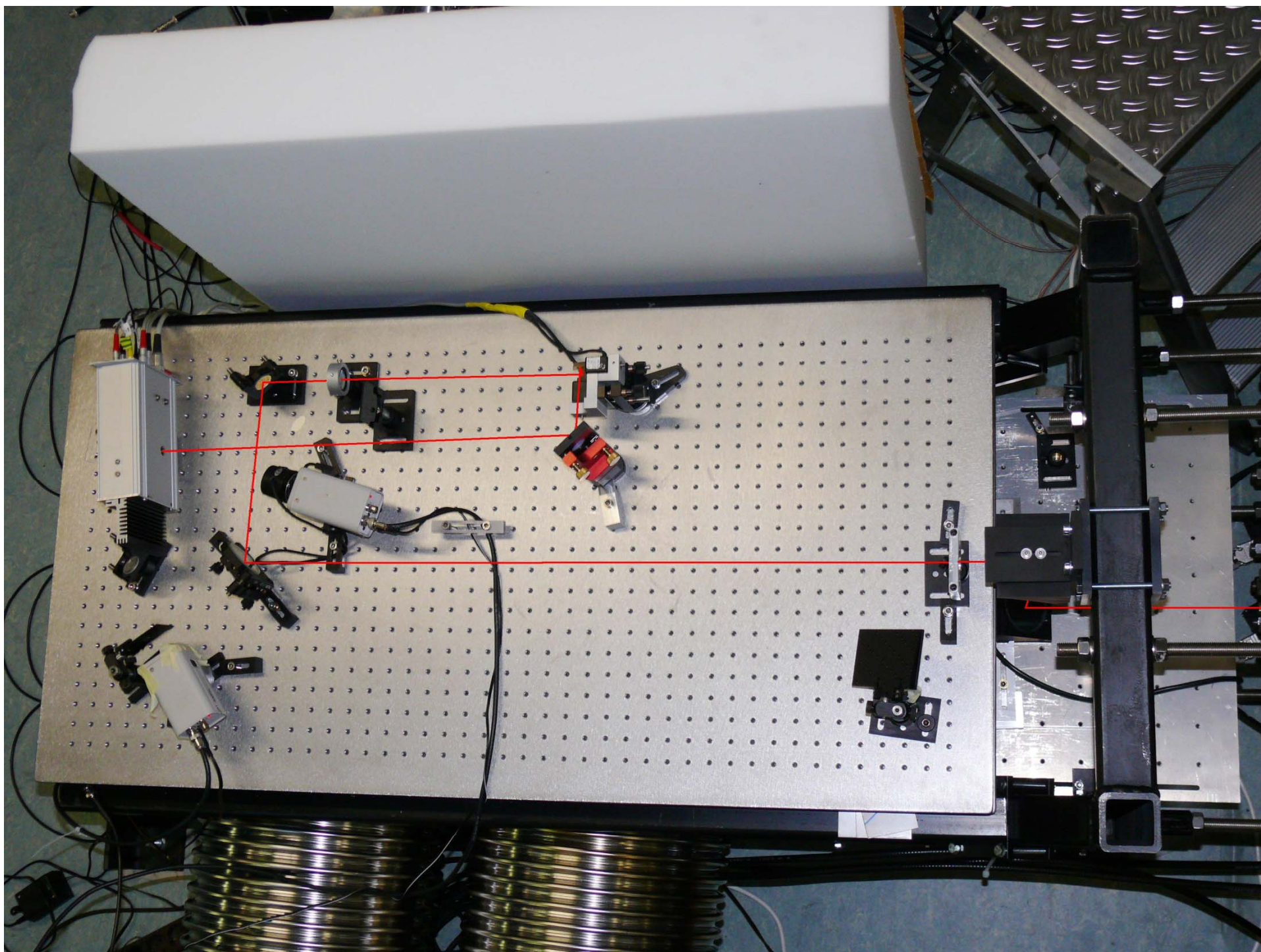
- Increase laser power
- Exchange main mirrors



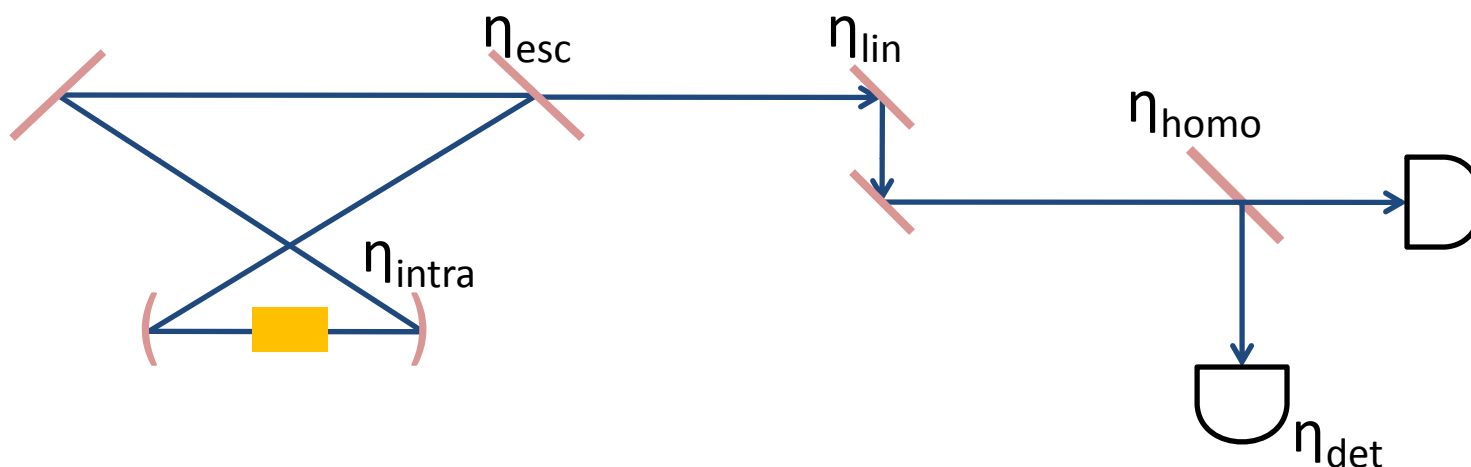
# Additional vacuum tank TCOc

- $75^3 \text{ cm}^3$
- Viton gaskets ( $10^{-6}$  mbar)
- Viewport between TCOb and TCOc  
(Will it be a problem?)  
So far we do not see any  
Isolated platform inside





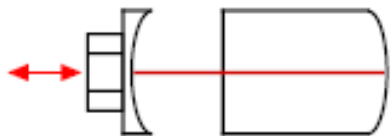
$$\eta_{\text{sqz}} = \eta_{\text{intra}} \eta_{\text{esc}} \eta_{\text{lin}} \eta_{\text{homo}} \eta_{\text{det}}$$



$\eta_{\text{intra}}$  – Intra-cavity Efficiency  
 $\eta_{\text{esc}}$  – Escape Efficiency  
 $\eta_{\text{lin}}$  – Transmission Efficiency  
 $\eta_{\text{homo}}$  – Homodyne Efficiency  
 $\eta_{\text{det}}$  – Detector Efficiency

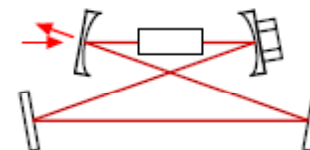
→ Intra-cavity nonlinear process  
 → Ratio between output coupling rate to total cavity decay rate  
 → From Cavity to Detection  
 → Square of the Fringe Visibility  
 → Photodetector Efficiency

## Hemilithic vs Bow-tie Configuration



### Hemilithic (Standing Wave)

- Fewer reflecting surfaces, thus having lower loss
- Negligible spatial and polarisation distortion through its normal incidence operation.
- Limited number of input ports/ reflected beams from normal incidence operation.
- Single air/crystal interface, but greater difficulty in exchange of crystals
- Squeezer in hemilithic configuration to be installed at GEO600.



