Laser interferometers to detect gravitational waves: focus on Virgo Laser and input optics

Lecture at Balaton summer school, Balaton Lake, Hungary
July 18th, 2017

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Outline

- A Laser interferometer to detect GW
- How to enhance the sensitivity?
- Advanced Virgo design
- Introduction to optical cavities, Optical phase modulator, Faraday isolator, Gaussian optics, optical cavities locking and mode matching telescopes principle
- The laser system
- The Injection system
- Laser frequency stabilization loop

The Virgo Experiment

- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector of gravitational waves
- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary
- Funding approved in Dec. 2009
- Construction in progress. End of installation: Fall 2016
- First science data in 2017

6 European countries
20 labs, ~250 authors

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
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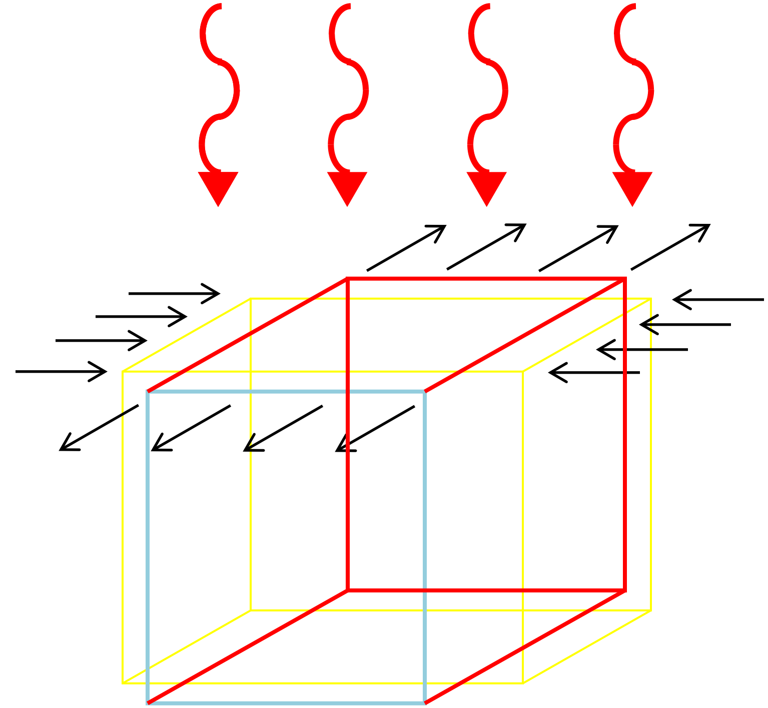
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest
Valencia Uni.

Seminar at LPL, June 16th, 2017

A Laser interferometer to detect GW

The physical Effect

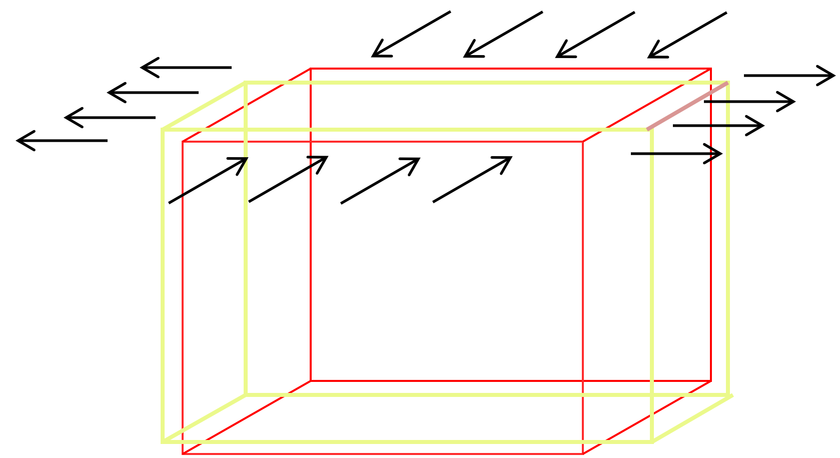


GW squeeze and stretch the space in perpendicular directions

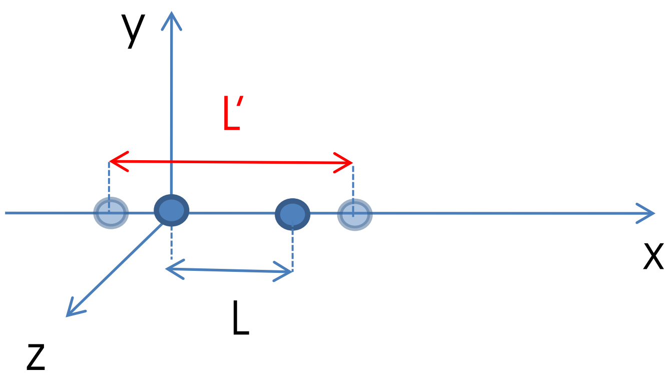
→ Deformation of elastic bodies
→ Displacement of free masses

To detect GW:

❑ monitor distances between free masses



The effect of Gravitational Waves on free falling masses



$$\boxed{\delta L \propto h\, L}$$

Very weak amplitude: $h \approx 10^{-21}$

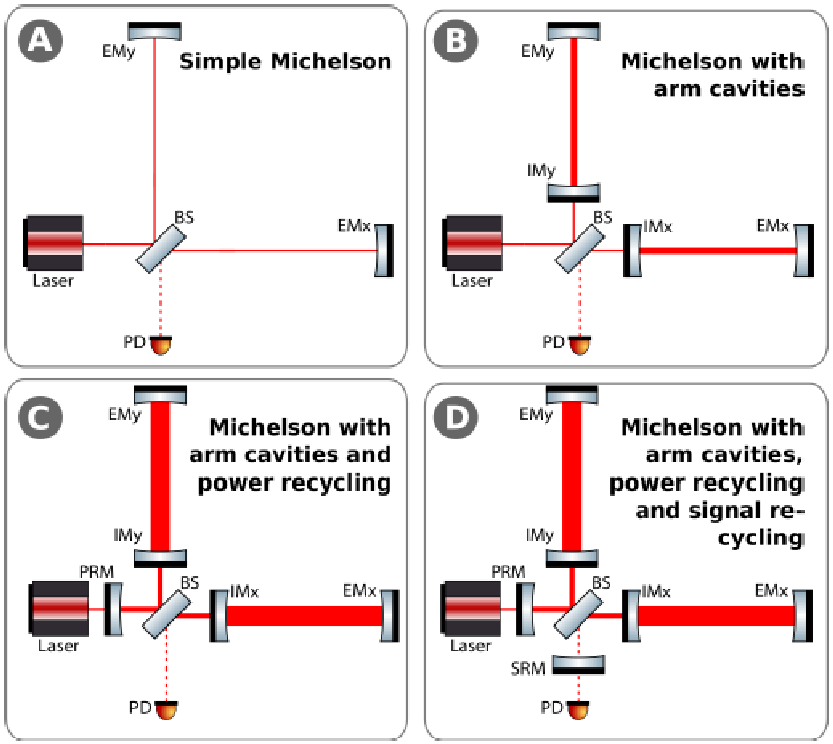
The distance between two masses separated by ~Km will change by $\boldsymbol{\delta L \approx 10^{-18}}$**m**

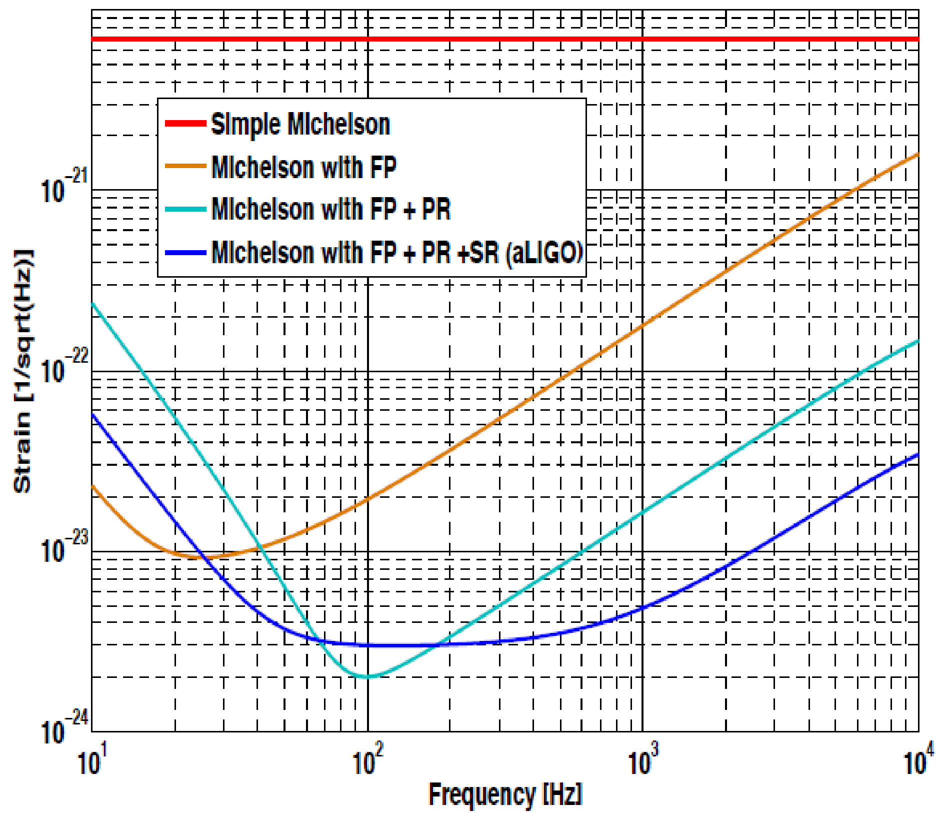
The solution:
use a Michelson Interferometer

Credits: LiGO

How to improve the Michelson interferometer sensitivity?

