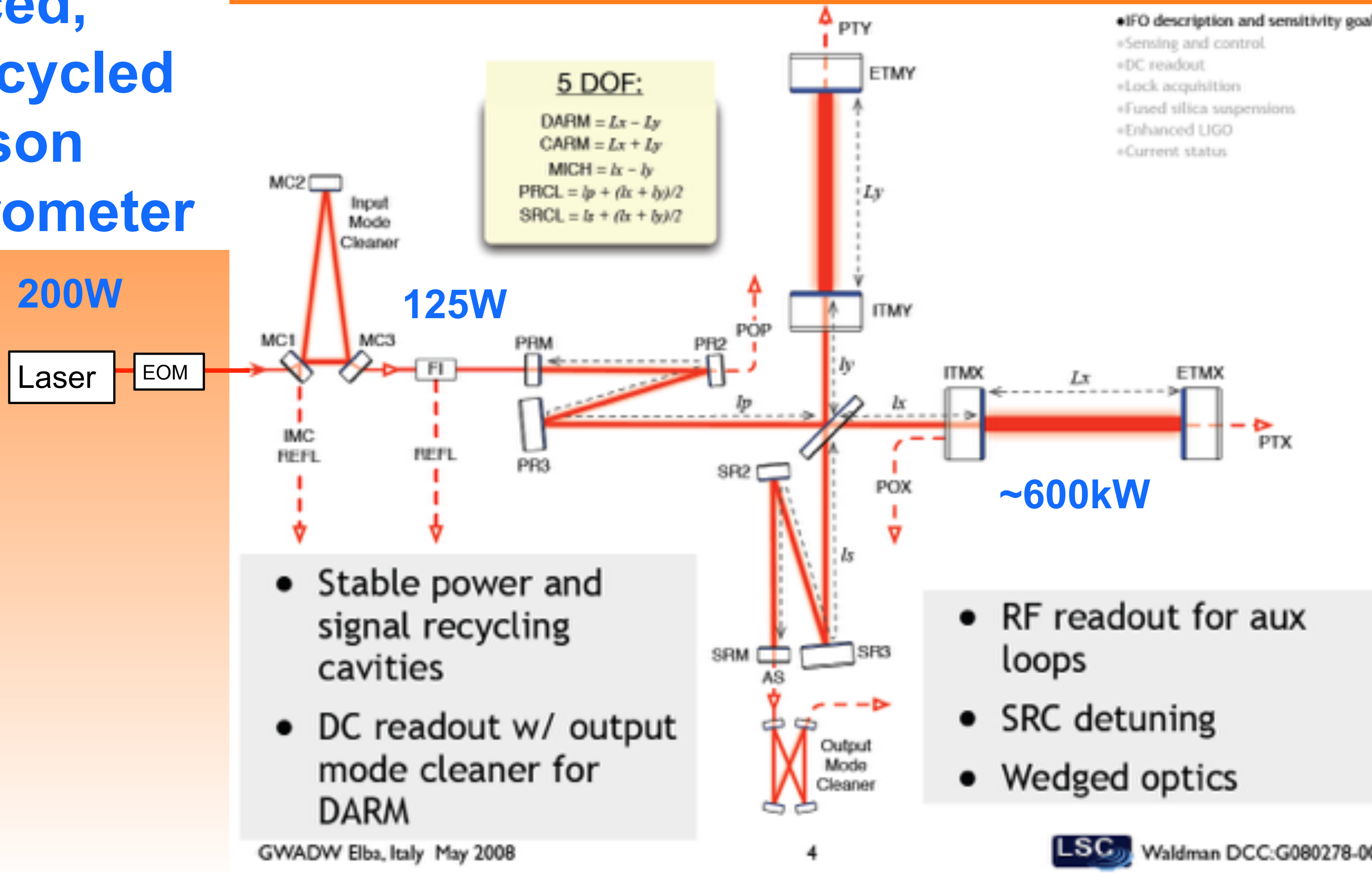
PSL Presentation at UF
September 4th, 2015
GM

Source Material:

- G1100452
- Optics Express, Vol 20(10), 10617 (2012)
- Dissertation presentation Jan Pöld (AEI, 2014)
- G1100837 (PSL Training Session, incl. movies)

Advanced LIGO

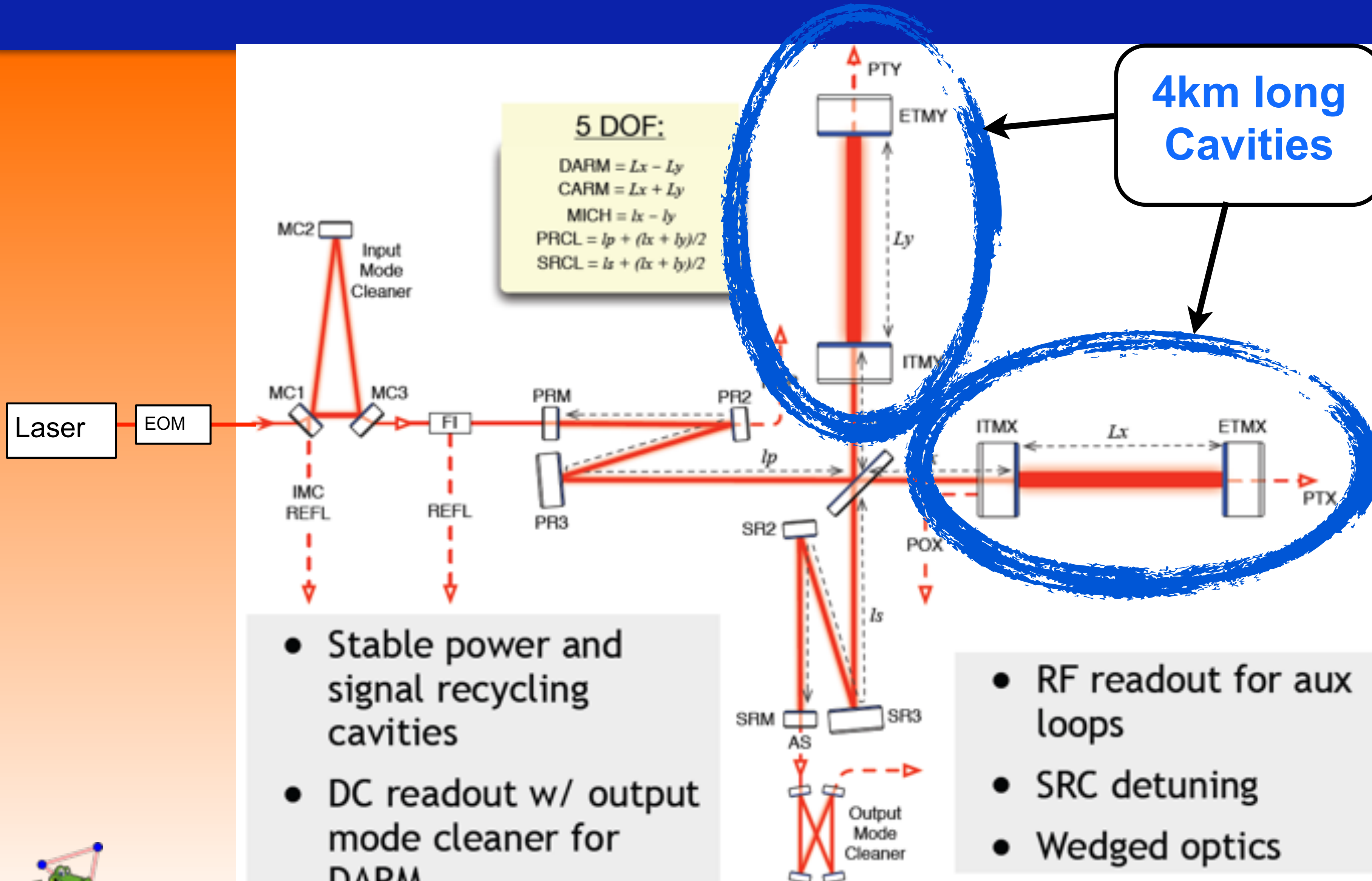
Cavity-enhanced, dual-recycled Michelson interferometer



- Stable power and signal recycling cavities
- DC readout w/ output mode cleaner for DARM

- RF readout for aux loops
- SRC detuning
- Wedged optics

Advanced LIGO



- Stable power and signal recycling cavities
- DC readout w/ output mode cleaner for DARM

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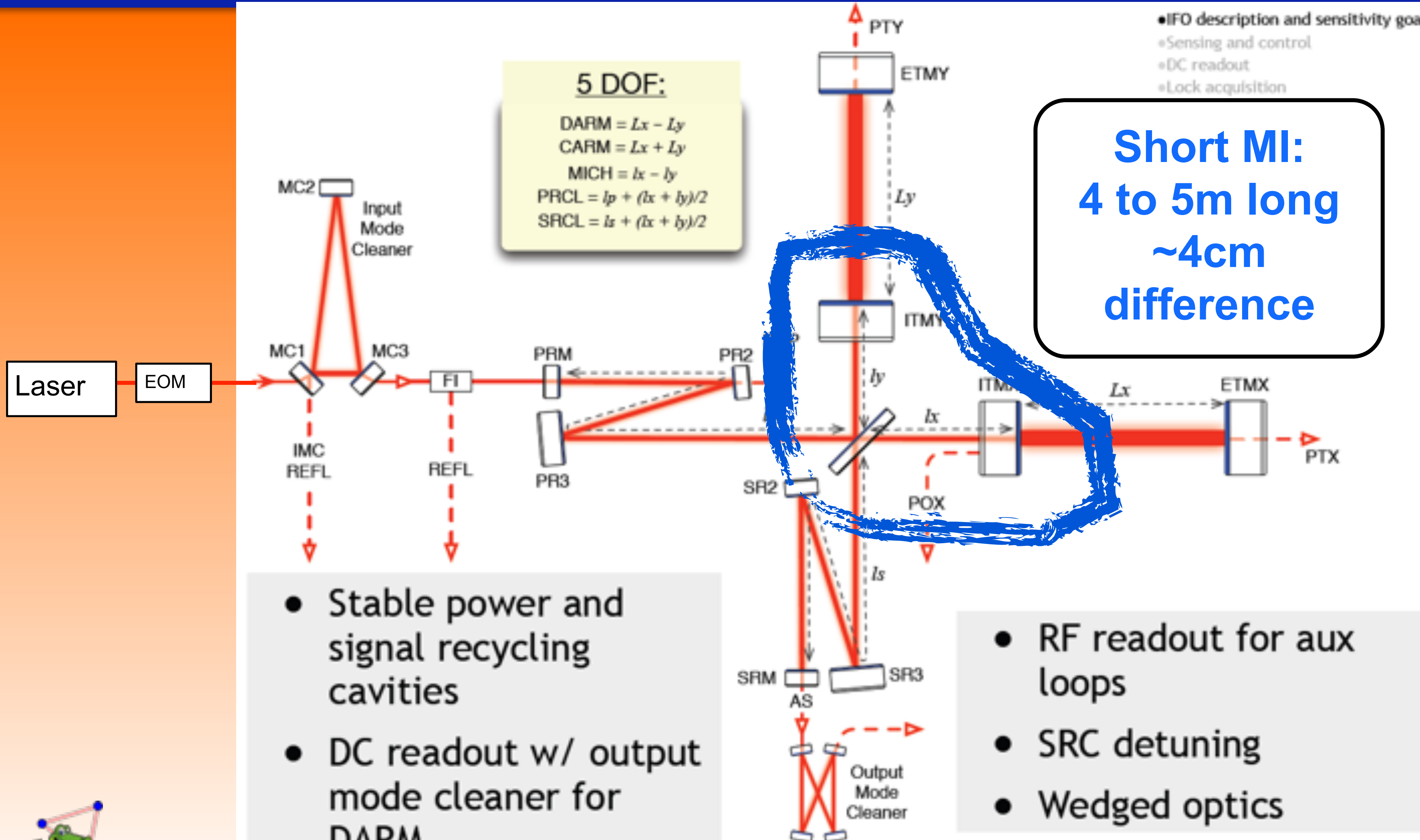
Advanced LIGO

•IFO description and sensitivity goals
•Sensing and control
•DC readout
•Lock acquisition