### Bow-tie (Travelling Wave)

- Inherent isolation to backscattered light
  - Less critical on additional Faraday isolation
- Bowtie configuration minimizes astigmatism.
- Ready access to multiple input ports/ reflected beams, due to their physical separation.
- Ability for easy exchange of crystals.
- The travelling wave characteristic makes the phase matching condition less dependent on temperature.

## Doubly Resonant Cavity

Cavity resonant at both fundamental (1064nm) and pump (532nm) wavelengths.

### Advantages

- Simplicity of obtaining a cavity length error signal (using the pump 532nm field)
- Assurance of optimum mode matching of the interacting fields.
- Non-matched spatial components of the pump field (to the cavity mode) filtered
- The pump field amplitude is resonantly enhanced, giving a higher nonlinear gain for the same input pump power.
  - Allows possibility of increasing the transmission of the output coupler at 1064nm to increase  $\eta_{\text{esc}}$ .
- Less critical to internal cavity losses.
- Provide additional signal for phase-matching locking (if required).

# OPO Design

## Nonlinear Crystal

Choice between 2 crystals: PPKTP and  $\text{MgO:LiNbO}_3$

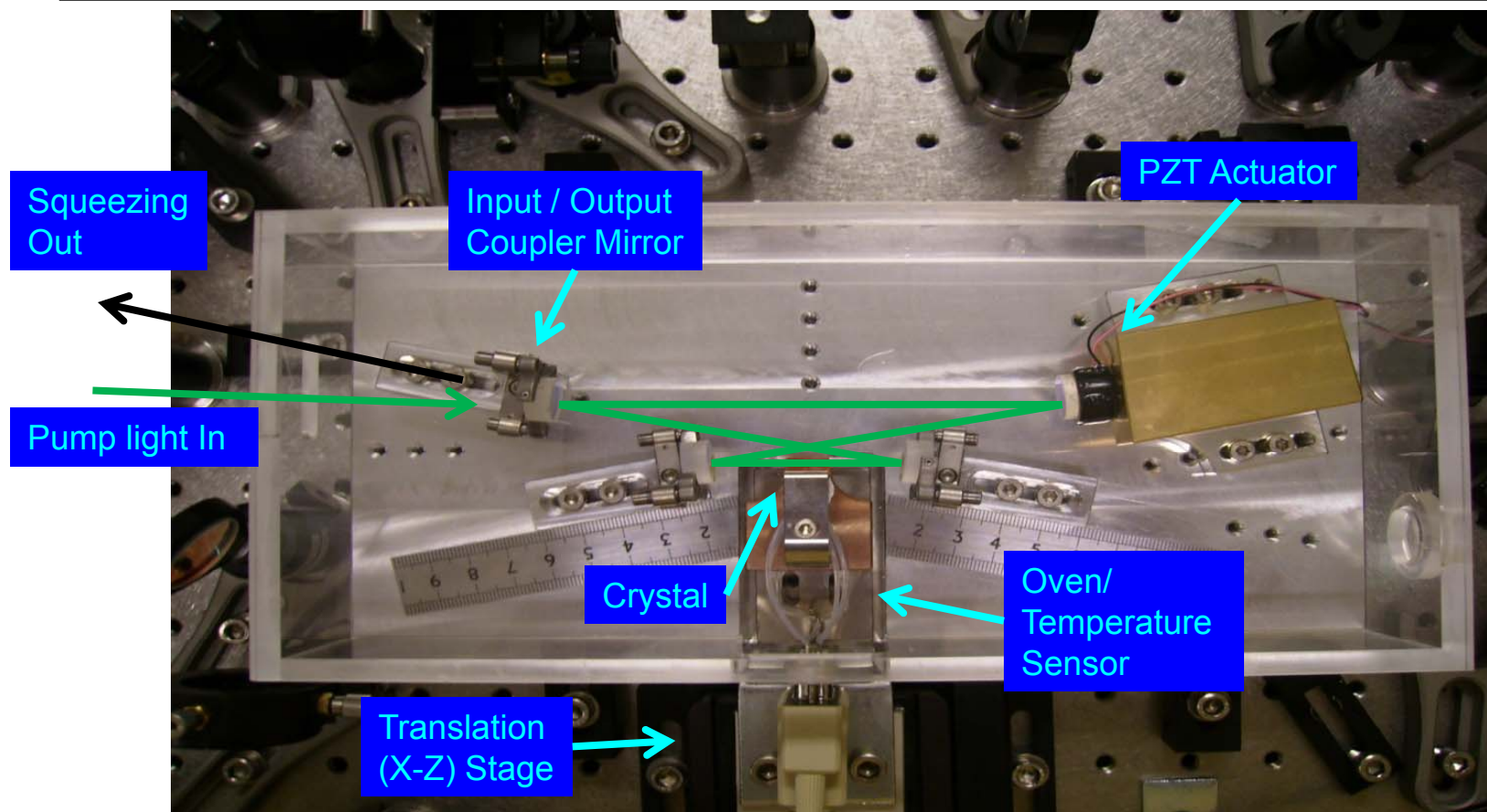
### PPKTP

- Very high nonlinearity via the use of the  $d_{33}$  of KTP.
- Grey tracking was a known problem when PPKTP is used near the UV wavelength (795/397 nm). To date, we have no data on grey tracking at 1064/532 nm.
- Best result obtained was > 9 dB squeezing (Tokyo University).

### MgO:LiNbO<sub>3</sub>

- Lower nonlinearity compare with PPKTP
- More robust than PPKTP.
- MgO doping is used to increase the photo-refractive damage threshold.
- Larger parasitic photothermal effects.
- Squeezer using  $\text{MgO:LiNbO}_3$  to be installed at GEO600.
- Best results obtained was > 10 dB of squeezing (AEI Hannover).

- **Configuration:** Doubly Resonant Bow-Tie Cavity
- **Crystal:** PPKTP [Flat-wedge geometry]
- **Finesses**  $\sim \mathcal{F} = 50$  for 1064nm,  $\sim \mathcal{F} = 100$  for 532nm
- **Temperature Control:** Oven and Newport Temperature Controller
- **Optical Path Length:**  $\sim 700$ mm
- **Physical Dimensions:**  $\sim 200$  mm x 150mm



## **Dispersion Compensation**

- The reflections at mirrors from dielectric coatings will produce a differential phase shift between the pump and fundamental fields. Dispersion compensation is required to co-resonate both fields, obtained through the use of a flat- (1-2 degree) wedge surface geometry of the nonlinear crystal.