Need to improve a lot the accuracy of the measurement from 0.02 λ (Michelson 1881) to 10^{-14} λ.



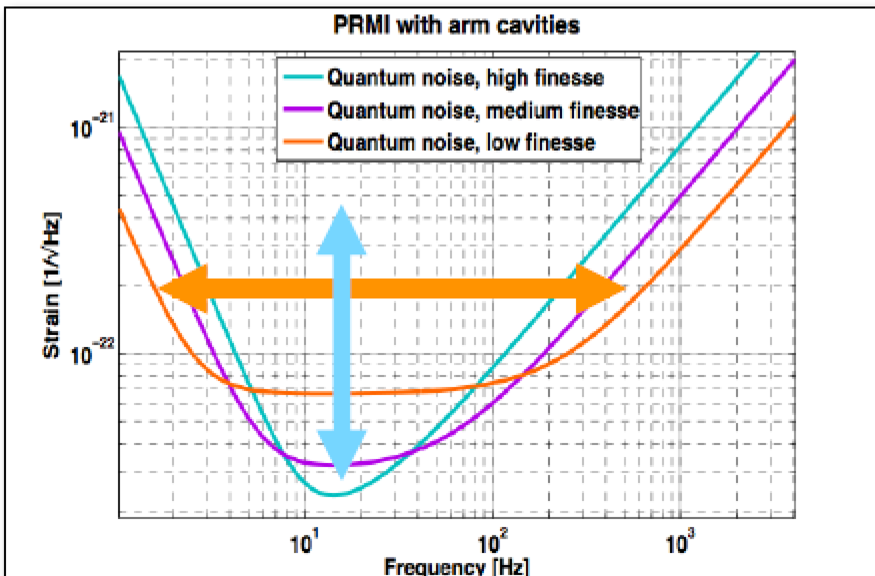


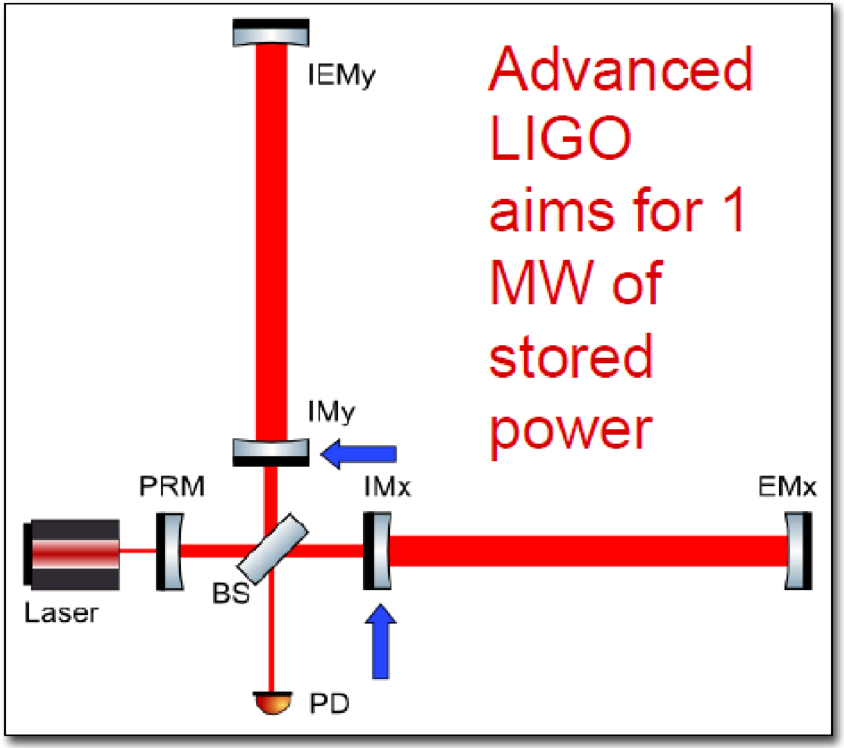
Credits: Stefan Hild (University of Glasgow)

NB: Considered km long arms.

Arm cavities

- ❑ Increasing the storage time in the arms by using arm cavities
- ❑ The Finesse of the arm cavities determines the bandwidth of the GW detector



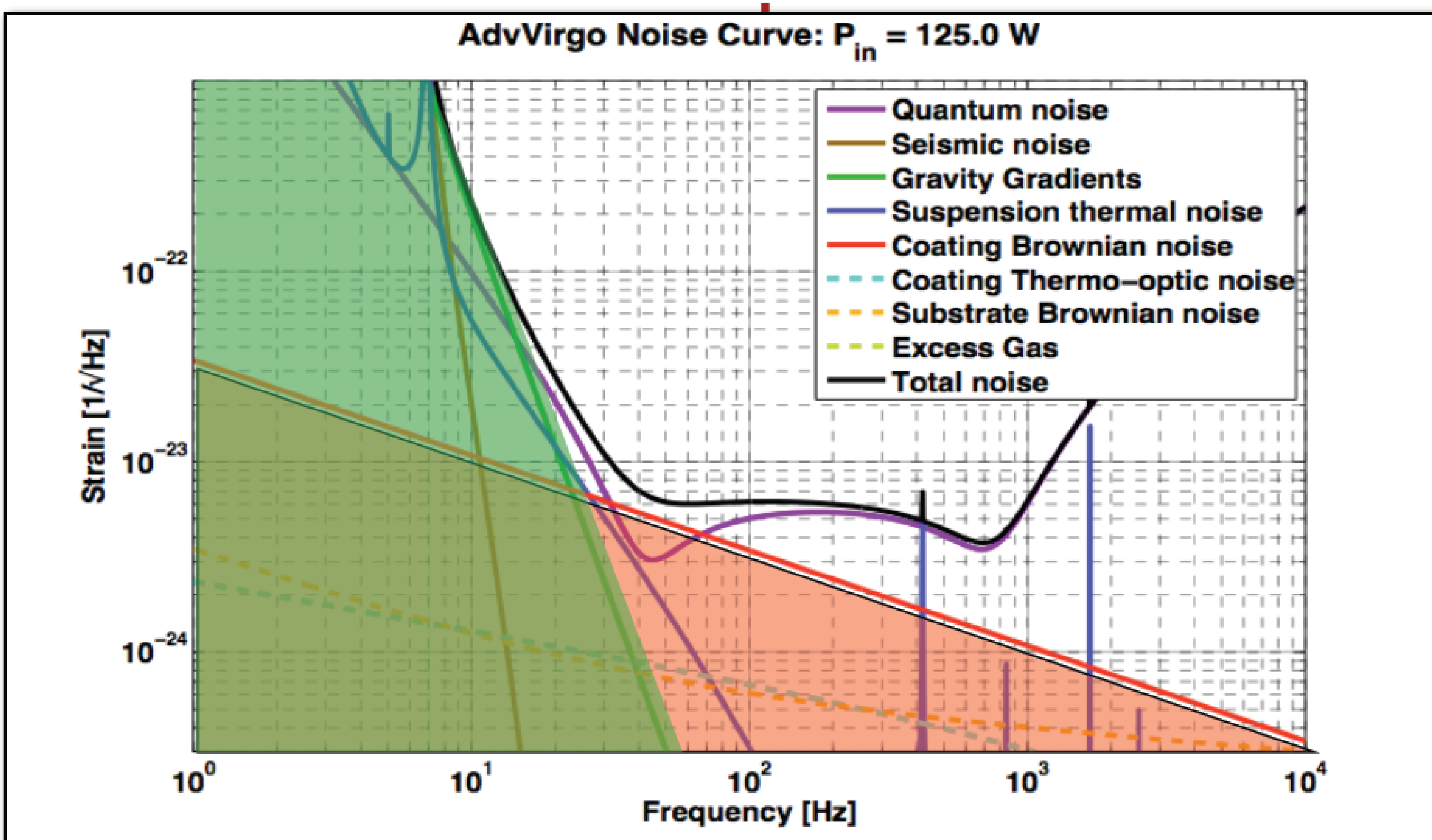


650 kW should be stored for AdV

Credits: Stefan Hild (University of Glasgow)

NB: Considered km long arms.

Typical sensitivity curve for Advanced Virgo



Credits: Stefan Hild (University of Glasgow)

Mostly limited by quantum noise over the whole bandwidth.
But also by gravity gradient noise at low frequency
and coating thermal noise in mid frequency range

Standard quantum noise limit

While shot noise contribution decreases with optical power, radiation pressure level increases:

wavelength

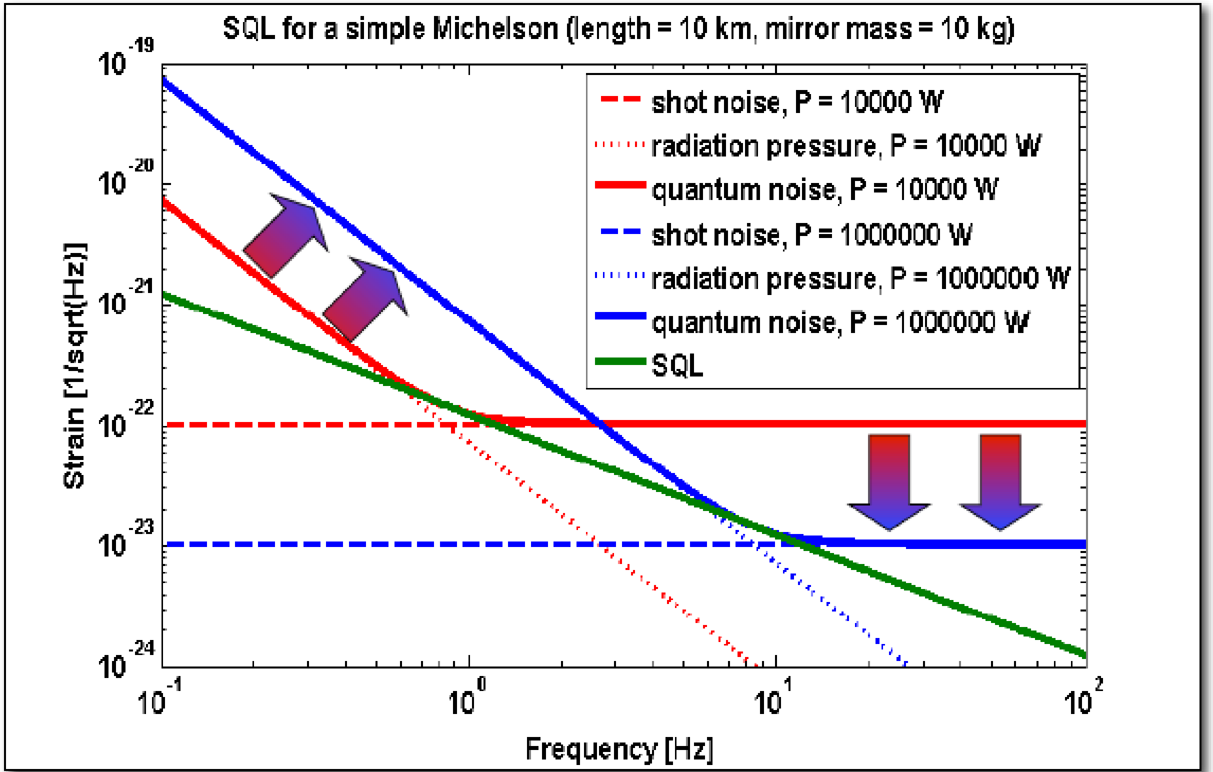
$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

optical power

Arm length

Mirror mass

$$h_{\rm rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$



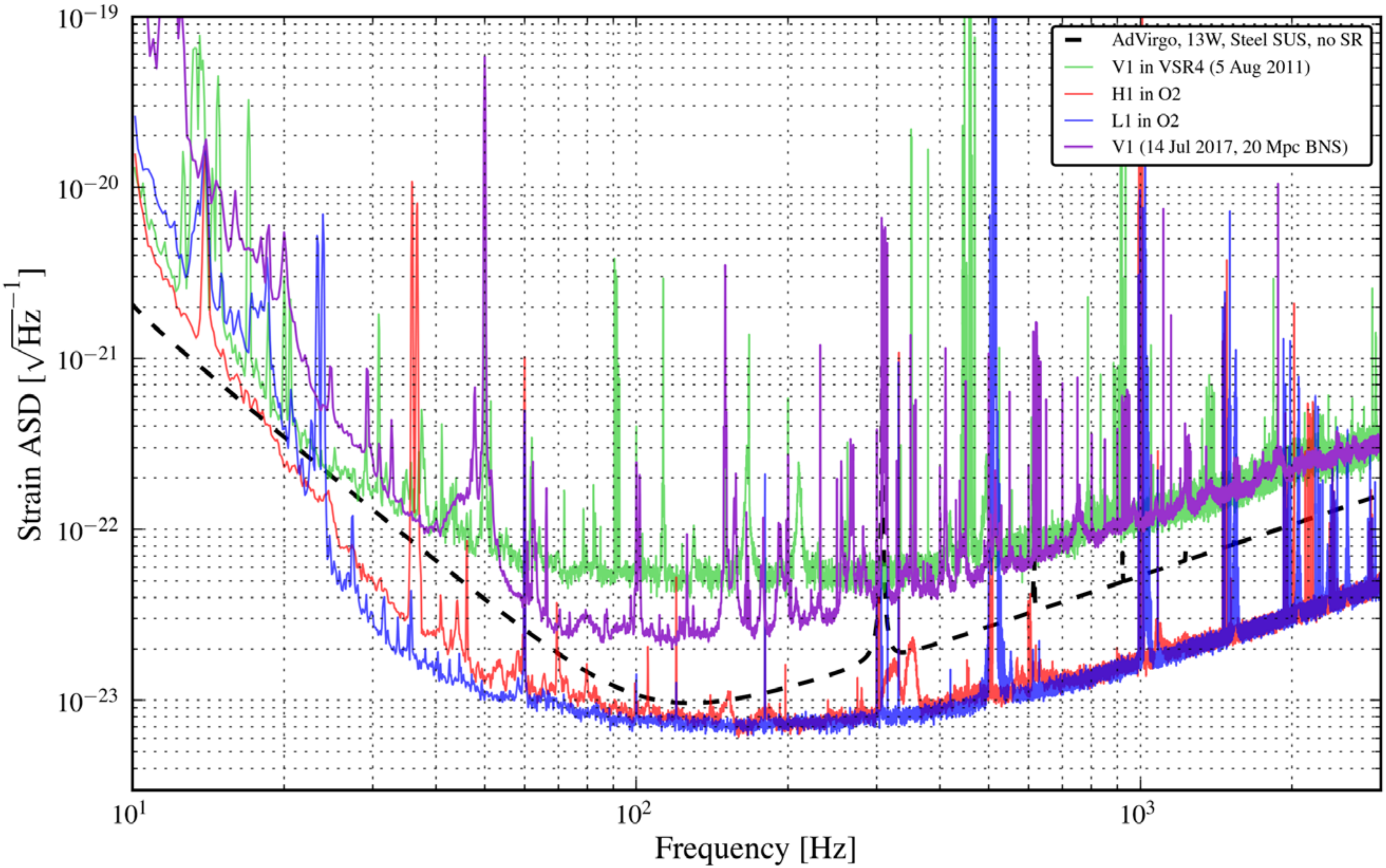
The SQL is the minimal sum of shot noise and radiation pressure noise.

Using a classical quantum measurement the SQL represents the lowest achievable noise.

V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)

Credits: Stefan Hild (University of Glasgow)

Typical sensitivity curves



Credits: D. Bersanetti (Virgo logbook entry #38630)

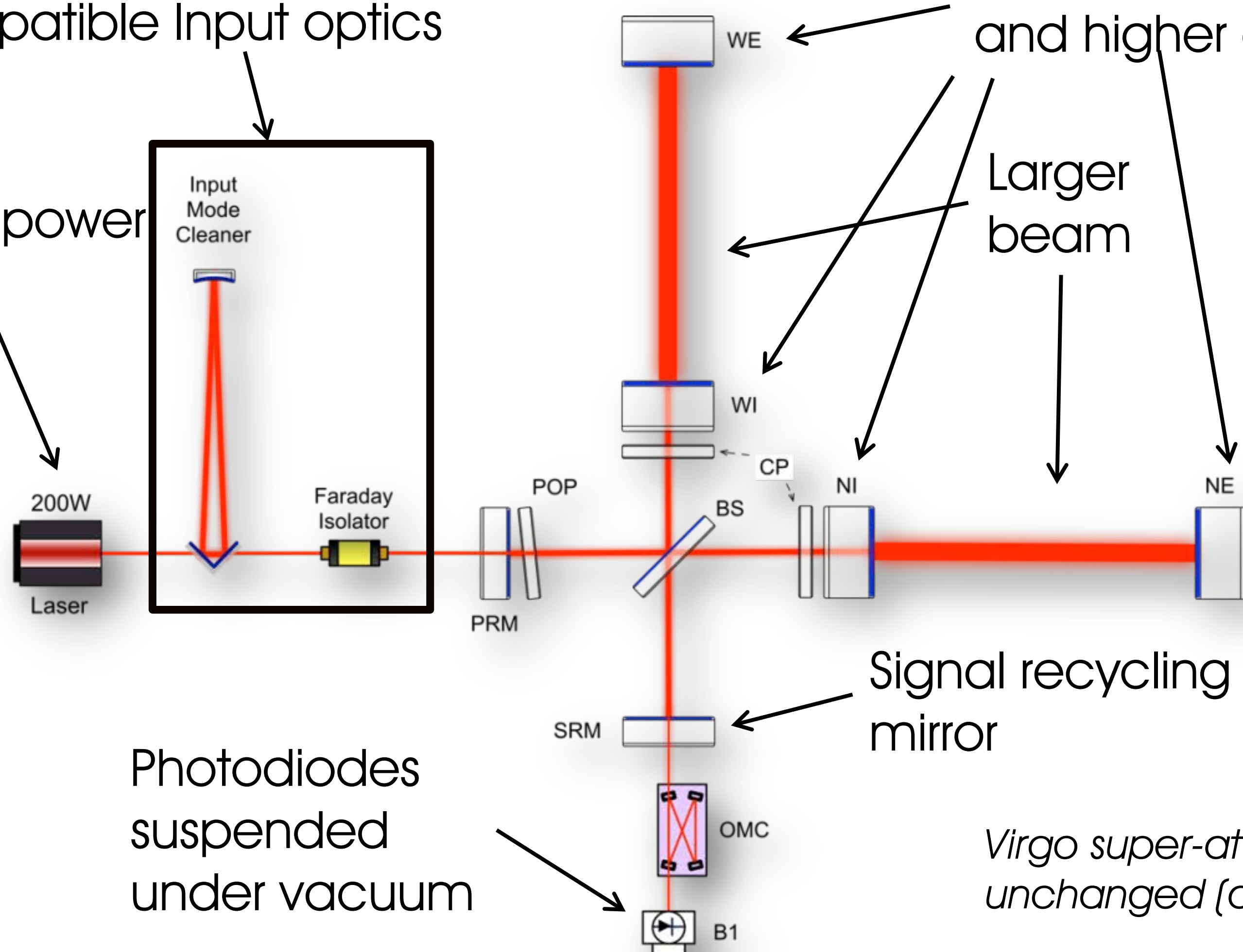
AdV Detector design:
Main changes respect to 1st generation