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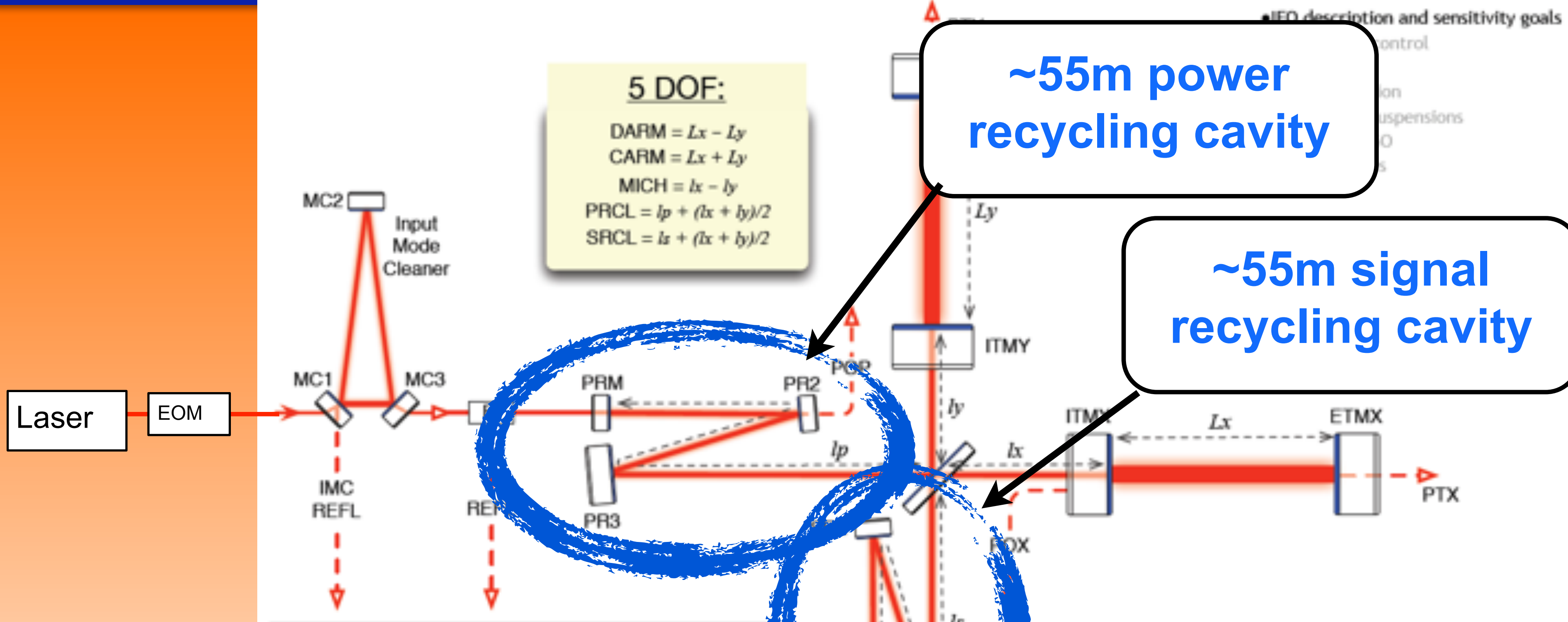
Advanced LIGO



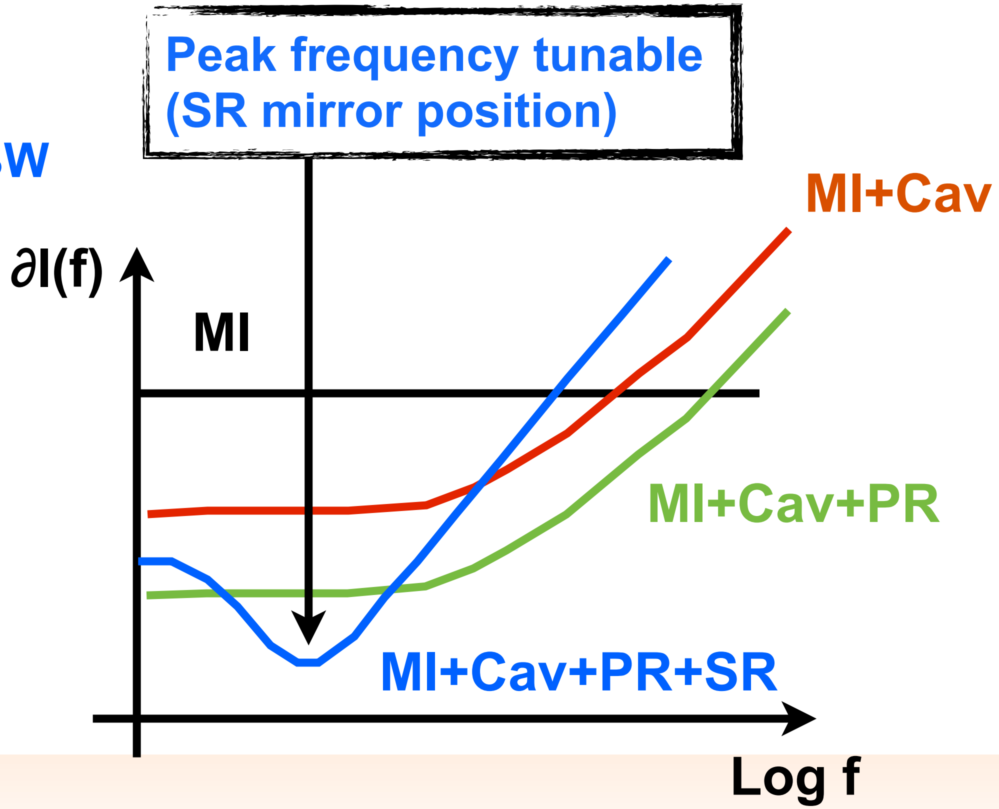
- Stable power and signal recycling cavities
- DC readout w/ output mode cleaner for DARM

- RF readout for aux loops
- SRC detuning
- Wedged optics

Advanced LIGO

Why this design?

- **MI:**
  - **optimum geometry (∂l-meter)**
  - **equal arms = common mode rejection of noise**
- **Cavities in arms**
  - **amplify phase shift**
    - **Trade-off between gain and BW**
- **Power Recycling**
  - **builds up power**
  - **cleans up mode**
- **Signal Recycling**
  - **builds up signal**
  - **Trade-off between gain and BW**



Advanced LIGO: Back on the envelope

Displacement Sensitivity:
Shot Noise only

$$P_{in} = 25W \quad N_{in} = 1.4 \cdot 10^{20} \frac{Ph}{s}$$

Power Recycling:

$$N_{PR} = \frac{1}{T_{PR}} N_{in} = \frac{N_{in}}{0.02} = 6.6 \cdot 10^{21} \frac{Ph}{s}$$

MI-Phase sensitivity:

$$\phi_{BS} = \frac{1}{\sqrt{N_{PR}}} = 1.2 \cdot 10^{-11} \frac{rad}{\sqrt{Hz}}$$

Arm cavity gain:

$$\phi_{cav} = \frac{T}{4} \phi_{BS} = 3.5 \cdot 10^{-14} \frac{rad}{\sqrt{Hz}}$$

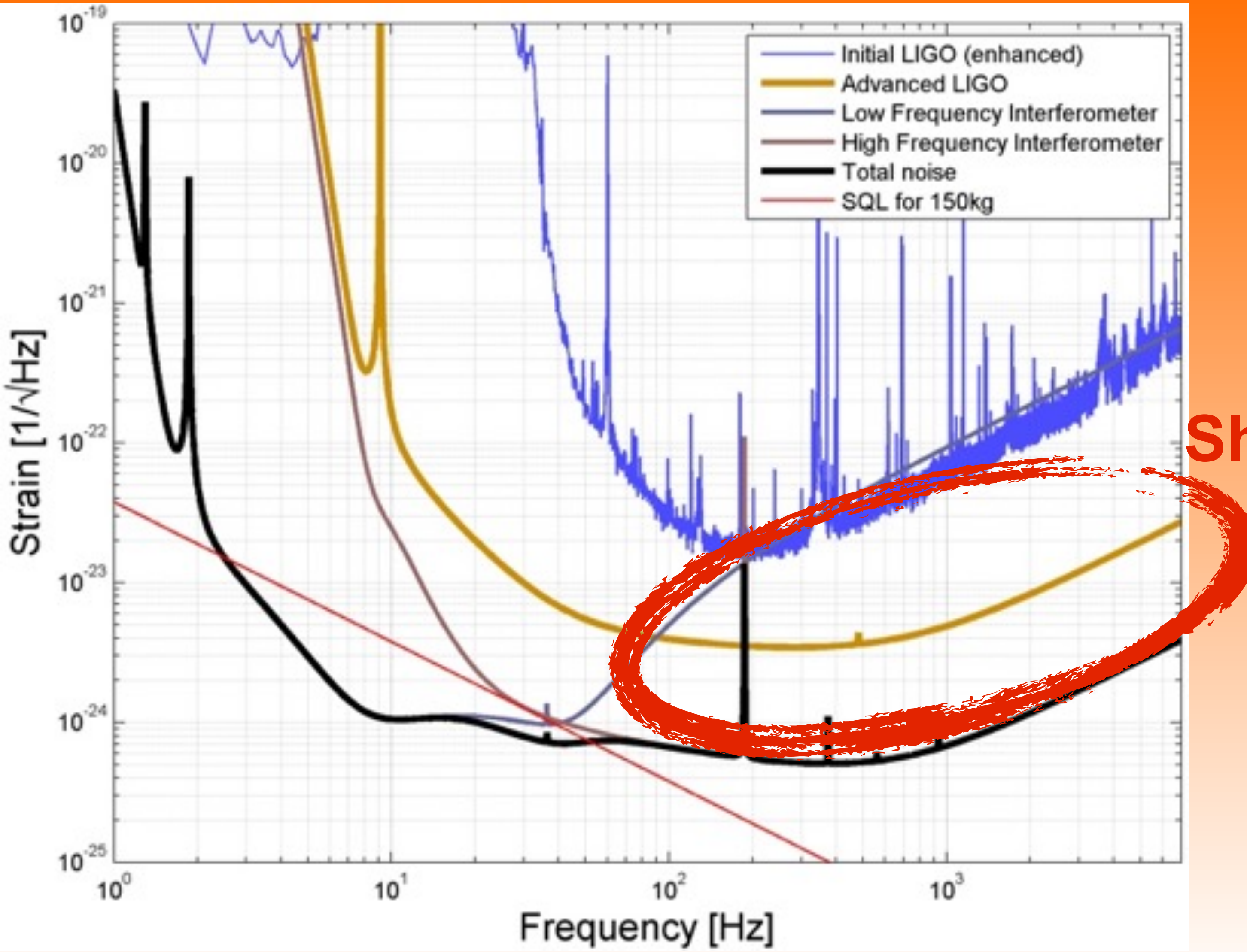
In length and strain:

$$h_{min} = \frac{\delta l}{L} = \frac{\phi_{cav}}{2\pi} \frac{\lambda}{L} = \frac{6 \times 10^{-21} m}{4000m} = \frac{1.5 \cdot 10^{-24}}{\sqrt{Hz}}$$