## **Cavity Length Control**

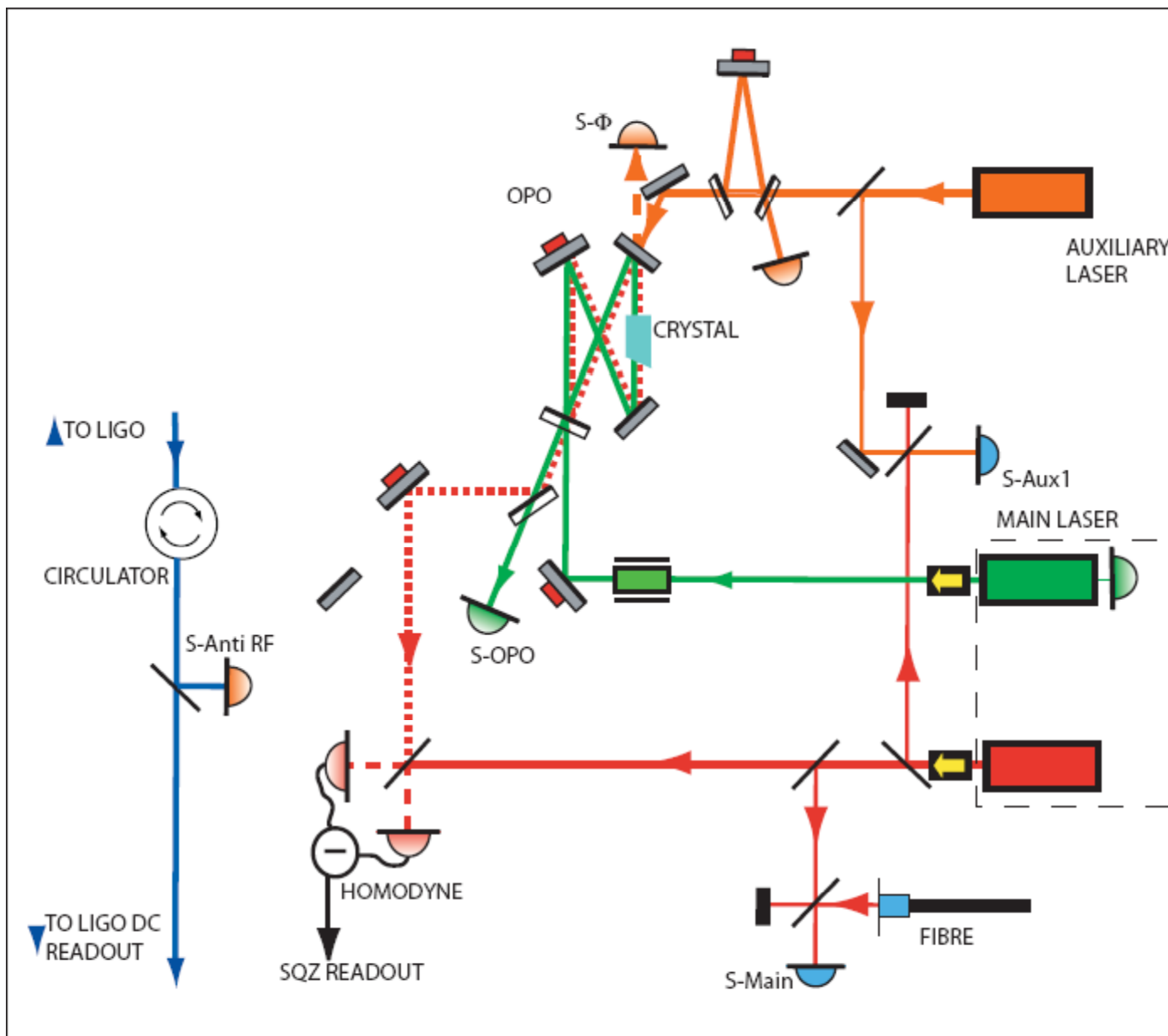
- Pound-Drever-Hall locking with cavity error signal derived from the reflected pump (532nm) field.
- Control of cavity length is done via a single PZT with a locking bandwidth of 20 kHz. If needed, a high speed PZT coupled with Molybdenum rod can extend the locking bandwidth to around 200 kHz.

## **Squeezed Quadrature and Local Oscillator (LO) phase control**

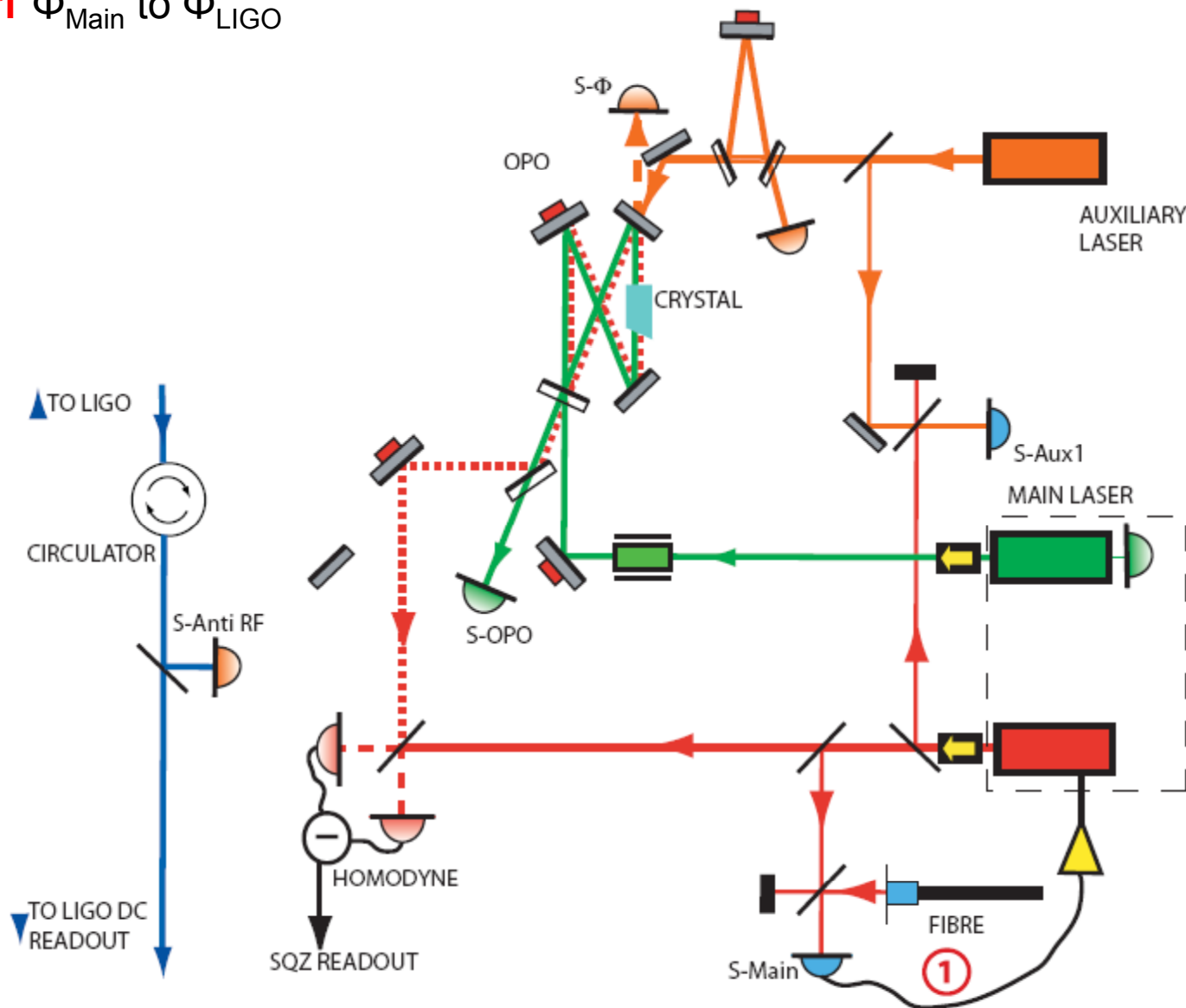
- Coherent (Frequent Shifted Sideband or F.S.S.) locking to implemented.