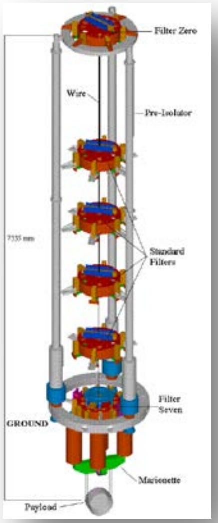
Higher power
Compatible Input optics

Heavier mirrors (40 kg)
and higher quality optics

Higher power
laser

Larger
beam





Signal recycling
mirror

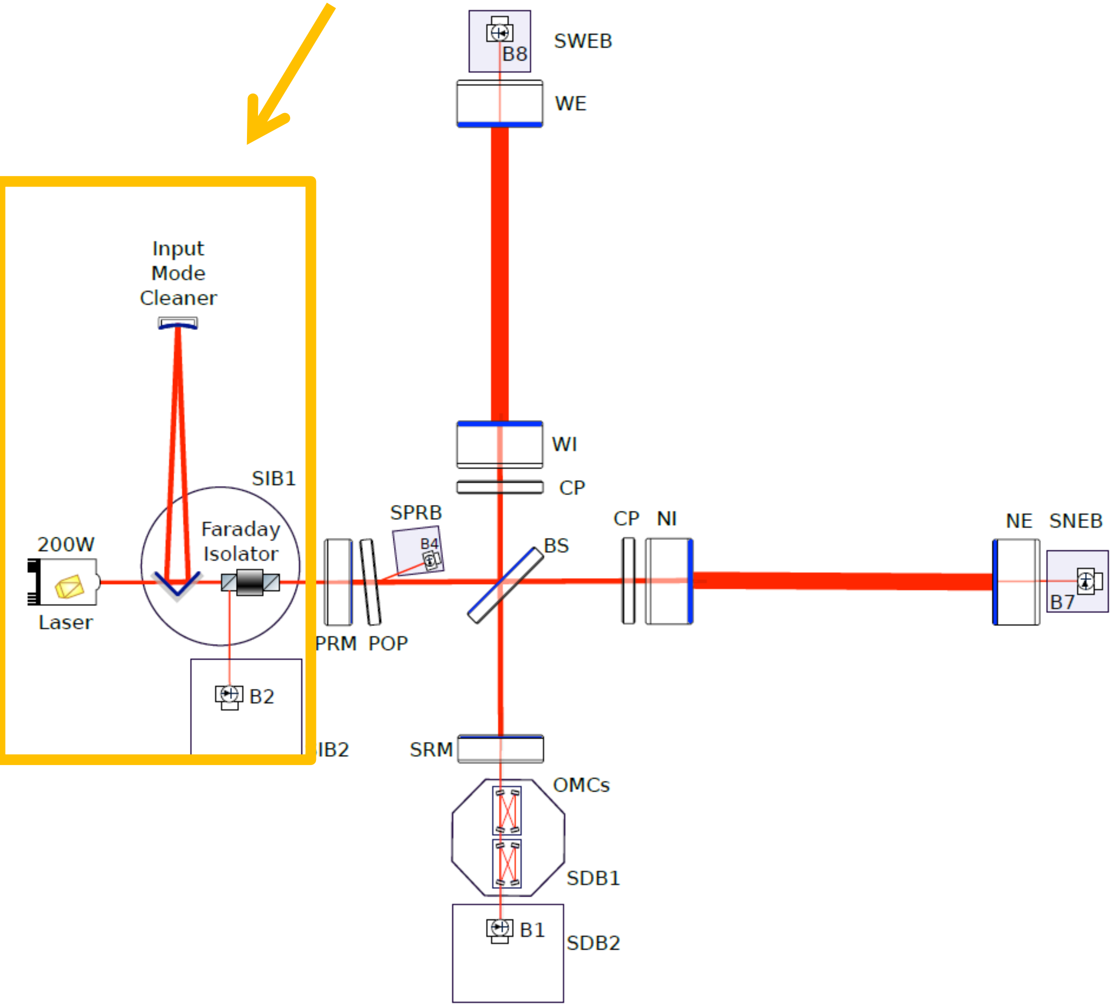
Photodiodes
suspended
under vacuum

Virgo super-attenuator kept unchanged (already compliant)

NB: Everything under vacuum (except the laser and some Input optics components)

Virgo Overview

I will talk about that part
The Laser and Injection (input optics) system



Advanced Virgo project baseline design

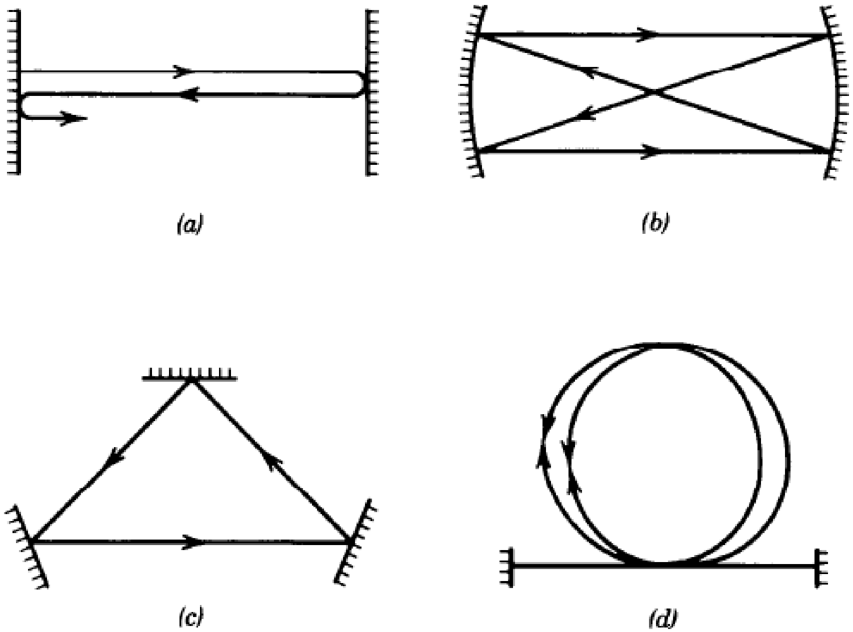
AdV Overview, Part I		
Subsystem and Parameters	**AdV design (TDR)**	**Initial Virgo**
Sensitivity		
Binary Neutron Star Inspiral Range	134 Mpc	12 Mpc
Anticipated Max Strain Sensitivity	$3.5 \cdot 10^{-24}/\sqrt{\mathrm{Hz}}$	$4 \cdot 10^{-23}/\sqrt{\mathrm{Hz}}$
Instrument Topology		
Interferometer	Michelson	Michelson
Power Enhancement	Arm cavities and Power Recycling	Arm cavities and Power Recycling
Signal Enhancement	Signal Recycling	n.a.
Laser and Optical Powers		
Laser Wavelength	1064 nm	1064 nm
Optical Power at Laser Output	>175 TEM_{00} W	20 W
Optical Power at Interferometer Input	125 W	8 W
Optical Power at Test Masses	650 kW	6 kW
Optical Power on Beam Splitter	4.9 kW	0.3 kW
Test Masses		
Mirror Material	Fused Silica	Fused Silica
Main Test Mass Diameter	35 cm	35 cm
Main Test Mass Weight	42 kg	21 kg
Beam Splitter Diameter	55 cm	23 cm
Test Mass Surfaces and Coatings		
Coating Material	Ti doped Ta_2O_5	Ta_2O_5
Roughness*	< 0.1 nm	< 0.05 nm
Flatness	0.5 nm RMS	< 8 nm RMS
Losses per Surface	37.5 ppm	250 ppm (measured)
Test Mass RoC	Input Mirror: 1420 m End Mirror: 1683 m	Input Mirror: flat End Mirror: 3600 m
Beam Radius at Input Mirror	48.7 mm	21 mm
Beam Radius at End Mirror	58 mm	52.5 mm
Finesse	443	50
Thermal Compensation		
Thermal Actuators	CO_2 Lasers and Ring Heater	CO_2 Lasers
Actuation points	Compensation plates and directly on mirrors	Directly on mirrors
Sensors	Hartmann sensors and phase cameras	n.a.

AdV figures vs Virgo
(Extract of AdV technical design report)

NB: 3km arm cavities linewidth=100Hz

Optical resonators: Introduction

Definition: An optical resonator, the optical counterpart of an electronic resonant circuit, confines and stores light at certain resonance frequencies. Light circulates or is repeatedly reflected within the system, without escaping. The simplest resonator comprises two parallel planar mirrors between which light is repeatedly reflected with little loss.
The frequency selectivity of an optical resonator makes it useful as an optical filter or spectrum analyzer. Its most important use, however, is as a “storage unit” within which laser light is generated. The laser is an optical resonator containing a medium that amplifies light. The resonator determines the frequency and spatial distribution of the laser beam. Because resonators have the capability of storing energy, they can also be used to generate pulses of laser energy.