Low pass filter of cavity:

$$h_{min}(150Hz) = h_{min} \cdot 2 = \frac{3 \times 10^{-24}}{\sqrt{Hz}}$$

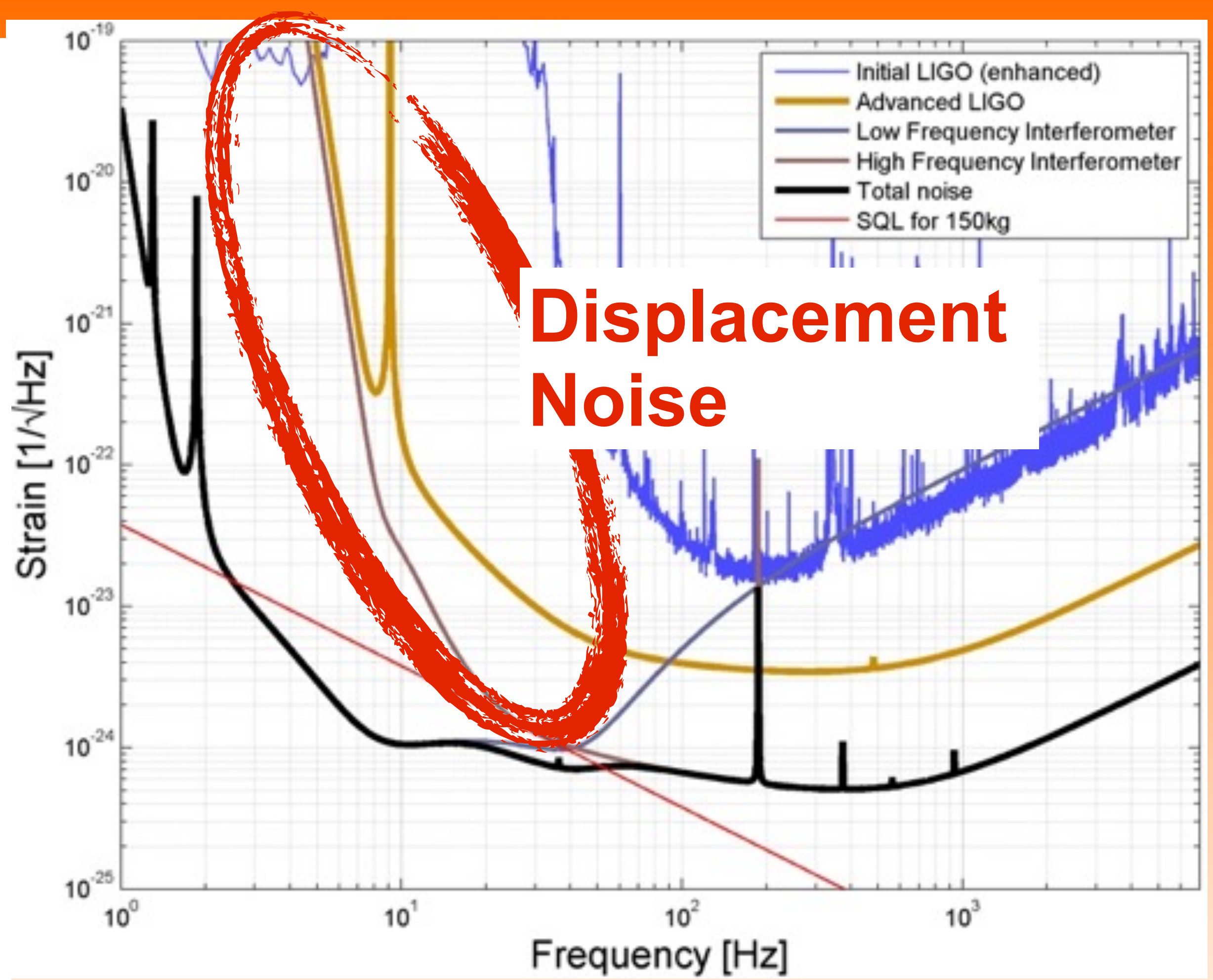
Advanced LIGO: Back on the envelope



Advanced LIGO: Back on the envelope

Displacement Noise:

- Seismic motion
- Environmental vibrations
- Thermal noise
  - Coating
  - Substrate
  - Suspension
- Radiation Pressure Noise
  - Fundamental (Quantum)
  - Technical
    - Unbalanced Arms
- Newtonian or Gravity gradient noise

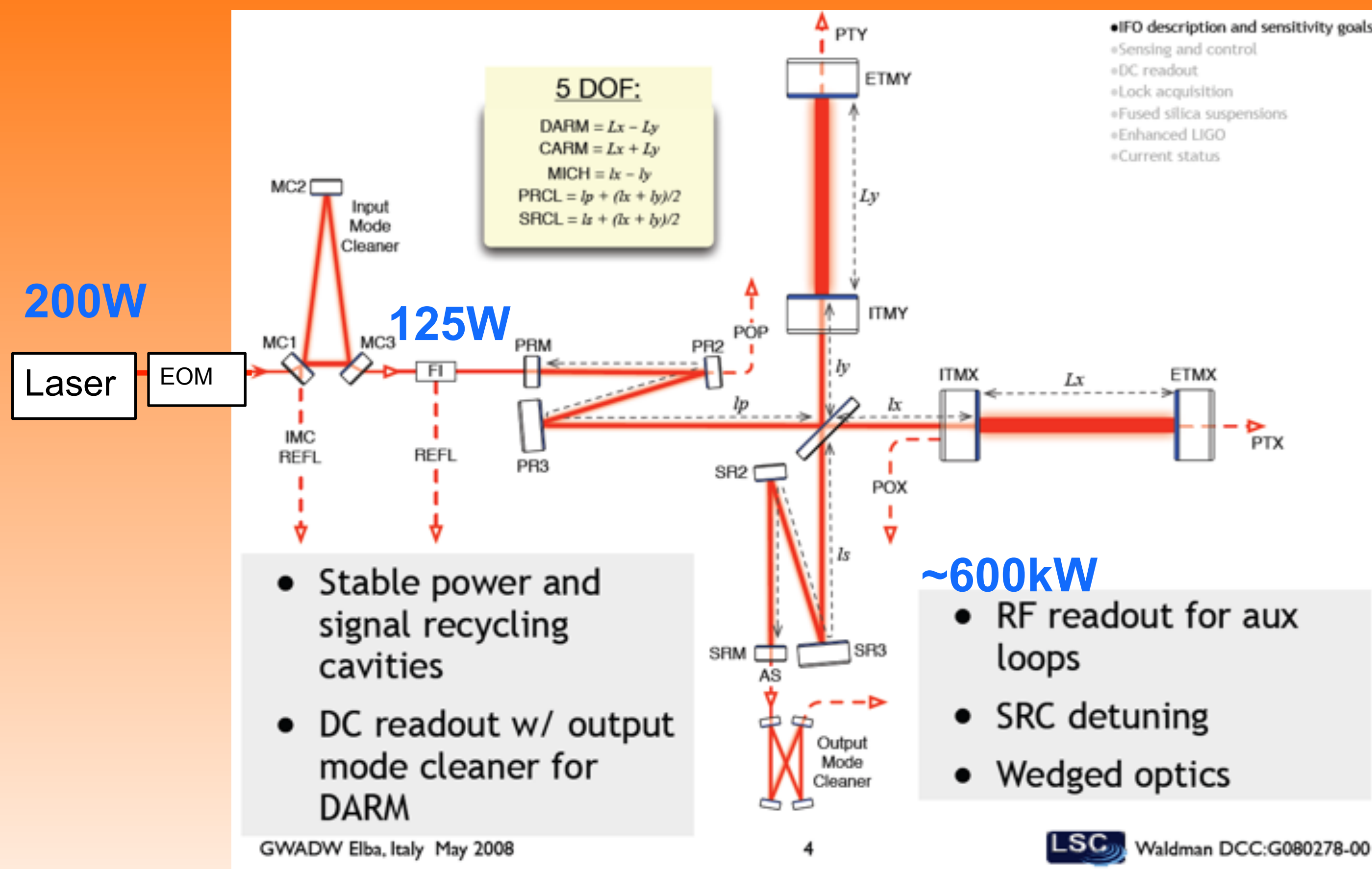


$$a \leq 2 \times 10^{-15} \frac{\text{m}}{\text{s}^2\sqrt{\text{Hz}}}$$

Advanced LIGO

Key systems:

- PSL
- IO
- Core Optics
- Suspensions
- SEI
- Main IFO
  - Mode matching
  - ISC, ASC
- Output Optics
- TCS
- AOS
- Photon calibrator
- …



PSL

PSL: Prestabilized Laser System

Designed, developed, tested, installed by Albert Einstein Institute, Hannover, Germany

Development Lead: Benno Willke
PSL-Lead at project-level: Peter King
PSL-Officer at LLO: Matt Heintze

PSL

Requirements:
- Stand alone Laser system
- Stabilized system

Requirement flow down:
- Top level:
  - 125W TE00 injected into IFO spatial mode
    - < 5W in higher order modes as defined by IFO
      - Saturates detectors
      - Creates stray light

PSL

Requirements:

- Stand alone Laser system
- Stabilized system

Requirement flow down:

- Top level:
  - 125W TE00 injected into IFO spatial mode
  - Laser frequency noise relative to CARM

$$\frac{\delta\nu}{\nu} \approx h \times (CARM \rightarrow DARM) \approx \frac{10^{-22}}{\sqrt{\mathrm{Hz}}}$$

$$\delta\nu \approx 3 \times 10^{-8} \frac{\mathrm{Hz}}{\sqrt{\mathrm{Hz}}}$$

relative to CARM

PSL

Requirements:

- Stand alone Laser system
- Stabilized system

Requirement flow down:

- Top level:
    - 125W TEM00 injected into IFO spatial mode
    - Laser frequency noise relative to CARM
    - Laser Amplitude noise = Relative Intensity Noise (RIN)

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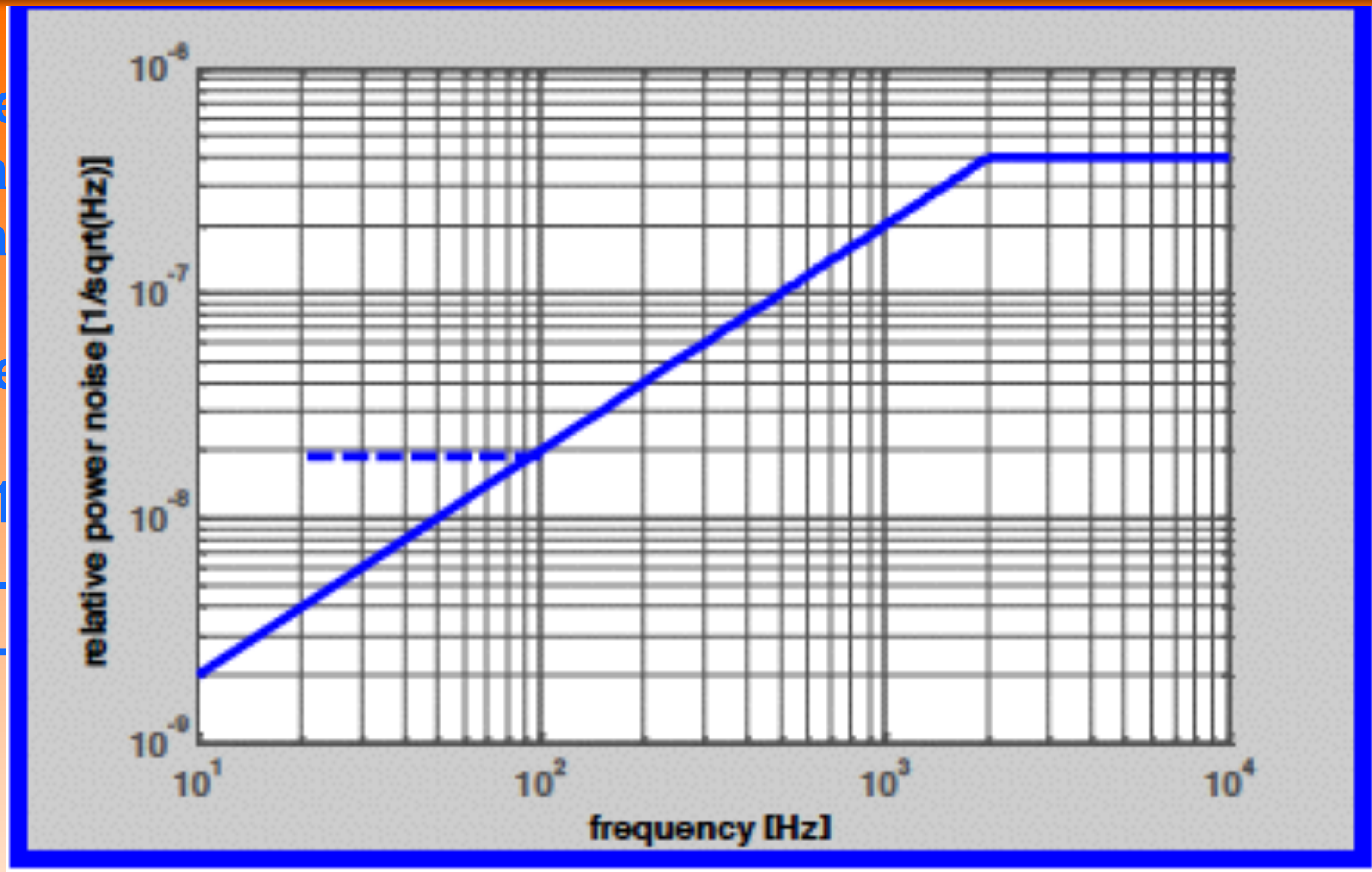


measured at input of IFO at 125W input power

PSL

Requirements:

- **Stand alone Laser system**
- **Stabilized system**

Requirement flow down:

- **Top level:**
  - **125W TE00 injected into IFO spatial mode**
  - **Laser frequency noise relative to CARM**
  - **Laser Amplitude noise = Relative Intensity Noise (RIN)**
  - **Beam pointing = beam jitter**
    - **Maintain alignment into IFO (active or passive)**

$$\tilde{a}_{10}^{\mathrm{max}}(f) \leq \frac{7\cdot 10^{-10}}{\sqrt{\mathrm{Hz}}}\sqrt{1+\left(\frac{230\,\mathrm{Hz}}{f}\right)^4}\left(\frac{10^{-8}\mathrm{rad}}{\Delta\Theta_{\mathrm{ITM}}}\right)$$

$$a_{10} = \frac{\delta x}{\omega} + i\frac{\delta\alpha}{\Theta}$$

PSL

Requirements:

- Stand alone Laser system
- Stabilized system

Requirement flow down:

- Top level
- ‘Propagate’ back through IO to PSL
  - IO filters Laser noise
    - reduces requirements of stand-alone laser
- IFO and IO provide control signals to suppress laser noise
  - Requires appropriate actuators within PSL (and IO)

PSL

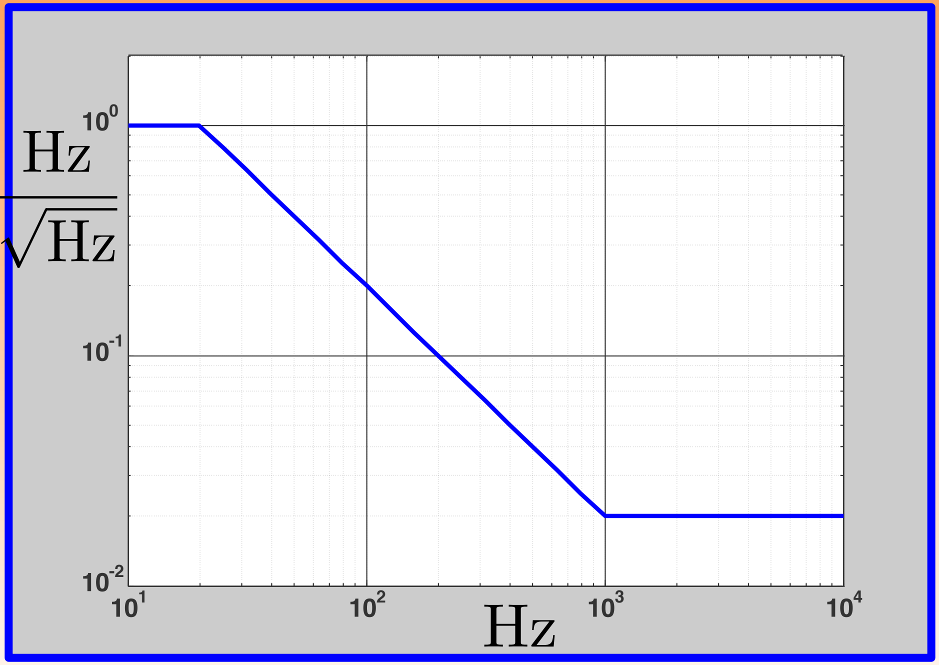
Requirements:

- **Stand alone Laser system**
  - **Power output: Deliver 165W TEM00 to IO**
  - **<5% of power in higher order modes**

PSL

Requirements:

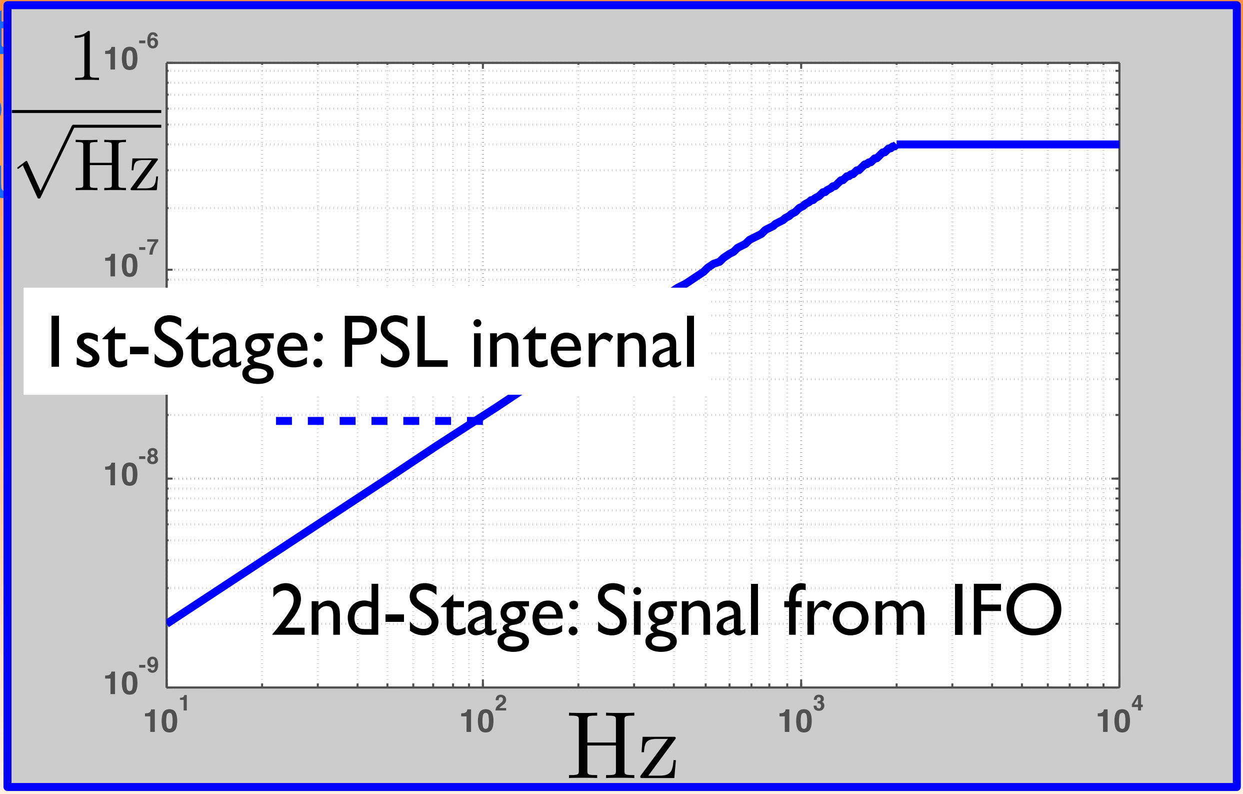
- Stand alone Laser system
  - Power output: Deliver 165W TEM00 to IO
  - <5% of power in higher order modes
  - laser frequency noise



PSL

Requirements:

- **Stand alone Laser system**
  - **Power out**
  - **<5% of po**
  - **laser frequ**
  - **RIN**

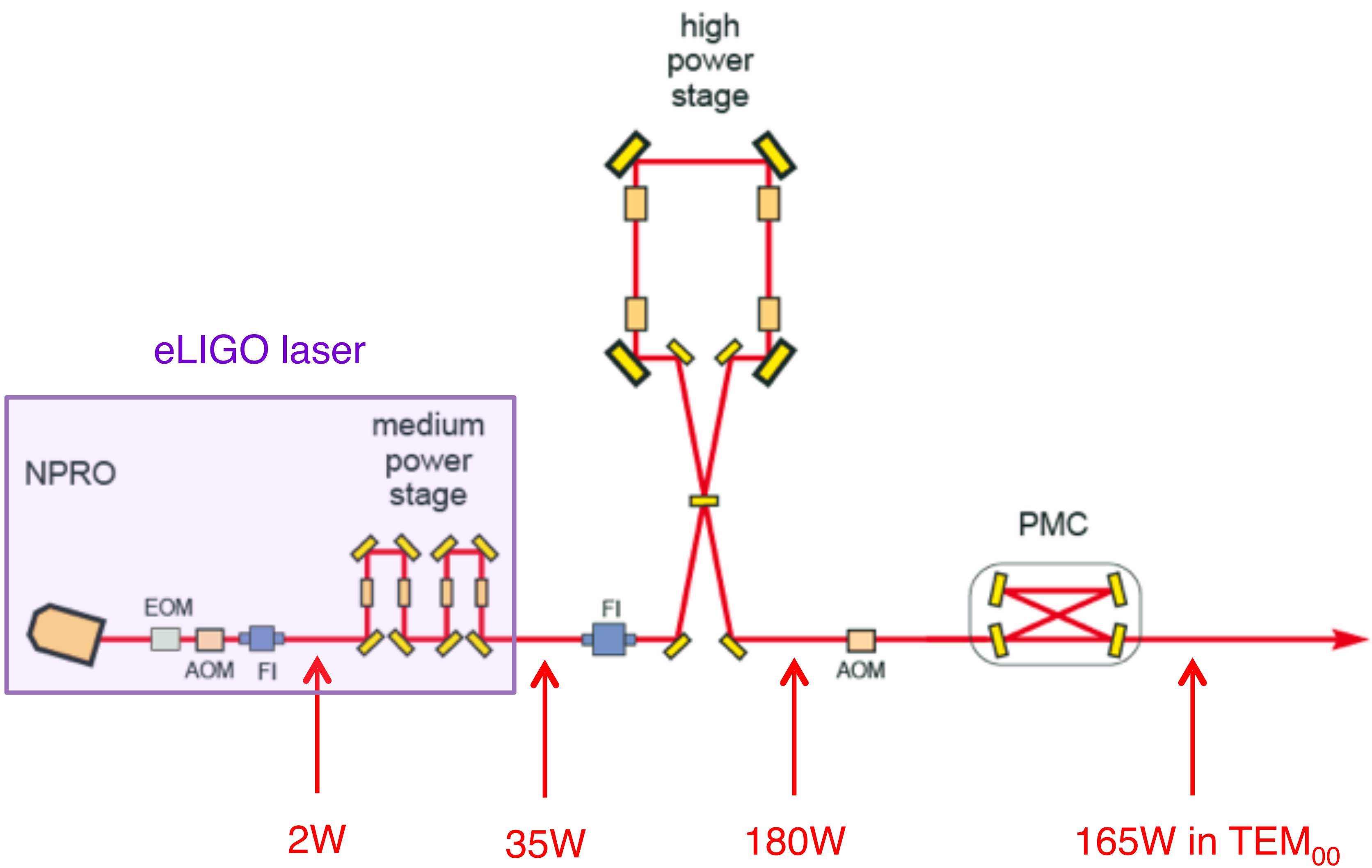


PSL

Requirements:

- Stand alone Laser system
  - Power output: Deliver 165W TEM00 to IO
  - <5% of power in higher order modes
  - laser frequency noise
  - RIN
  - Laser frequency drift: < 100kHz over 100s
  - Laser power drift: < 5% over 24h