## **Temperature**

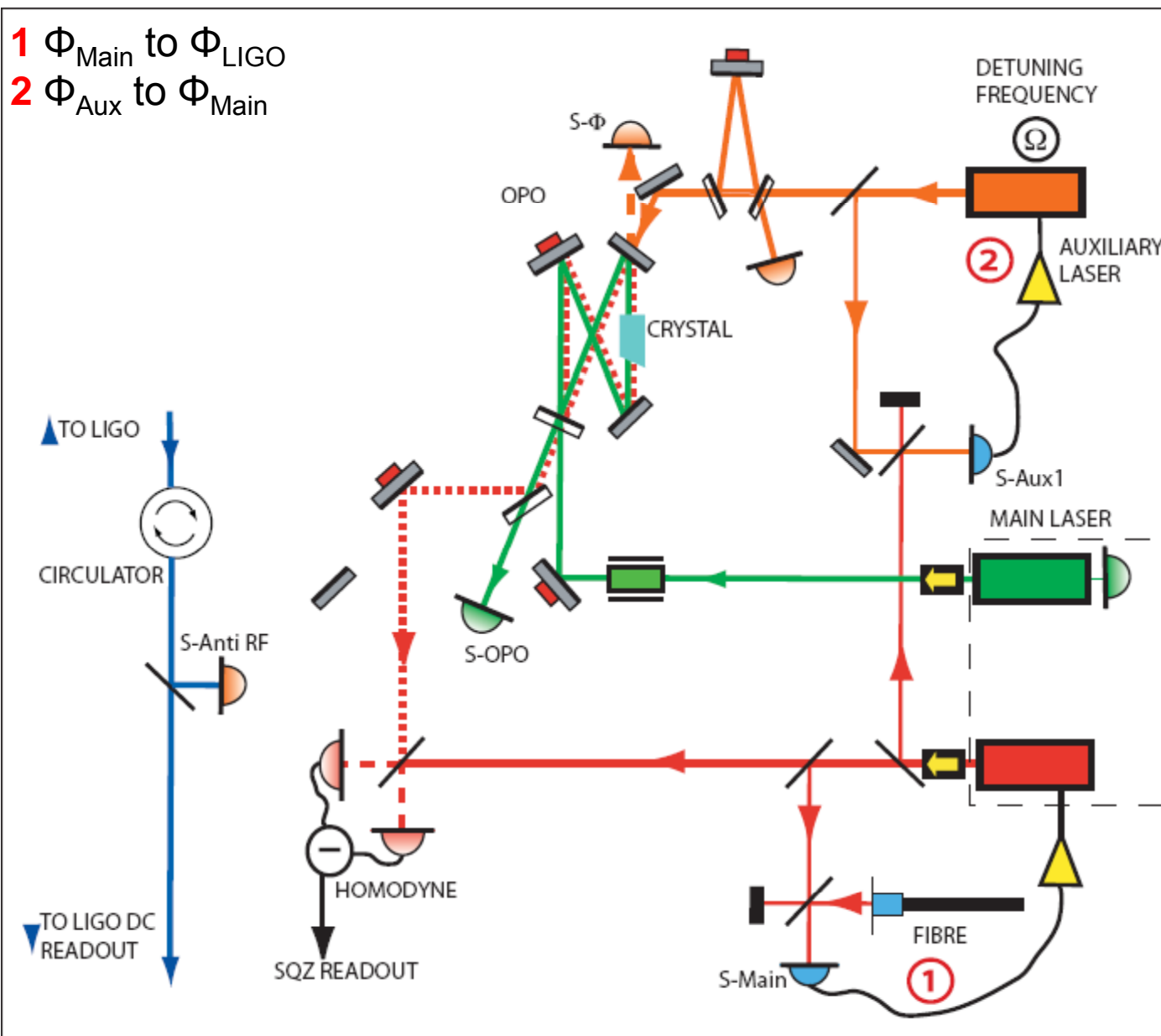
- A Newport temperature controller (Series 3040) can be used to control the crystal phase matching temperature accurate to  $\pm 1$  mK (long term stability).



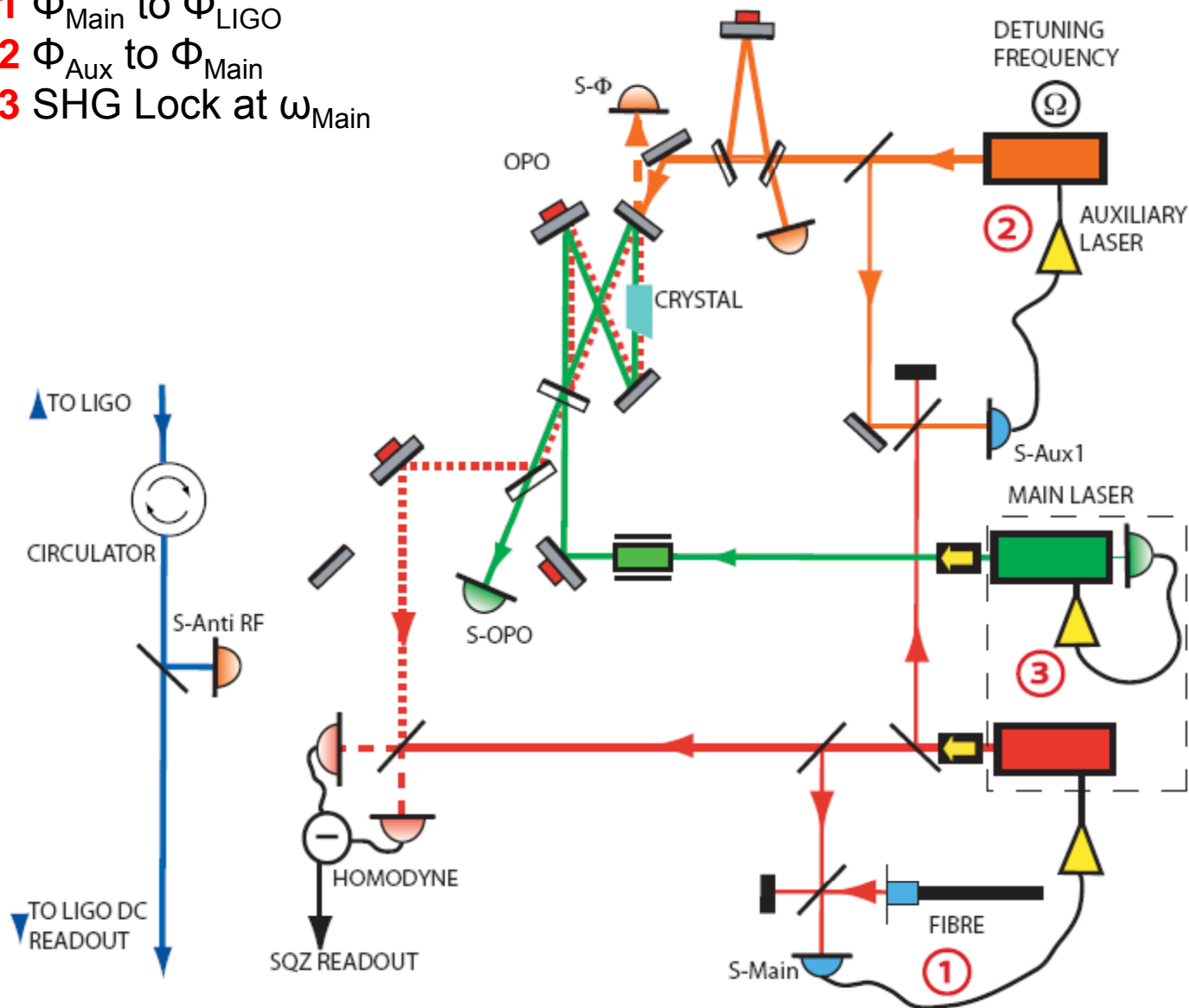
1  $\Phi_{\text{Main}}$  to  $\Phi_{\text{LIGO}}$