Typical optical resonators: Plane-mirror resonator (a), Spherical mirror-resonator (b), Ring resonator (c), Fiber ring resonator (d)

Optical cavities Basics

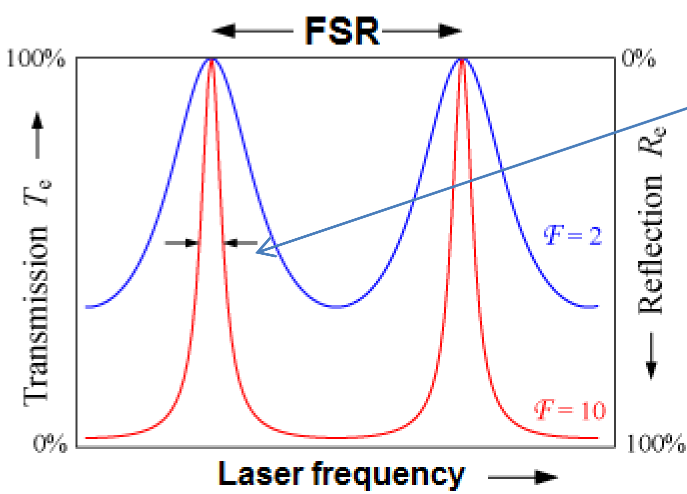
- A laser beam can pass through an optical cavity if :
  - The cavity length is a multiple of an half of the wavelength
  - The laser frequency is a integer multiple of the Free spectral range
  - The laser beam is aligned with respect to the cavity axis
  - The cavity mirrors are aligned one respect to the other
  - The laser beam has the right dimensions / divergence

Same condition

FSR=c/2*L

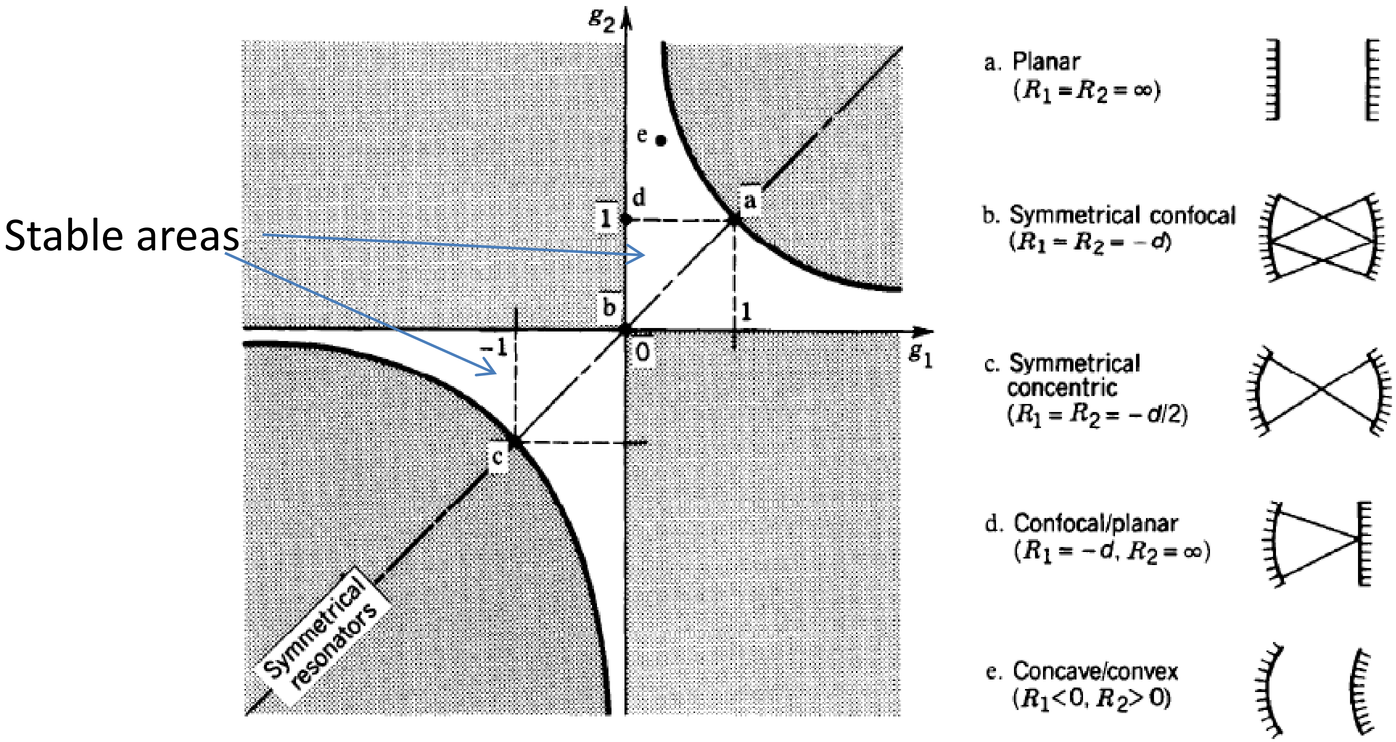
c: speed of the light
L: cavity length

δν=FSR/F



→ Increasing the finesse (F) you can reduce the linewidth of the cavity.
→ by choosing properly all the parameters F and FSR you can design a cavity which will filter out the frequency noise of your laser and you can improve the mono chromaticity of this one.

Optical resonators stability



Stability diagram

The criteria is: $0 \leq g_1 g_2 \leq 1$ where $g_i = 1 - L/R_i$ where L, is the cavity length and R_i , the radius of curvature of the optics

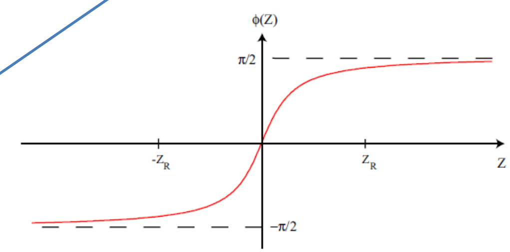
Gaussian beams are modes of spherical-mirrors resonators (they represent the solution of Helmholtz equation in the paraxial approximation).
In the paraxial approximation, the full expression of the electric field of the fundamental Gaussian beam (TEM00) is:

$$\frac{E(x,y,z)}{E_0} = \frac{1}{[1+(z/z_R)^2]^{1/2}} \exp[-\frac{k z_R r^2}{2(z^2+z_R^2)}] \cdot \exp[-i\frac{k z r^2}{2(z^2+z_R^2)}] \exp[i \tan^{-1}(\frac{z}{z_R})] \exp(-ikz)$$

It can be written:

$$\frac{E(x,y,z)}{E_0} = \frac{w_0}{w(z)} \exp[-\frac{r^2}{w^2(z)}] \cdot \exp[-i\frac{kr^2}{2R(z)}] \cdot \exp\{-i[kz-\phi(z)]\}$$

Gouy phase shift $\phi(z) = \tan^{-1}(\frac{z}{z_R})$

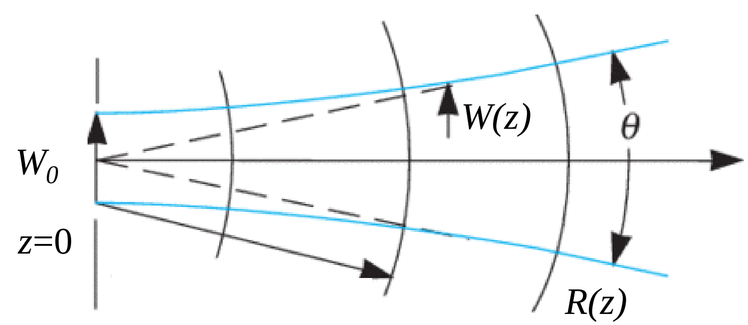


The Gaussian beam intensity I transversally varies as:

$$I = I_0[W_0/W(z)]^2 \exp[-2(x^2+y^2)/W^2(z)]$$

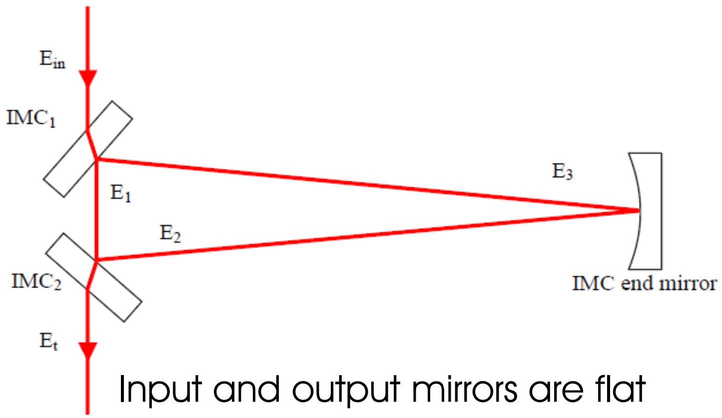
$$w(z) = w_0\sqrt{1+(\frac{z}{z_R})^2} \quad R(z) = z[1+(\frac{z_R}{z})^2]$$

Rayleigh range $z_R = \frac{\pi n w_0^2}{\lambda_0}$



E. Genin

An example: The Virgo Input Mode Cleaner



Input and output mirrors are flat
The third mirror is curved : RoC=185.1m
The cavity length is 143.34m

Considering that E_{in} is the field at the input of the IMC cavity, E_1, the field after M_1 , E_2, the field after M_2 and E_3, the field after M_3 mirror, we can write the transmitted field at the output of the IMC cavity as:

$$E_t = \frac{t_1 t_2}{1 + r_1 r_2 r_3 \exp(i(2\phi + \pi/2))} E_{in}$$

From this equation, we can deduce the power transmittance of this cavity at resonance:

$$T = \left(\frac{t_1 t_2}{1 - r_1 r_2 r_3} \right)^2$$

If we consider that $R_3=1$, $T_1=(t_1)^2$; $T_2=(t_2)^2$; $R_1=1-L_1-T_1$; $R_2=1-L_2-T_2$ and $L_{RT}=L_1+L_2$ we can write the **cavity throughput** as:

$$T = \frac{4 T_1 T_2}{(T_1 + T_2 + L_{RT})^2}$$

The cavity **Finesse** is defined as: $F = \dfrac{\pi \sqrt{r_1 r_2}}{1 - r_1 r_2}$ Thus, $T_1 + T_2 + L_{RT} = \dfrac{2\pi}{F}$

$$T_1 + T_2 + L_{RT} = \frac{4\pi f_p}{FSR}$$

where f_p **is the cavity pole.**

The **mean lifetime of a photon** in an optical cavity can be written as:

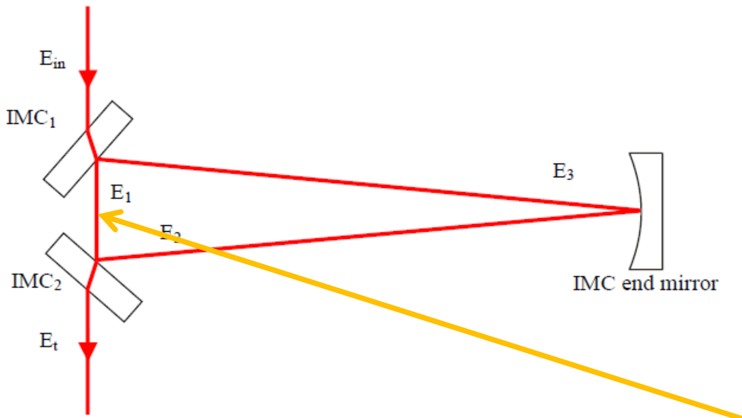
$$\tau_{ph} = \frac{\text{time needed to run a round-trip}}{\text{Total losses over a round-trip}} = \frac{2L/c}{T_1 + T_2 + L_{RT}}$$