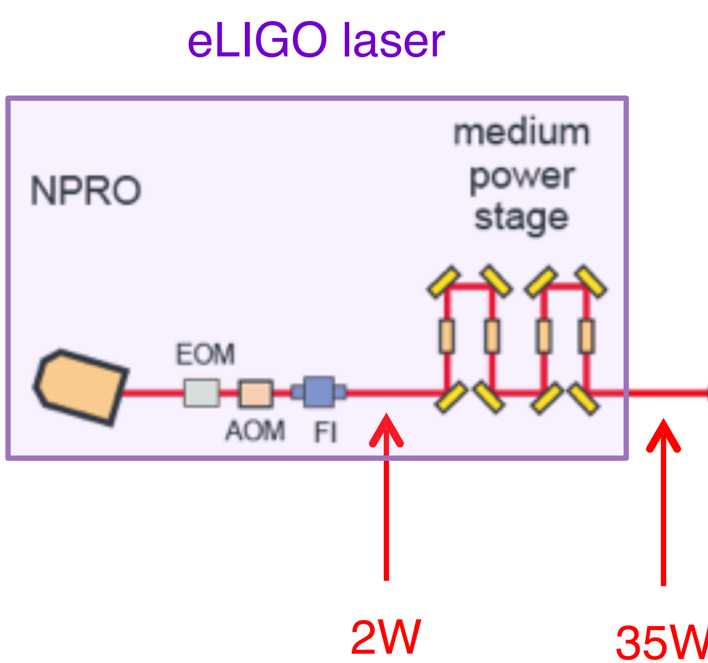
advanced LIGO laser - layout

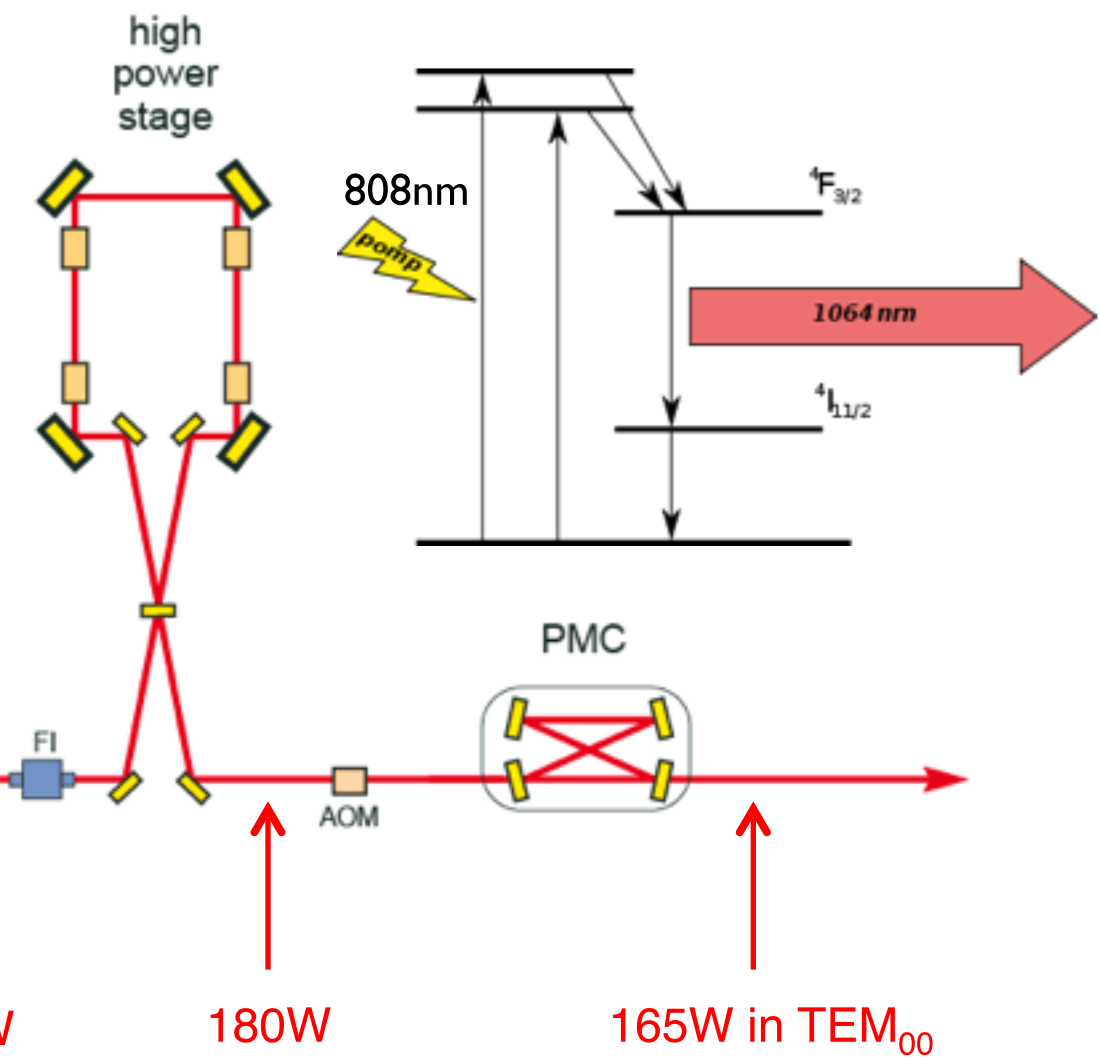


advanced LIGO laser - layout

NPRO: Non-planar ring oscillator

- Ultra-stable master (passive)
- Laser crystal: Nd:YAG
- Diode laser pumped (808nm)
- ~10kHz/rtHz @ 1Hz
- Same lasers we have in lab!





advanced LIGO laser - layout

EOM:

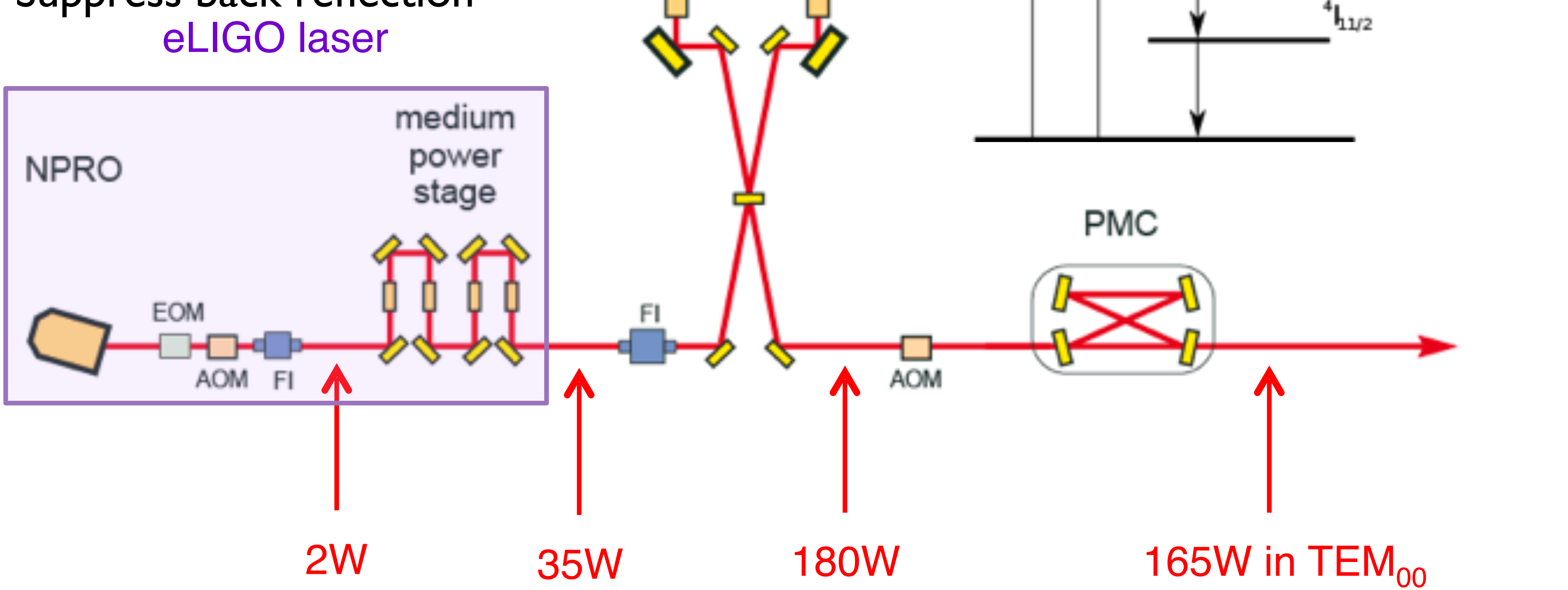
- Phase modulation
- Phase correction

AOM:

- Power stabilization

FI:

- Suppress back reflection

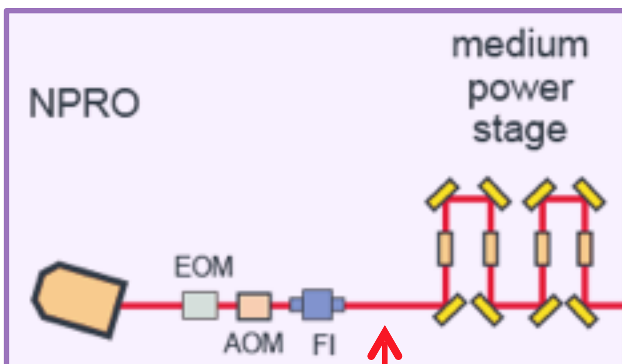


LIGO

eLIGO laser

high

eLIGO laser



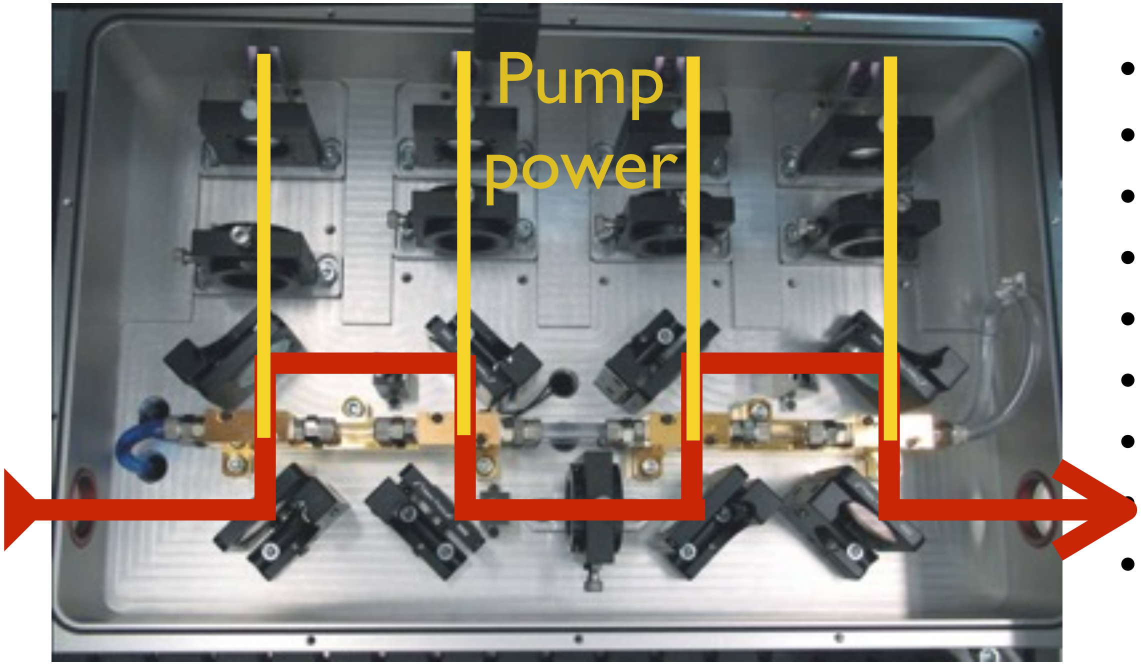
2W

35W

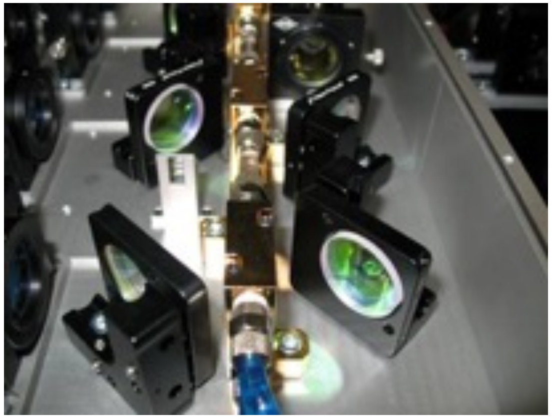
180W

165W in TEM_{00}

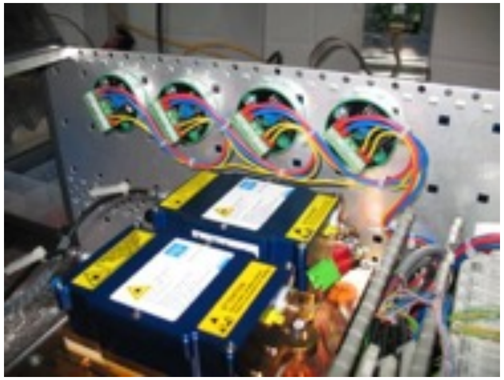
eLIGO Laser System



- 4 stage Nd:YVO_4
- water cooled
- fiber coupled pump diodes
- pump power 4 x 32 W
- seed power 1.7 W
- output power 35 W
- pump light pickups
- laser pickups
- temperature monitoring