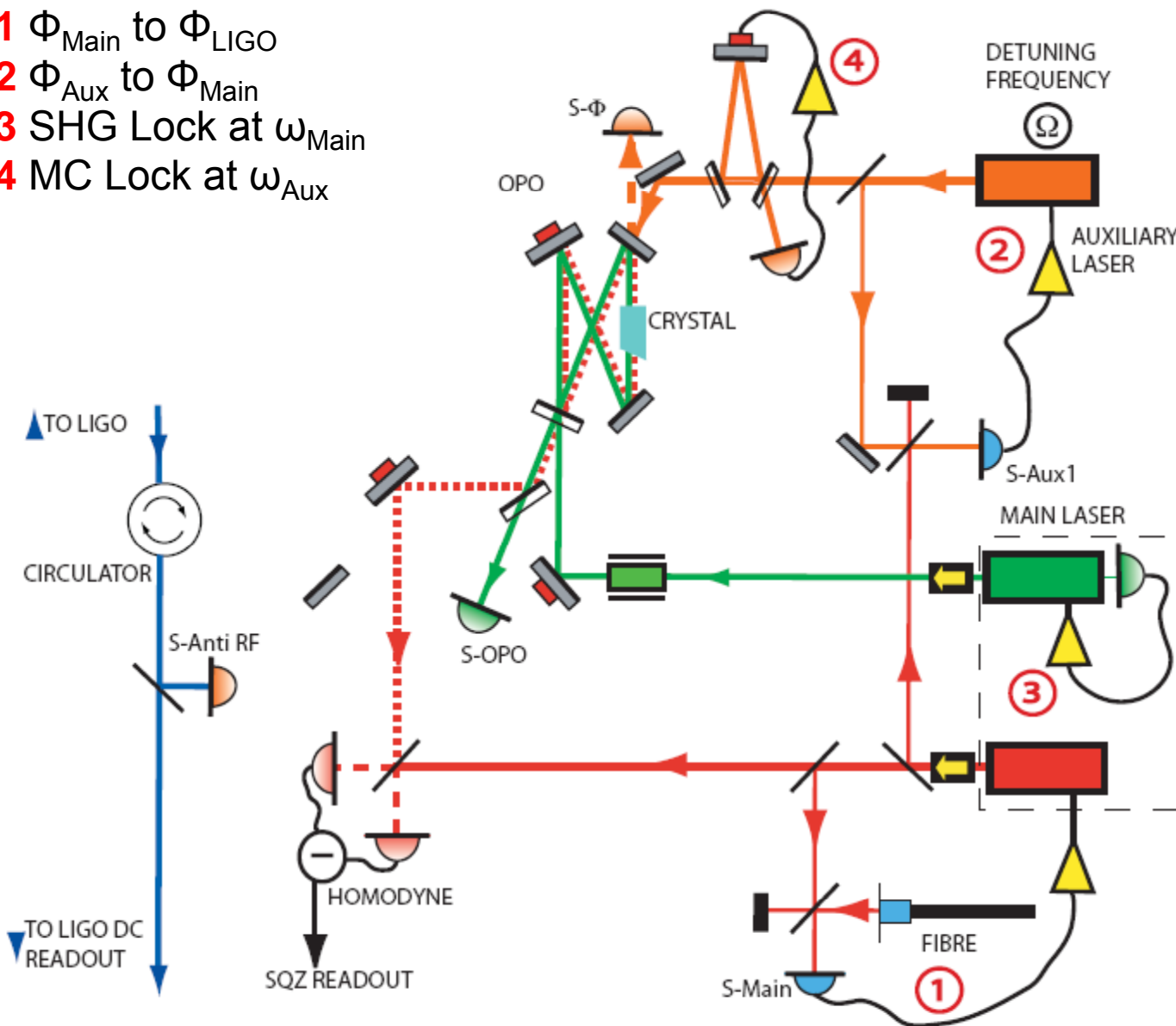
- 1  $\Phi_{\text{Main}}$  to  $\Phi_{\text{LIGO}}$
- 2  $\Phi_{\text{Aux}}$  to  $\Phi_{\text{Main}}$



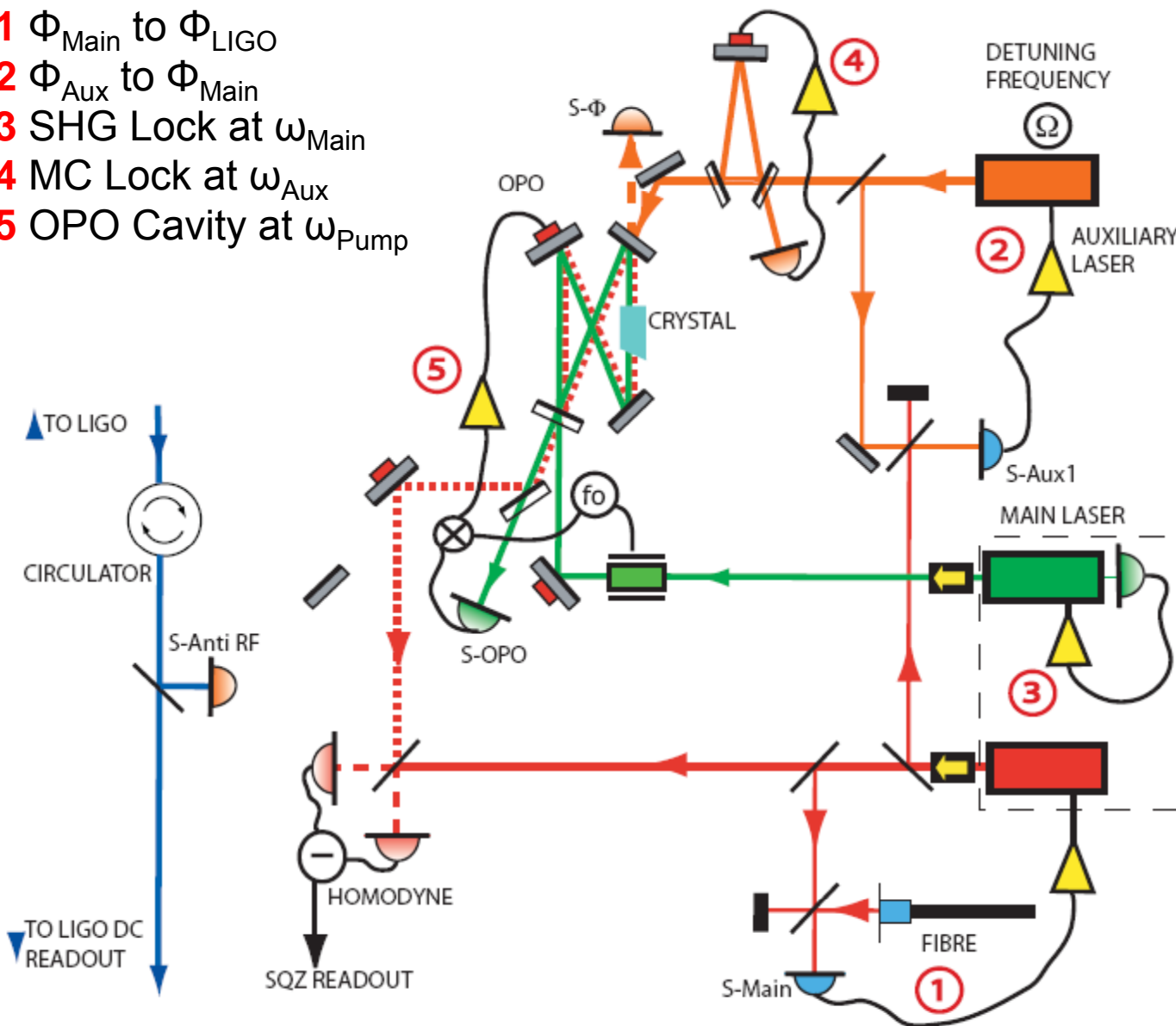
- 1  $\Phi_{\text{Main}}$  to  $\Phi_{\text{LIGO}}$
- 2  $\Phi_{\text{Aux}}$  to  $\Phi_{\text{Main}}$
- 3 SHG Lock at  $\omega_{\text{Main}}$