It can be also written as $\tau_{ph} = \dfrac{1}{4\pi f_p}$

Cavity stability:
$g_1=1$
$g_2=1-143.34/185.1=0.22$
Thus, $g_1 g_2=0.22$

Other parameters::
FSR=c/2L=1045129 Hz
F=1000
$f_p = 522 Hz$
$\tau_{ph} = 150 us$

An example: The Virgo Input Mode Cleaner



Input and output mirrors are flat
The third mirror is curved : RoC=185.1m
The cavity length is 143.34m

The cavity beam waist size can be computed as follow:

$$w_0^2 = \frac{L\lambda}{\pi}\sqrt{\frac{g_1 g_2 (1 - g_1 g_2)}{(g_1 + g_2 - 2 g_1 g_2)^2}}$$

With g_1g_2=0.22, L=143.34m, λ=1064nm
We find: w_0=5.08 mm

It is located between the input and output mirrors

For a linear cavity the transverse vertical and horizontal modes have the same resonance frequency (degenerated), for a ring cavity this is not true. If the cavity has an odd number of mirrors (as the IMC), the modes TEMmn with an odd mode number relative to the ring plane (m =odd) are non-degenerated respect to the modes TEMnm having the same mode number relative to the plane perpendicular to the ring (see VIR-NOT-LAS-1390-120 for more details) .

→ Vertical and horizontal misalignment modes are filtered

in a different way due to the odd number of mirrors in the IMC cavity

$$d\nu_{even}(m+n) = \frac{FSR}{\pi}(m+n)a\cos(\sqrt{g})$$

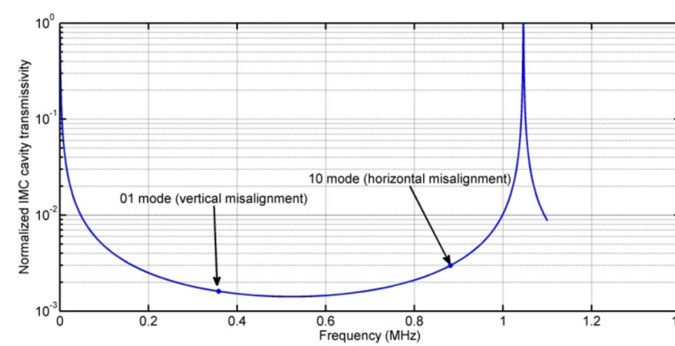
$$d\nu_{odd\_vert}(m+n) = \frac{FSR}{\pi}(m+n)a\cos(\sqrt{g})$$

$$d\nu_{odd\_hor}(m+n) = \frac{FSR}{2} + \frac{FSR}{\pi}(m+n)a\cos(\sqrt{g})$$

$$d\nu_{01} = 360kHz$$

$$d\nu_{10} = 822.5kHz$$

$$d\nu_{20} = d\nu_{02} = 760kHz$$



Optical cavities properties

- ❑ The Fabry–Perot cavities are used for :
  - ❑ Laser frequency stabilization (spectral mode cleaning).
  - ❑ Beam jitter filtering.
  - ❑ Laser beam Shape Filtering (Spatial Mode cleaning).

In order to keep the beam always completely transmitted by an optical resonator the laser frequency has to be stabilized respect to the cavity or the contrary…

The transmitted power is not a good-enough error signal because it has no sign so we use the Pound-Drever-Hall locking technique.

Optical side-bands are needed using optical phase modulation.

Electro-optic modulation

The Pockels effect is the linear electro-optic effect:

- The refractive index of a medium is modified proportionally to the applied electric field strength.
- This effect can occur only in non-centrosymmetric materials.

In a crystal the refractive index change induced by an electric field can be described by the modification of the index ellipsoid:

$$\left(\frac{1}{n^2}\right)_1 x^2 + \left(\frac{1}{n^2}\right)_2 y^2 + \left(\frac{1}{n^2}\right)_3 z^2 + 2\left(\frac{1}{n^2}\right)_4 yz + 2\left(\frac{1}{n^2}\right)_5 xz + 2\left(\frac{1}{n^2}\right)_6 xy = 1$$

The linear perturbation of the coefficient induced by the electric field can be written as:

$$\Delta\left(\frac{1}{n^2}\right)_i = \sum_{j=1}^{3} r_{ij} E_j$$

Pockels effect in uniaxial crystals

Applying the electric field along z axis of an uniaxial crystal (as Rubidium Tytanile Phosphate (RTP), LINbO3, KTP,…), the index ellipsoid becomes:

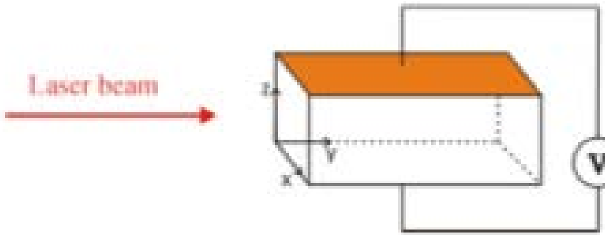
$$\frac{(x^2+y^2)}{{n_o}^2}+\frac{z^2}{{n_e}^2}+r_{13}E_z x^2+r_{23}E_z y^2+r_{33}E_z z^2=1$$

The crystal axis remains the same and the new indexes are:

$$n_x = n_o - 0.5{n_o}^3 r_{13}E_z$$
$$n_y = n_o - 0.5{n_o}^3 r_{23}E_z$$
$$n_z = n_e - 0.5{n_e}^3 r_{33}E_z$$

$$[r]=\begin{bmatrix} 0 & 0 & r_{13} \\ 0 & r_{22} & r_{23} \\ 0 & 0 & r_{33} \\ 0 & r_{42} & 0 \\ r_{51} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Material EO tensor



Using this effect, phase and amplitude modulations of a laser beam can be done.

Phase Modulator

Phase shift induced by electric field applied along the z axis for a linearly polarized beam with a polarization along z is:

$$\Gamma = \frac{2\pi}{\lambda} n_z L = \frac{2\pi}{\lambda} L(n_e - 0.5{n_e}^3 r_{33} E_z)$$ with $E_z = V/d$

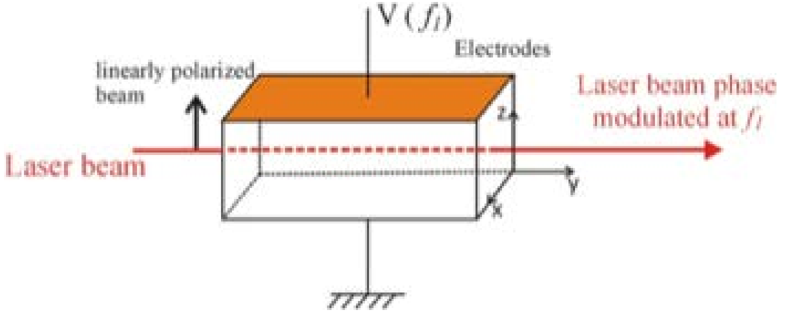
V is the voltage applied on the crystal, L is the length of the electrode, d is the thickness of the crystal.
The Electric field at the output of the EOM applying a voltage modulated at $f_1 = \omega_1/2\pi$ can be written:

$$E_{out} = E_0 \exp(i\omega t) \exp(i\Gamma(t))$$

where $\Gamma(t) = \Gamma_0 - (\pi L/\lambda) r_{33} n_z^3 (V_0/d) sin(\omega_1 t)$

The modulation depth is defined as:

$$m = (\pi L/\lambda) r_{33} n_z^3 (V_0/d)$$



❑ We use the Pound-Drever-Hall locking technique [1] :

Using phase modulation, two new frequencies are present in the laser frequency spectrum, these two frequencies are chosen so that they are reflected by the cavity (smaller than the Free Spectral Range).

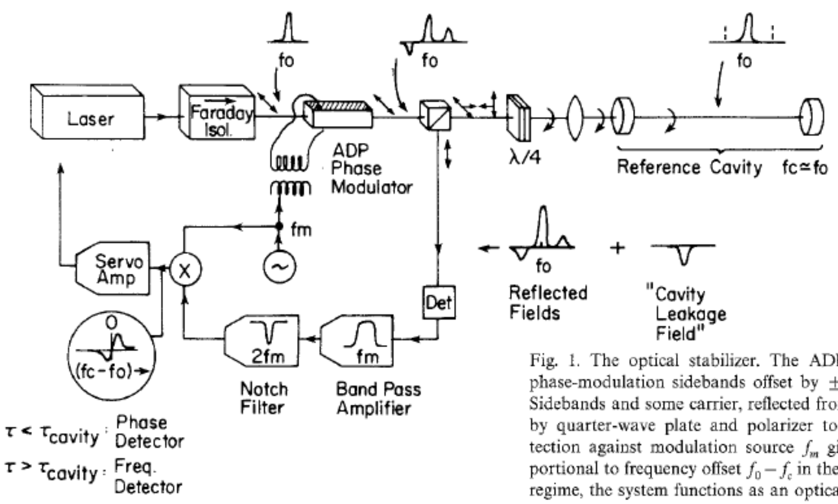
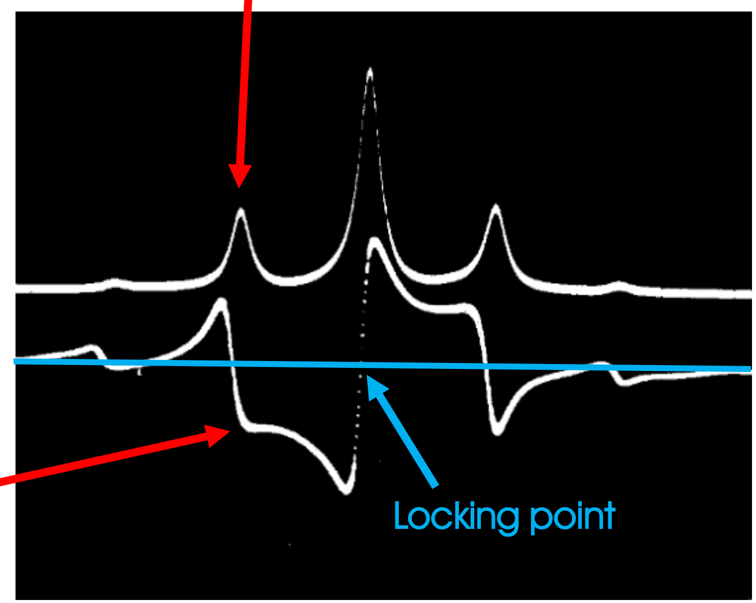