Diode Box



- 4 pump diodes
- water cooled heat sink
- temperature interlocks
- diode power supplies
- peltier driver boards with power supply
- Beckhoff interface

Pump diodes located in different room. Fiber coupled

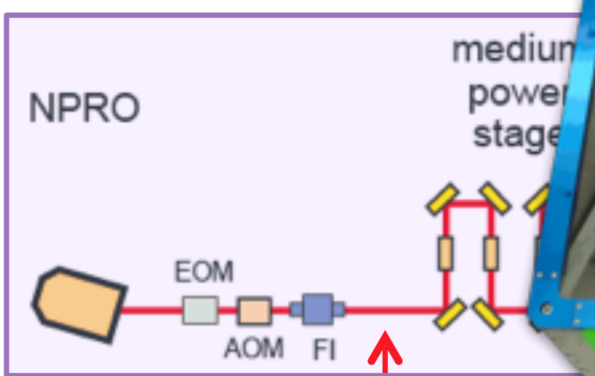
LIGO

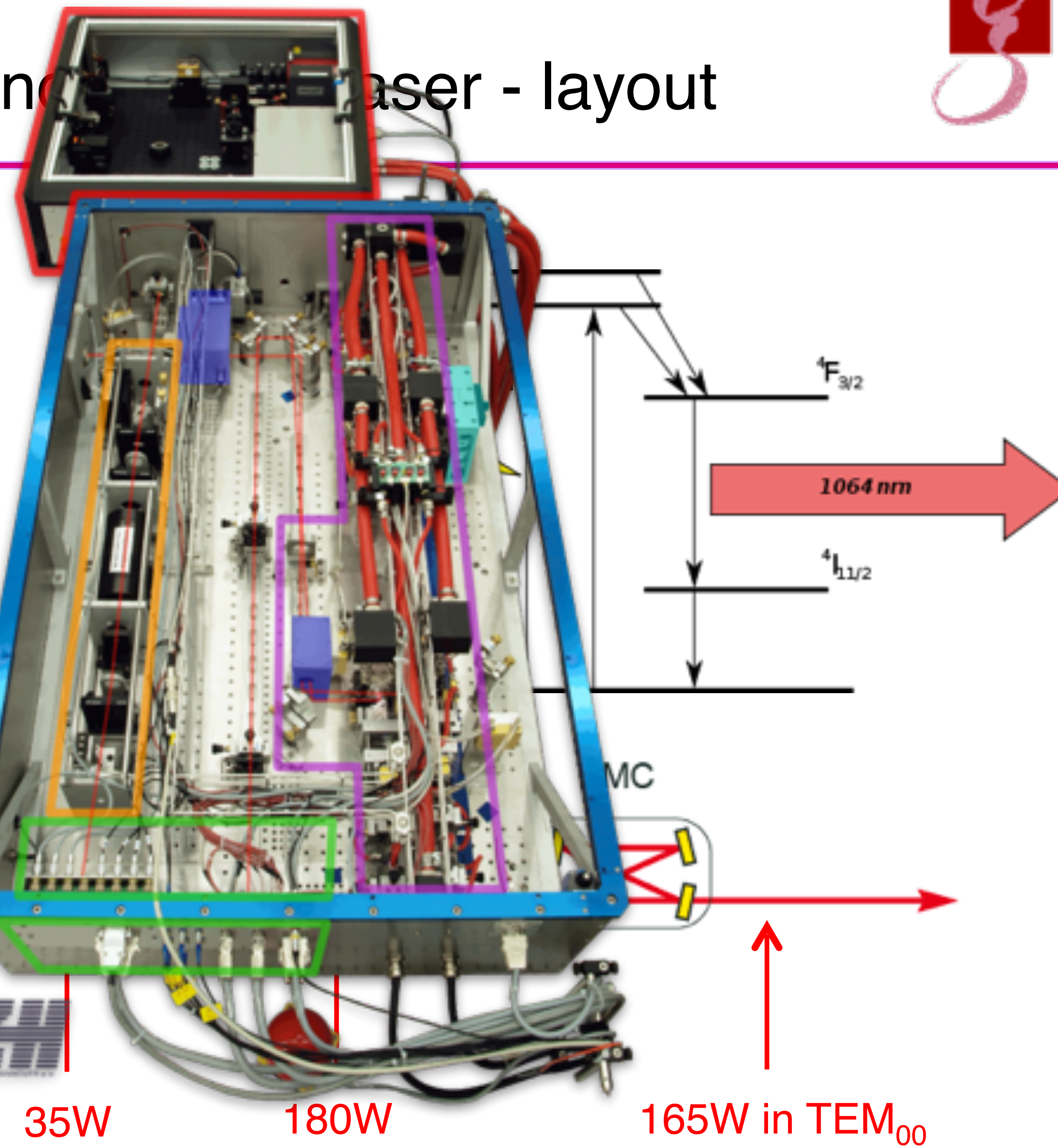
advanc… aser - layout

EOM:
- Phase modulation
- Phase correction

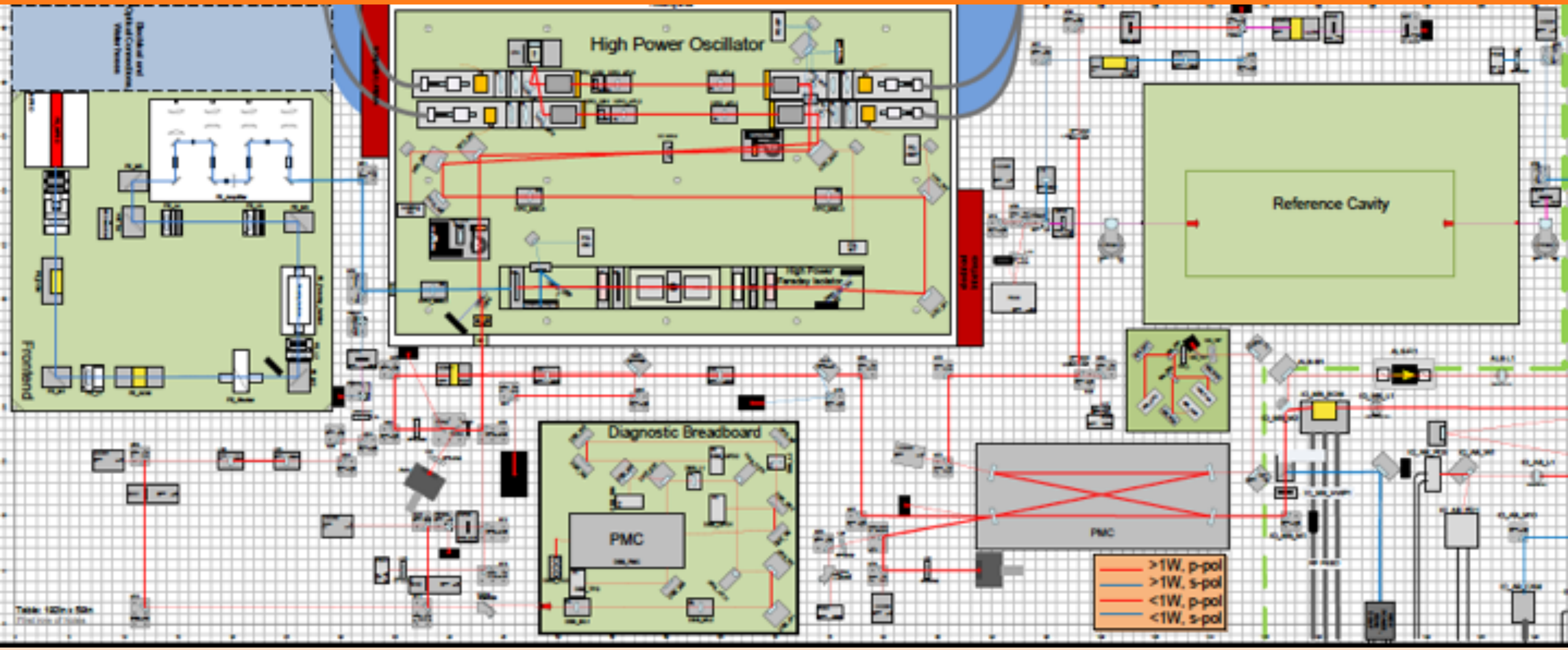
AOM:
- Power stabilization

FI:
- Suppress back reflection

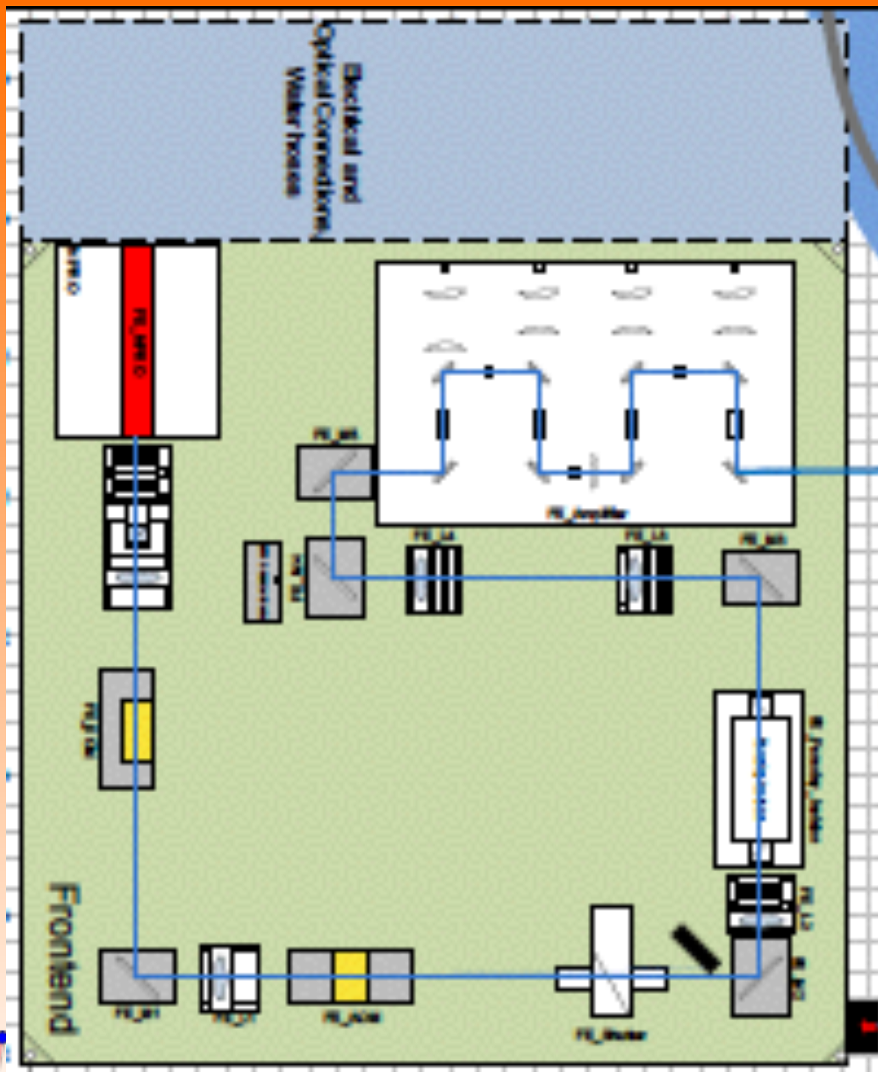




PSL


High Power Oscillator
Reference Cavity
Frontend
Diagnostic Breadboard
PMC
PMC
>1W, p-pol
>1W, s-pol
<1W, p-pol
<1W, s-pol