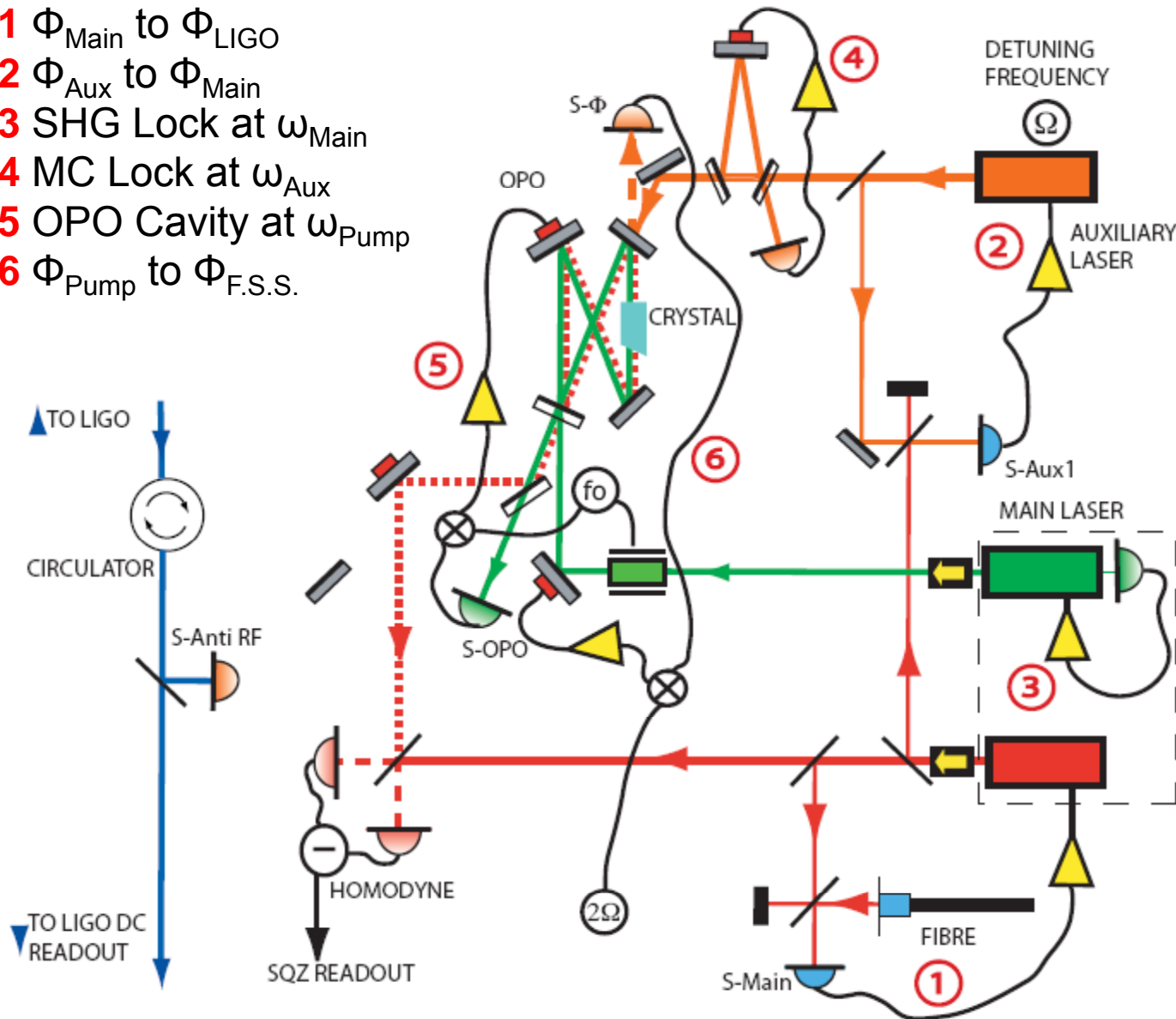
- 1  $\Phi_{\text{Main}}$  to  $\Phi_{\text{LIGO}}$
- 2  $\Phi_{\text{Aux}}$  to  $\Phi_{\text{Main}}$
- 3 SHG Lock at  $\omega_{\text{Main}}$
- 4 MC Lock at  $\omega_{\text{Aux}}$



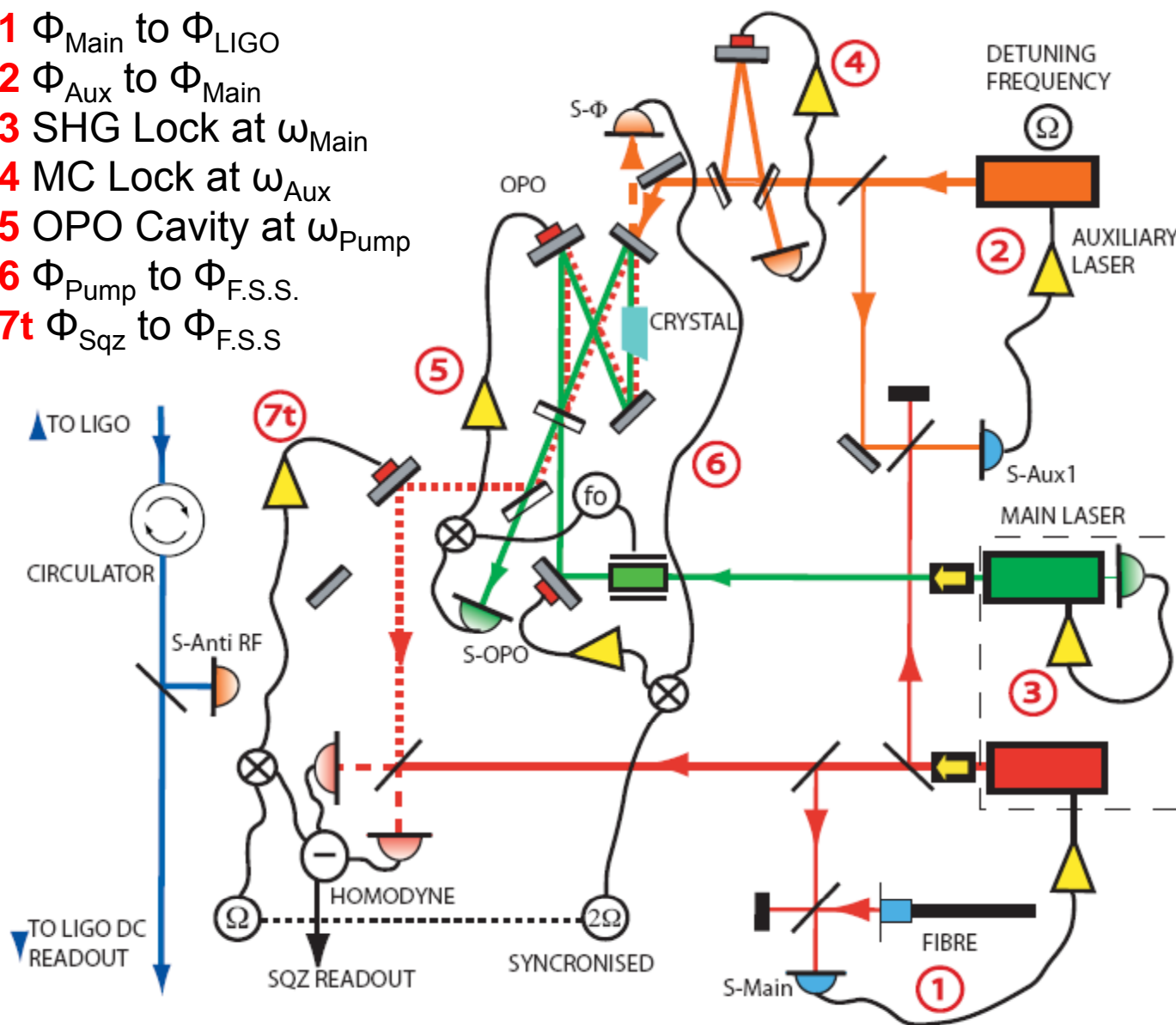
- 1  $\Phi_{\text{Main}}$  to  $\Phi_{\text{LIGO}}$
- 2  $\Phi_{\text{Aux}}$  to  $\Phi_{\text{Main}}$
- 3 SHG Lock at  $\omega_{\text{Main}}$
- 4 MC Lock at  $\omega_{\text{Aux}}$
- 5 OPO Cavity at  $\omega_{\text{Pump}}$