Fig. 1. The optical stabilizer. The ADP phase modulator produces phase-modulation sidebands offset by $\pm f_m$ from carrier frequency f_c. Sidebands and some carrier, reflected from reference cavity, are steered by quarter-wave plate and polarizer to detector. Phase-sensitive detection against modulation source f_m gives bipolar error signal proportional to frequency offset $f_0 - f_c$ in the adiabatic regime. In transient regime, the system functions as an optical phase detector (see text)

Transmitted signal



Reflected demodulated signal

Laser Frequency or Cavity scan

[1]Drever, R. W. P.; Hall, J. L.; Kowalski, F. V.; Hough, J.; Ford, G. M.; Munley, A. J.; Ward, H. (June 1983). "Laser phase and frequency stabilization using an optical resonator" (PDF). Applied Physics B. **31** (2): 97–105. doi:10.1007/BF00702605.

❑ Faraday Isolator (FI)

Optical diode, avoid back reflected light. Used for example before an optical linear cavity.

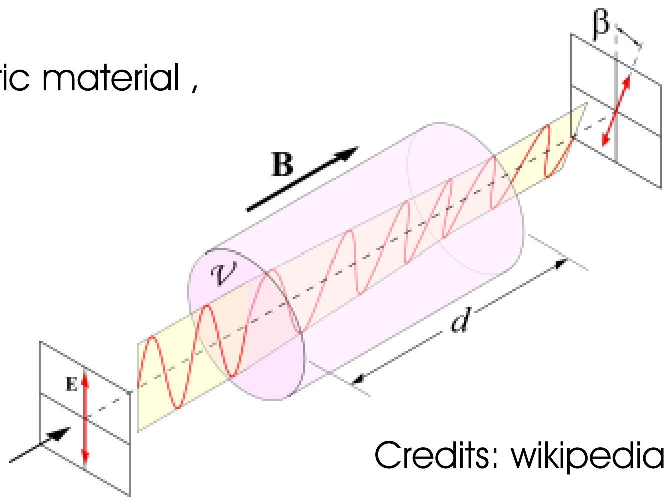
The main component of the Faraday Isolator is a Faraday Rotator: an optical device that rotates the light polarization due to the Faraday effect.
- Faraday effect: an interaction between light and magnetic field in a medium.
- Left and right circularly polarization waves propagate at slightly different speeds (circular birefringence).
- A linear polarization can be decomposed into the superposition of two opposite circularly polarized components with the same amplitude and different phases.
-Faraday effect induces a relative phase shift which results in a rotation of the orientation of a linearly polarized wave.

The angle β depends on The Verdet constant *V* of the magneto-optic material , The strength of the magnetic field **B** and the length of the crystal *d*

$$\beta = V\, d\, \boldsymbol{B}$$

For example, for V=-40 rad/T/m (for Terbium Galllium Garnett), *d*=18mm and **B**=1.09 Tesla

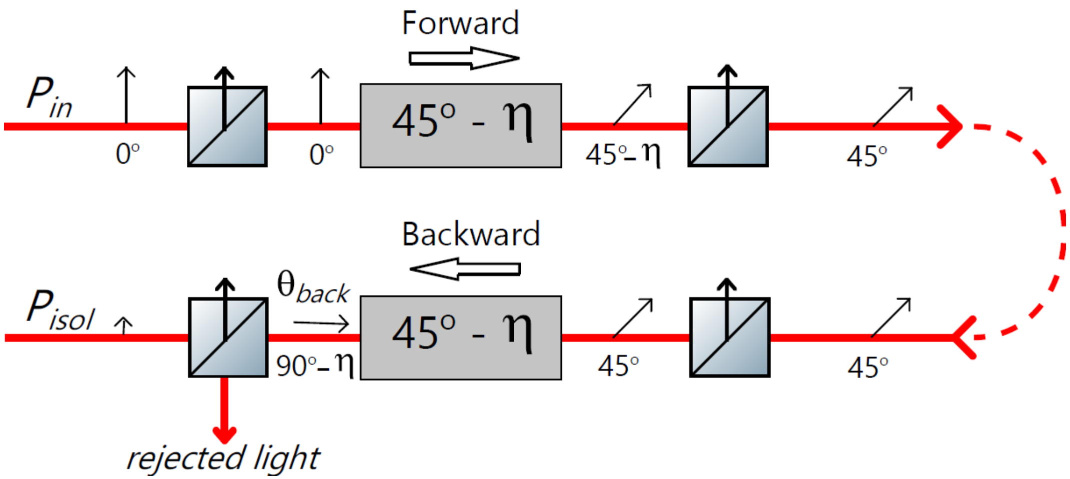
$$\beta = \pi/4 \text{ thus 45 degrees}$$



Credits: wikipedia

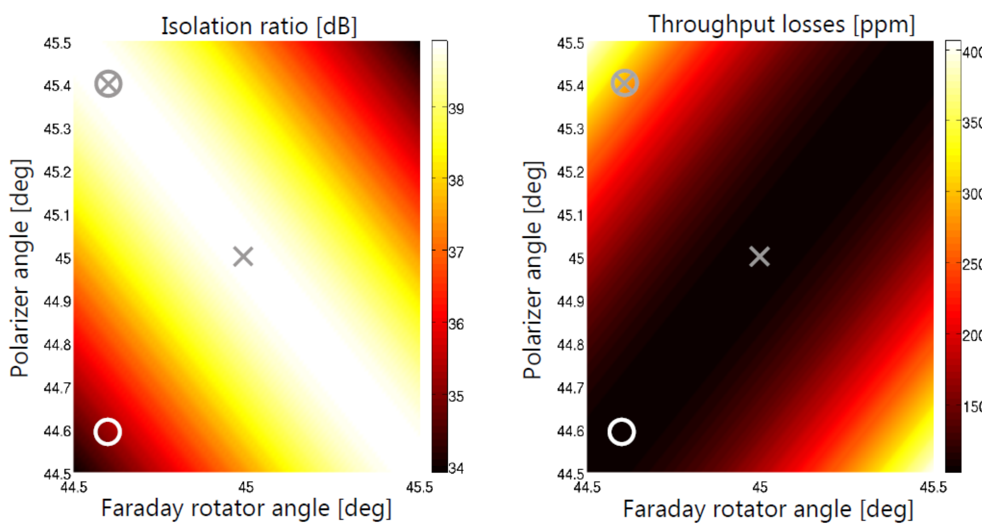
Note that *V* depends on the wavelength and the temperature.

Faraday isolator: real case



If for some reasons you don't exactly rotate by 45 degrees the linear polarization you will:
-worsen the isolation factor
-Increase the throughput losses

$$IF = -10 \cdot \log_{10}\left(\frac{P_{isol}}{P_{in}}\right)$$



$$TL = L_{Forward} \cdot (1 - cos^2(\eta))$$

Faraday isolator: limiting effects at high power

❑There are 3 main effects which can affect the isolator behaviour and are related to the absorption of NIR light in the magneto-optic medium when we operate at high power and in ultra high vacuum conditions

1. Transmitted wavefront distortion (called also thermal lensing because the main effect is a focusing of the laser beam)
2. Thermally induced depolarization
3. Verdet constant change with temperature

References:
[1] E. Khazanov et al, Compensation of Thermally Induced Modal Distortions in Faraday Isolators, IEEE Journ. Quant. Electr., 40 (10), (2004).
[2] E. Khazanov et al, Investigation of self-induced depolarization of laser radiation in terbium gallium garnet, IEEE Journ. Quant. Electr., 35 (8), (1999).
[3] N. P. Barnes and L. B. Petway, Variation of the Verdet constant with temperature, J. Opt. Soc. Am. B/Vol. 9, No. 10, (1992).
[4] The Virgo Collaboration, In-vacuum optical isolation changes by heating in a Faraday isolator, Appl.Opt., Vol.47(31), 5853-5861, (2008).
[5] O. Palashov, D. Zheleznov, A. Voitovich, V. Zelenogorsky, E. Kamenetsky, E. Khazanov, R. Martin, K. Dooley, L. Williams, A. Lucianetti, V. Quetschke, G. Mueller, D. Reitze, D. Tanner, E. Genin, B. Canuel, and J. Marque, High-vacuum compatible high-power Faraday isolators for gravitational-wave interferometers, JOSA B, Vol. 29, Issue 7, pp. 1784-1792 (2012).