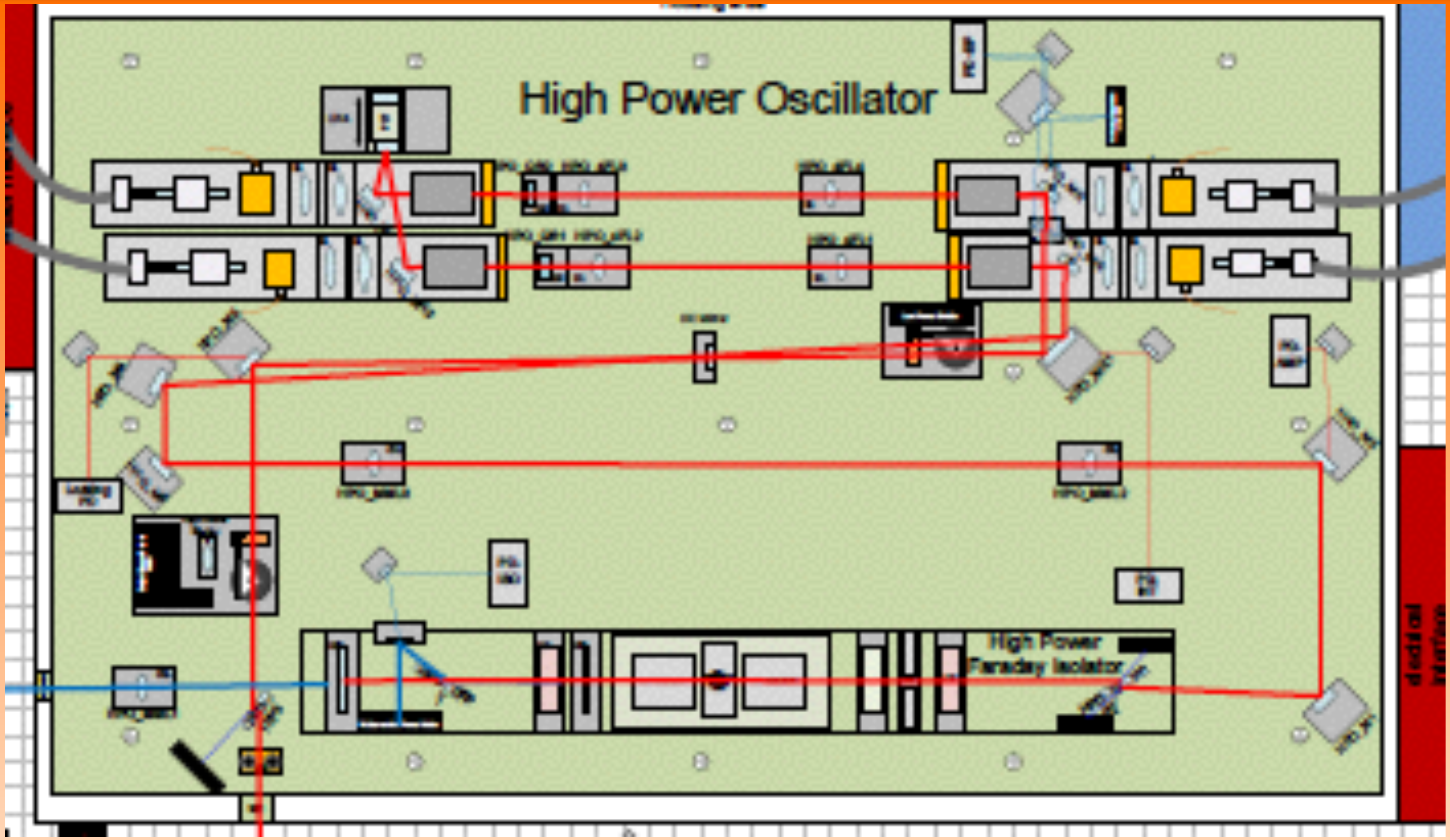
PSL



eLIGO Laser =
aLIGO front end

Nd:YVO4 crystals pumped by 808nm diode lasers

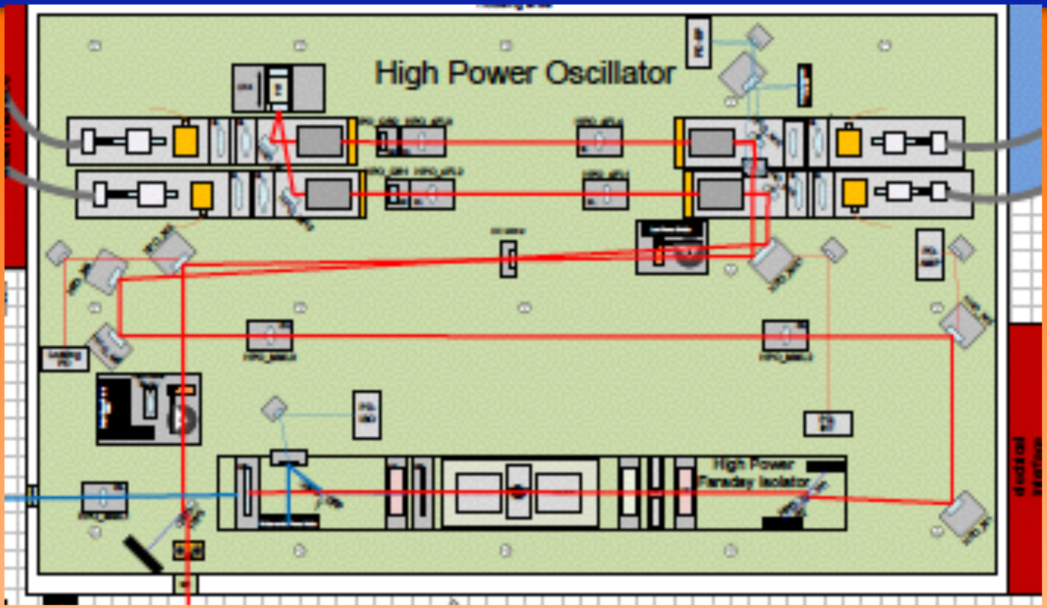
PSL



Injection locked ring laser, forced to emit on the injected laser frequency

- laser frequency identical to master laser
- Pumped by four ~200W diode laser arrays, fiber coupled

PSL



Ring laser:

- ‘Point’ design. Requires certain pump power to create thermal lens in Nd:YAG rods to stabilize laser resonator.
- Water-cooled

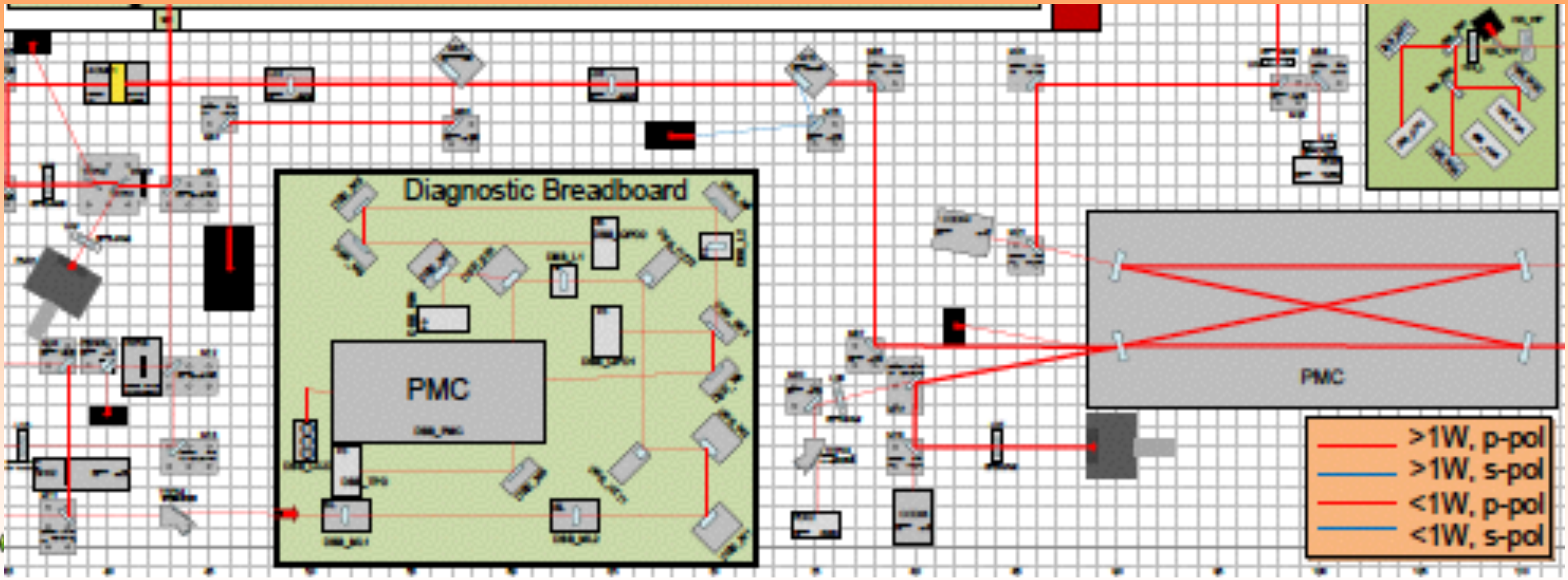
Laser system can only operate at full power

- Current low power operation (25W input at PRM) works w/o high power oscillator (slave laser)!

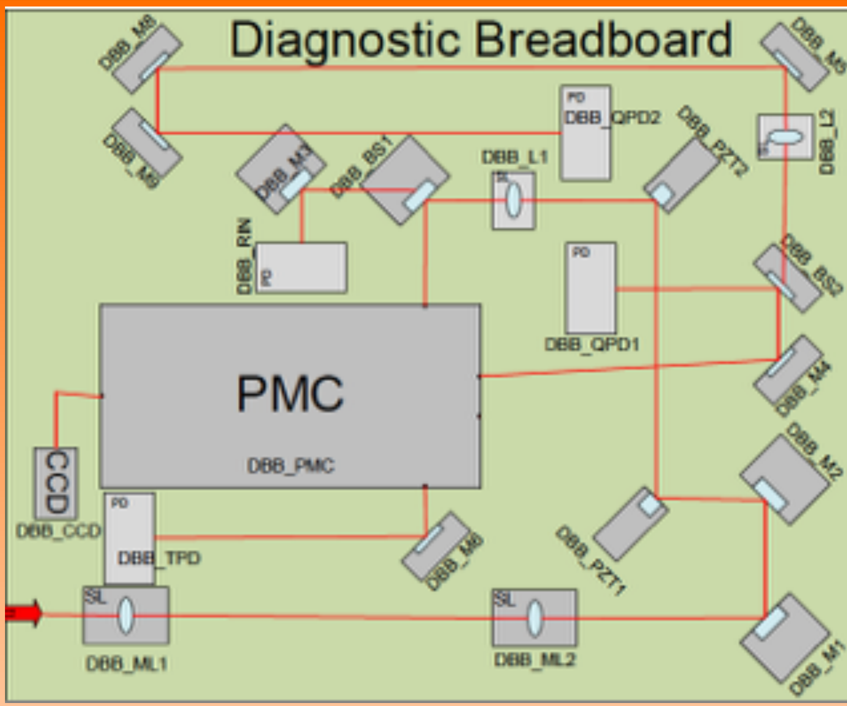
PSL

Auxiliary parts of PSL:

- Diagnostic Breadboard (see Paul for details)
- Pre-mode cleaner: Bow tie cavity to spatially filter laser field
- 1st Stage intensity stabilization system (ISS)
  - Sensor prior to Input Optics!!