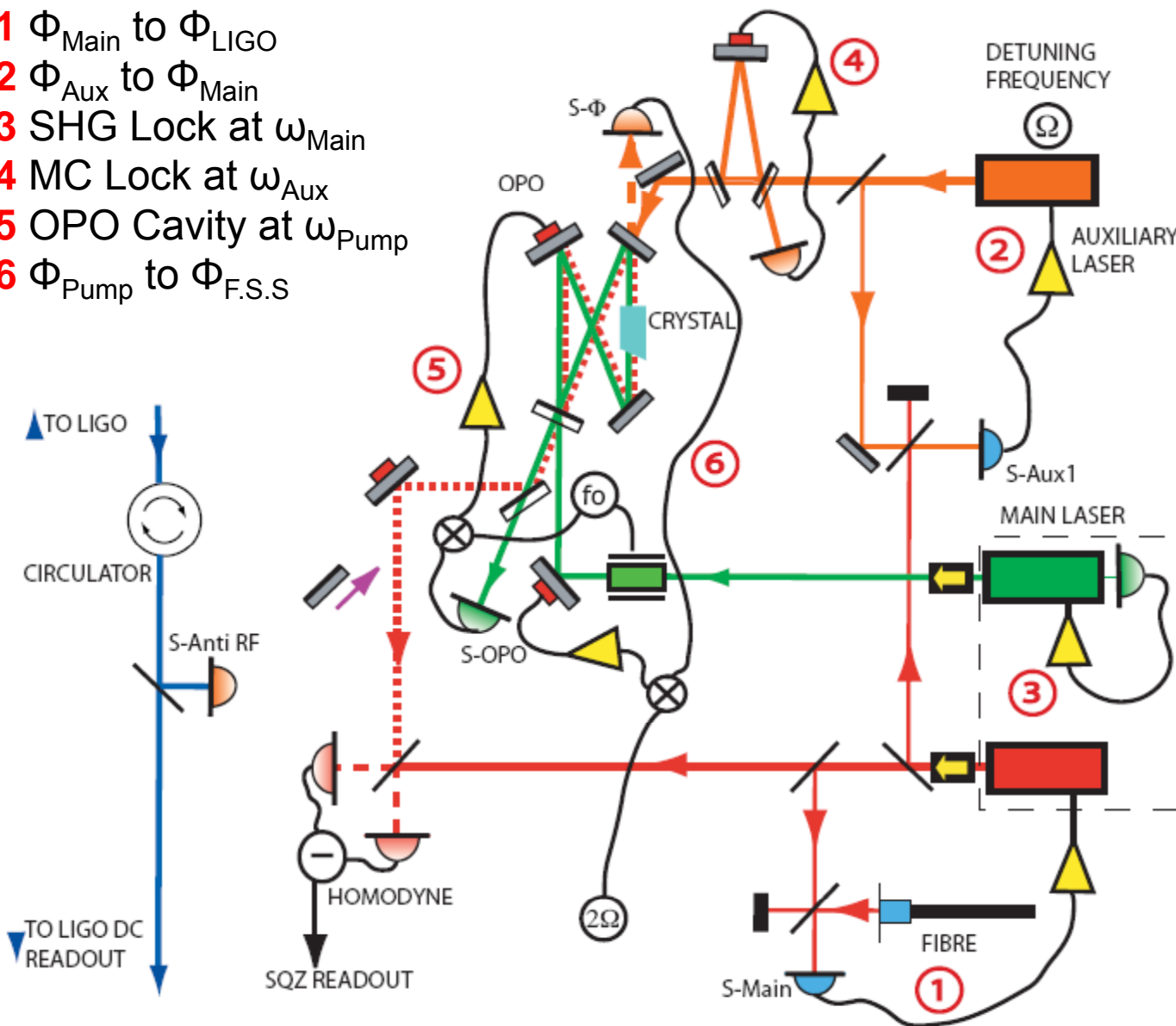
- 1  $\Phi_{\text{Main}}$  to  $\Phi_{\text{LIGO}}$
- 2  $\Phi_{\text{Aux}}$  to  $\Phi_{\text{Main}}$
- 3 SHG Lock at  $\omega_{\text{Main}}$
- 4 MC Lock at  $\omega_{\text{Aux}}$
- 5 OPO Cavity at  $\omega_{\text{Pump}}$
- 6  $\Phi_{\text{Pump}}$  to  $\Phi_{\text{F.S.S.}}$



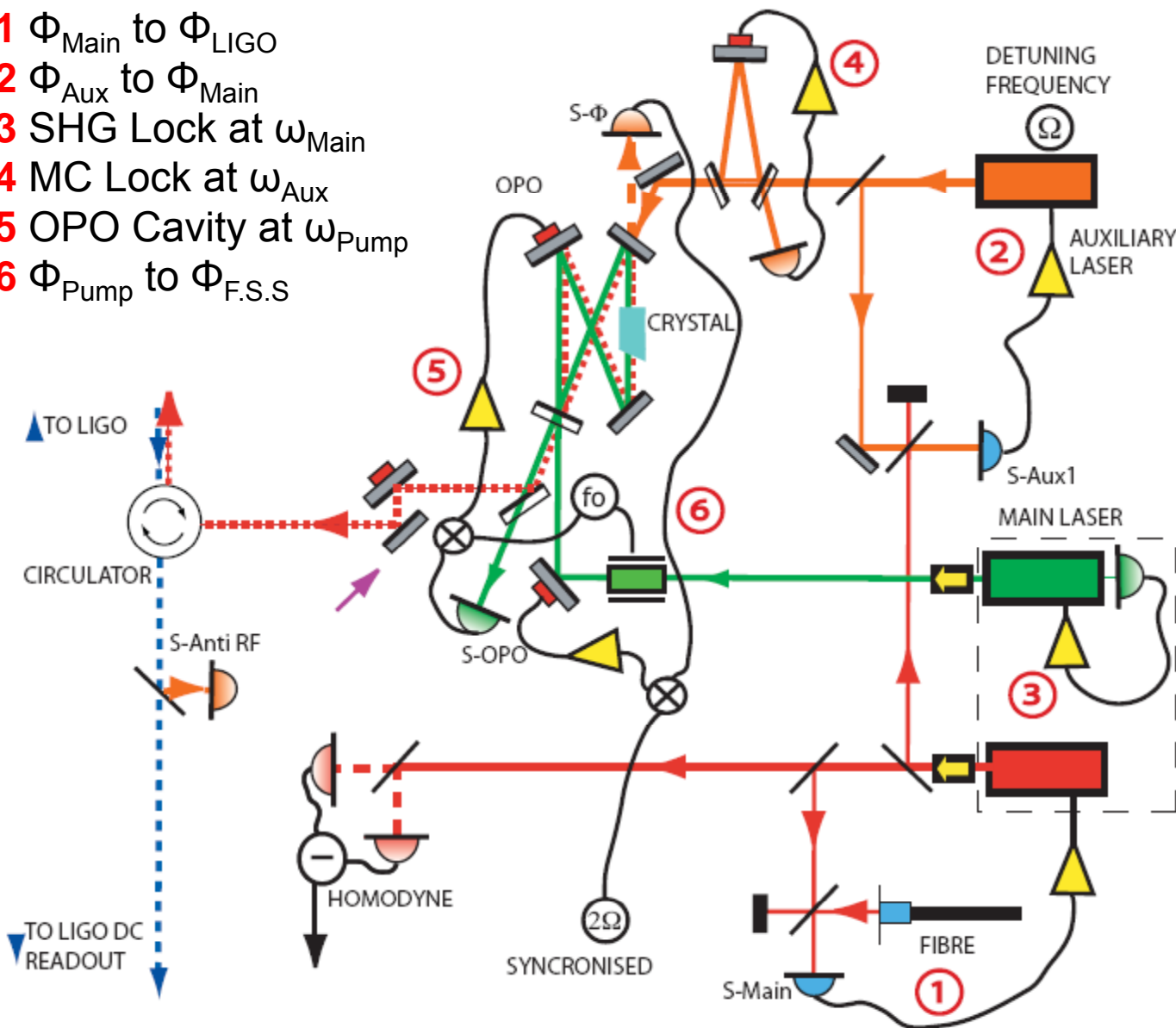
- 1  $\Phi_{\text{Main}}$  to  $\Phi_{\text{LIGO}}$
- 2  $\Phi_{\text{Aux}}$  to  $\Phi_{\text{Main}}$
- 3 SHG Lock at  $\omega_{\text{Main}}$
- 4 MC Lock at  $\omega_{\text{Aux}}$
- 5 OPO Cavity at  $\omega_{\text{Pump}}$
- 6  $\Phi_{\text{Pump}}$  to  $\Phi_{\text{F.S.S.}}$
- 7t  $\Phi_{\text{Sqz}}$  to  $\Phi_{\text{F.S.S.}}$