PSL

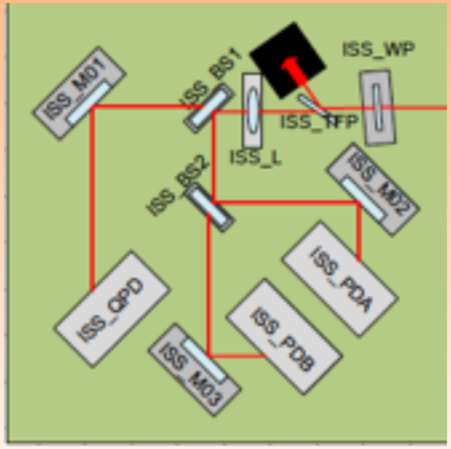


DBB:
Mode Analyzer Cavity
Power monitor
Pointing monitor (QPD1&2)

- with respect to PMC

ISS:

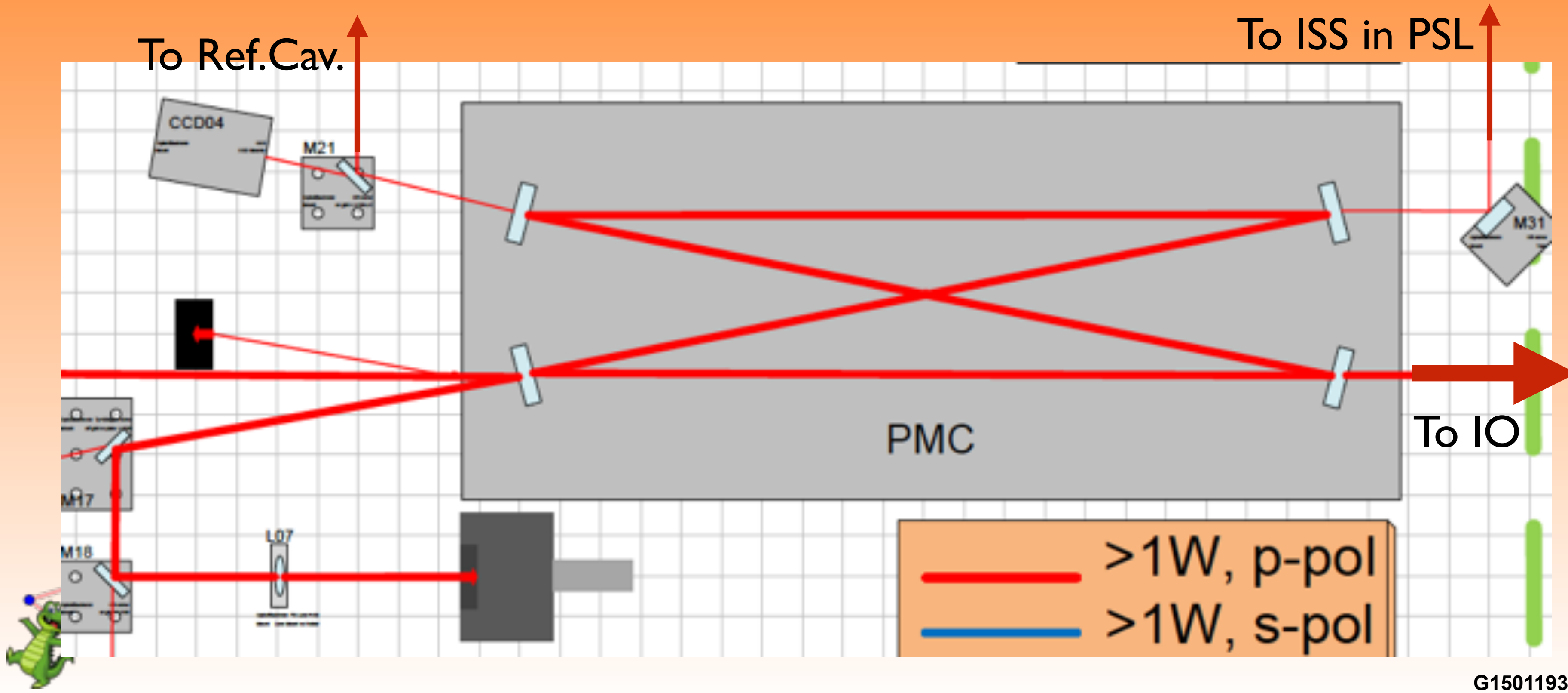
- PDA: Creates error signal
- PDB: Out of loop signal
- QPD to maintain alignment
  - PD sensitivity depends on position on active element



PSL

High power laser beam:

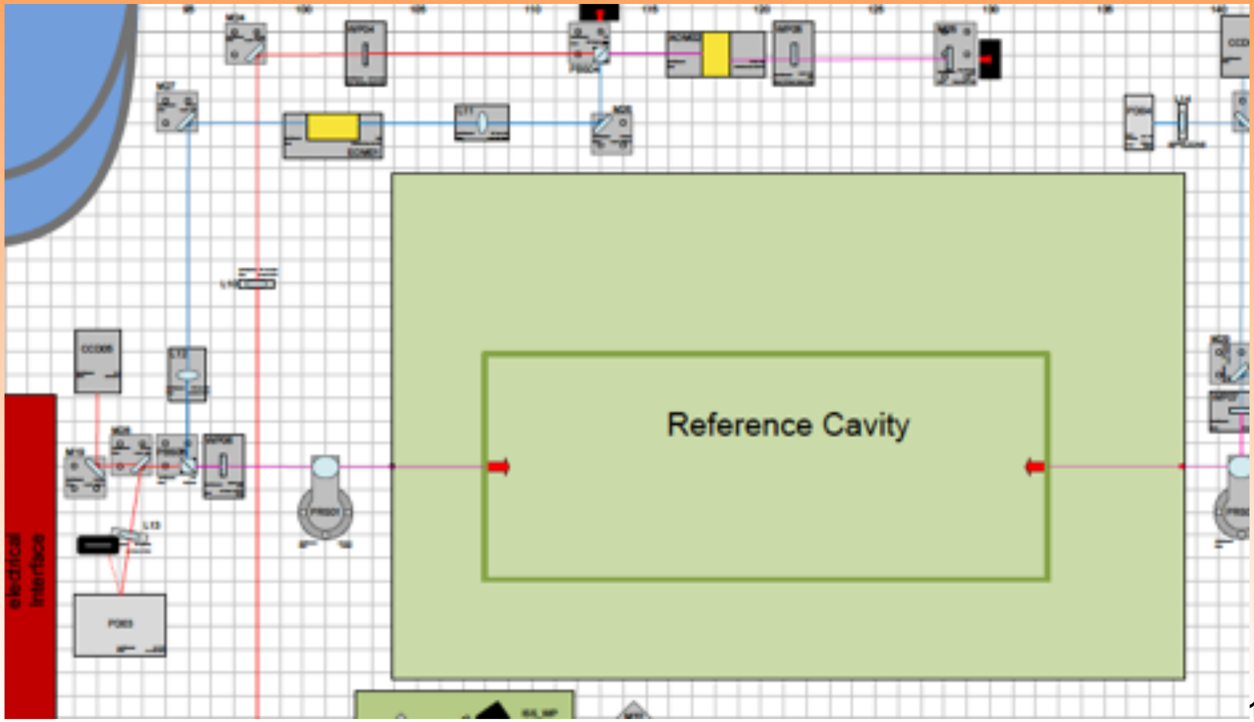
- Fairly bad spatial mode quality (thermal distortions …)
  - incl. beam jitter
- Pre-Mode Cleaner (PMC) filters spatial distortions
  - Locked to laser frequency via PDH signal



PSL

Reference Cavity:

- Glass cavity in thermally isolated vacuum tank
- 1st Frequency stabilization system
- Offset lock:
  - SB generated in AOM, locked to cavity
  - Sideband frequency tunable

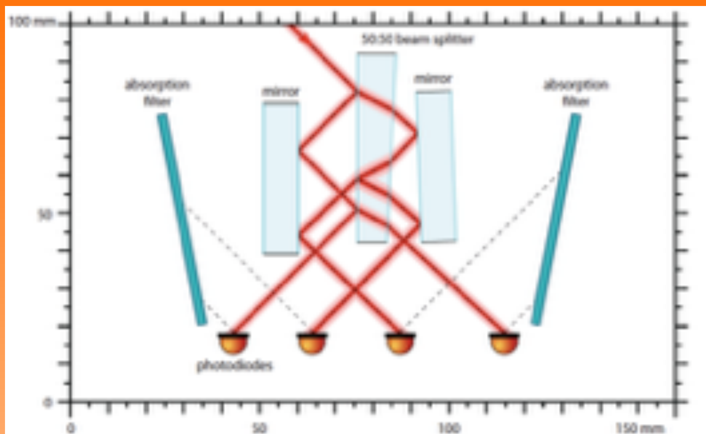


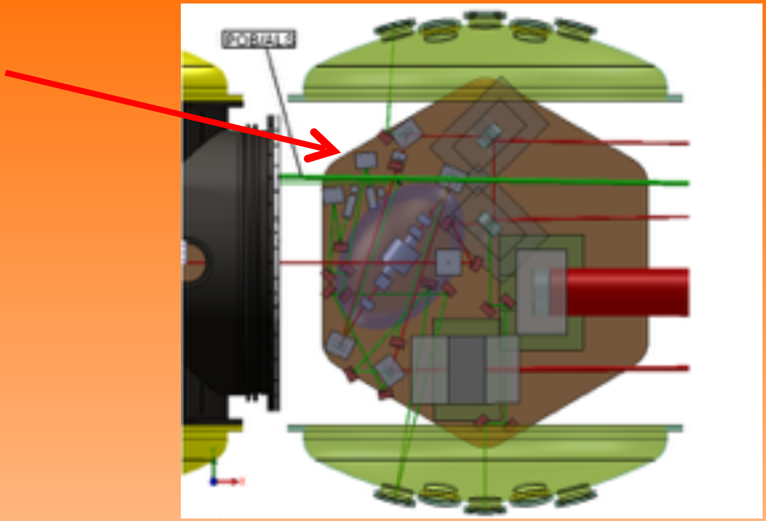
PSL

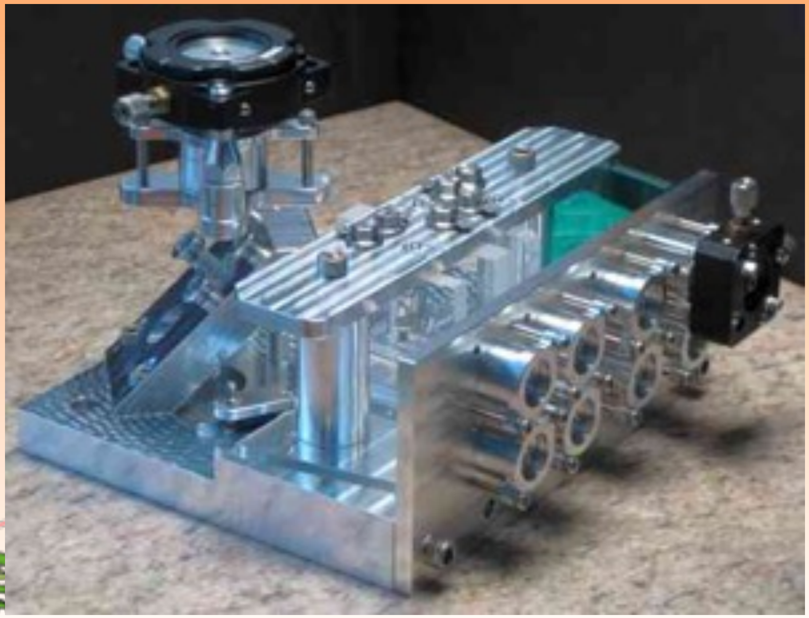
Sensors external to PSL:

- Frequency:
  - Input Mode Cleaner (IMC)
  - Common Arm Cavities (CARM)
- Intensity:
  - 2nd ISS uses signal in HAM2 after IO

PSL







- four photodiodes per detector
  - In-loop
  - Out of loop
- each aligned to lowest pointing coupling
- 50mA photocurrent per photodiode
- in dust-free environment with reduced pointing fluctuations
- installed in HAM 2

PSL

Sensors external to PSL:

- Frequency:
  - Input Mode Cleaner (IMC)
  - Common Arm Cavities (CARM)
- Intensity:
  - 2nd ISS uses signal in HAM2 after IO

General issues with PSL:

- Beam pointing from PSL table (out of IO) might be higher than expected due
  - Acoustic noise and water flow shakes IO periscope
- 2nd ISS loop not yet 100% functional
  - Sees also stray light from IOT2R
  - Needed for high power operation only (not yet)
- …