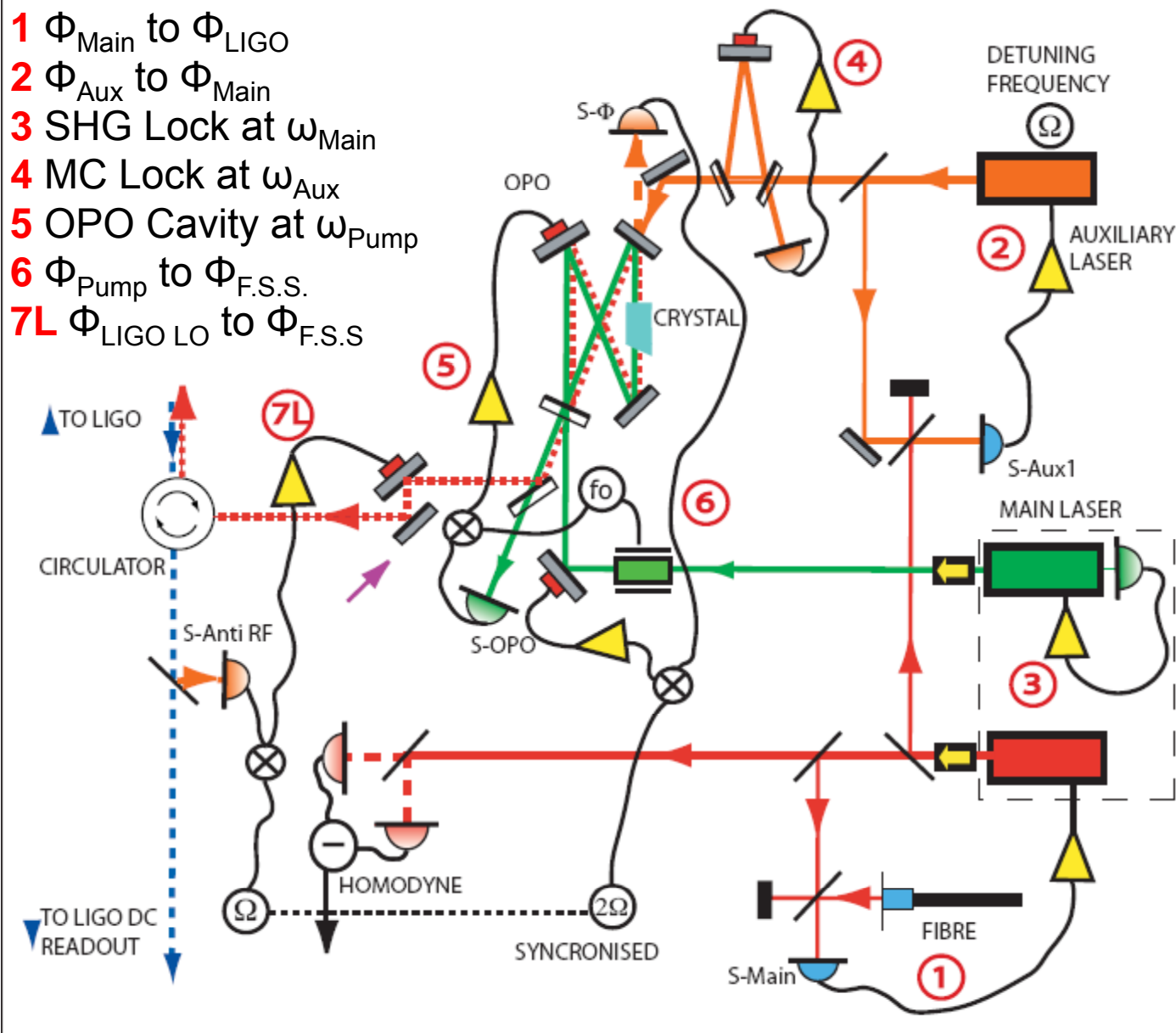


- 1  $\Phi_{\text{Main}}$  to  $\Phi_{\text{LIGO}}$
- 2  $\Phi_{\text{Aux}}$  to  $\Phi_{\text{Main}}$
- 3 SHG Lock at  $\omega_{\text{Main}}$
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- 5 OPO Cavity at  $\omega_{\text{Pump}}$
- 6  $\Phi_{\text{Pump}}$  to  $\Phi_{\text{F.S.S}}$



- 1  $\Phi_{\text{Main}}$  to  $\Phi_{\text{LIGO}}$
- 2  $\Phi_{\text{Aux}}$  to  $\Phi_{\text{Main}}$
- 3 SHG Lock at  $\omega_{\text{Main}}$
- 4 MC Lock at  $\omega_{\text{Aux}}$
- 5 OPO Cavity at  $\omega_{\text{Pump}}$
- 6  $\Phi_{\text{Pump}}$  to  $\Phi_{\text{F.S.S}}$





# H1 Squeezer Time Line



- ❑ Fixed start date for H1 experiment: 2/15/2011
- ❑ Fixed end date for H1 experiment: 10/3/2011

Better be ready!

# Plan

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- ❑ Setting up the lasers (MIT/LHO)
  - Critical path: building the electronics
  - Grad student from MIT
  - Electronics support from LHO
- ❑ Building and commissioning the OPO (ANU)
  - Grad student from ANU
  - Electronics support from LHO
- ❑ Characterization of the squeezer (ANU/LHO)
- ❑ Homodyne detector (AEI)
- ❑ Experiment at H1

# Person power

Item	Task	Time
Grad student (MIT)	Laser setup	1 FTE/3 years
Grad student (ANU)	OPO setup	1 FTE/3 years
Grad student (AEI)	Homodyne detector	2 months
Scientist	Organizational	$\frac{1}{4}$ FTE/3 years
LIGO scientist/EE	Electronics	$\frac{1}{2}$ FTE/2 years
Scientist/postdoc	H1 Experiment	8 months
Optical engineer	Faraday isolator	2 months
ANU scientist	OPO setup	A lot
Postdoc(?)	Support	$\frac{1}{2}$ FTE/3 years

# Budget

Task	Cost (k\$)
Optics	322
Electronics	121
Travel	59
ANU contribution	-13
AEI contribution	-3
Advanced LIGO contribution	-25
<b>Total without travel</b>	<b>418</b>
<b>Total with travel</b>	<b>477</b>
OPO technical risk	50



# Funding Profile (Rough Estimate)

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- ❑ Equipment costs

- 88% first year
- 10% second year
- 2% last year

- ❑ Salary

- 33% for each year

- ❑ Travel

- 40% first years
- 40% second year
- 20% third year