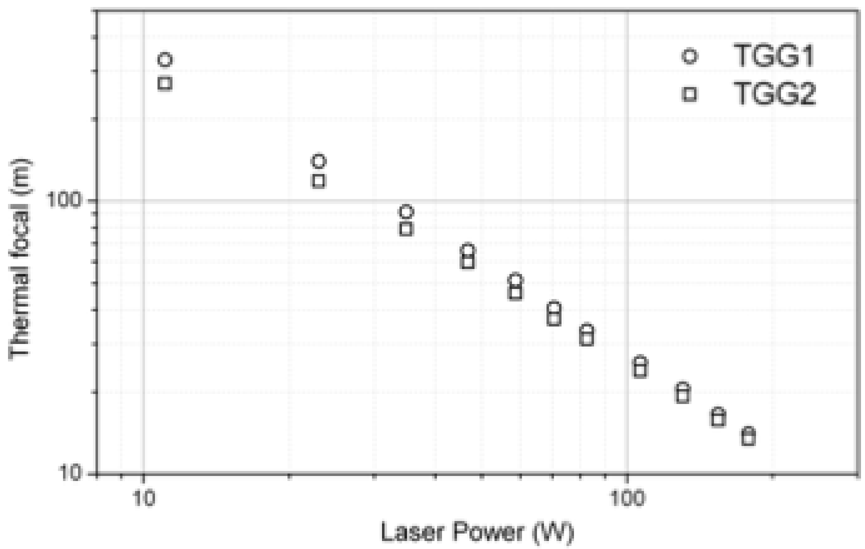
Faraday isolator: Thermal lensing

Thermal lensing in TGG crystals:

$$f = \frac{\pi \kappa w^2}{L\alpha P(\mathrm{d}n/\mathrm{d}T)},$$

Material absorption

Laser power



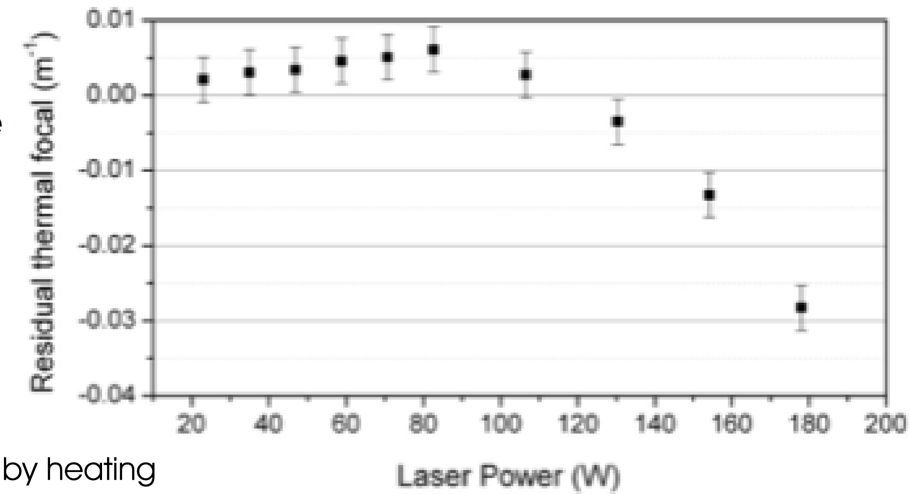
TGG1: 2300 ppm/cm
TGG2: 2600 ppm/cm

Looking for a power independent compensation

DKDP as a compensation material: make passive compensation in optical materials because of its large negative dn/dT

$dn/dT_{DKDP} = -4.4\ 10^{-5}\ K^{-1}$

$dn/dT_{TGG} = 1.9\ 10^{-5}\ K^{-1}$

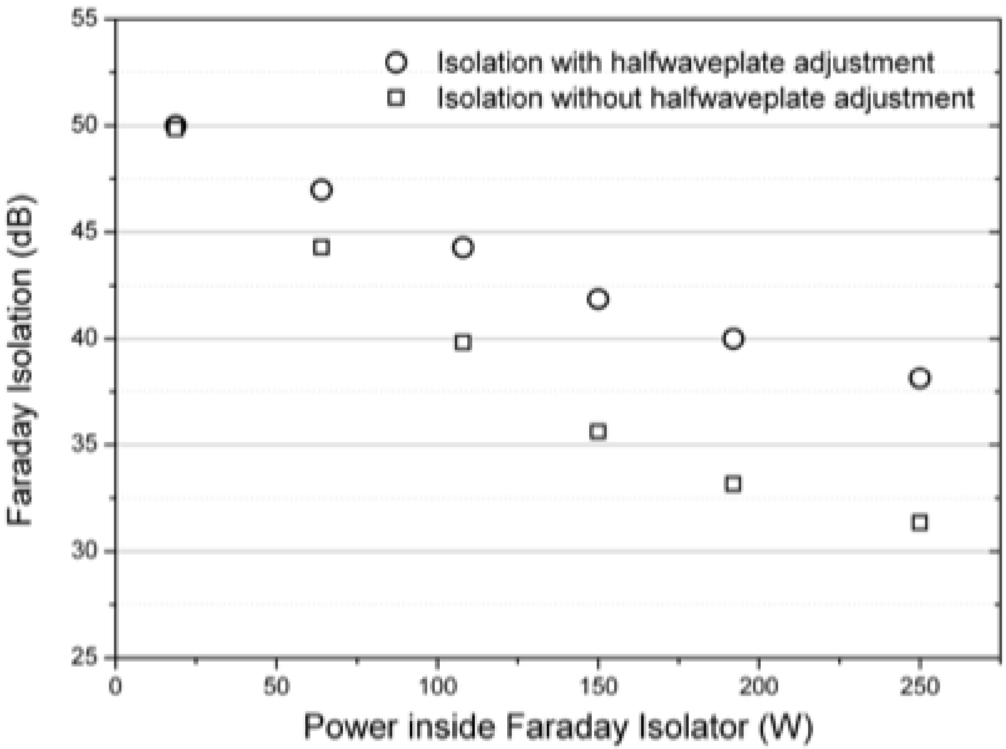


[1] The Virgo Collaboration, "In-vacuum optical isolation changes by heating in a Faraday isolator," Appl. Opt. **47**, 5853-5861 (2008)

Faraday isolator: Verdet constant change with temperature

Thermal isolation change due to the modification of the rotation angle when the TGG crystal is heated. Linked to the temperature dependence of the Verdet constant:

$$\frac{\partial \beta}{\partial T} = \frac{\partial V}{\partial T} dB$$



Change of isolation when power inside FI is modified or when thermal condition changed.
Effect compensable by introducing a half wave plate inside FI. By tuning the plate the optimum isolation is recovered [3]

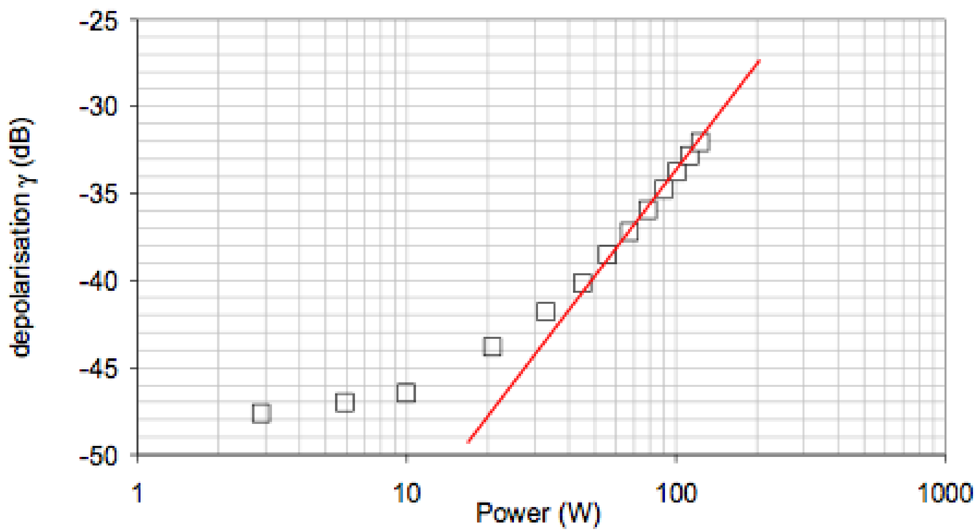
[1] N. P. Barnes and L. B. Petway, Variation of the Verdet constant with temperature, J. Opt. Soc. Am. B/Vol. 9, No. 10, (1992).
[2] The Virgo Collaboration, In-vacuum optical isolation changes by heating in a Faraday isolator, Appl.Opt., Vol.47(31), 5853-5861, (2008).
[3] The Virgo Collaboration, "In-vacuum Faraday isolation remote tuning," Appl. Opt. 49(25), (2010)

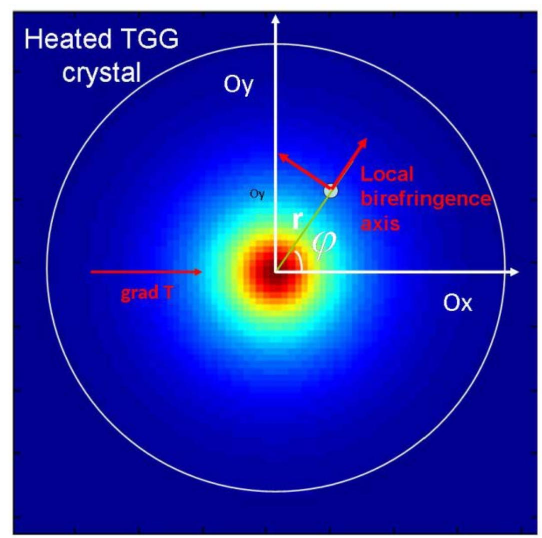
Faraday isolator: Thermal depolarization

Thermal depolarization inside TGG crystal is a limiting effect for Faraday isolation: measured by placing TGG between crossed polarizers.

When the crystal is submitted to a high power laser beam, its absorption generates a radial gradient of temperature corresponding to the radial intensity profile of the heating beam.
This gradient creates some constraints inside the crystal which results in linear birefringence and therefore depolarization of the light.

At high power: $\gamma_{depol} \propto \dfrac{1}{P^2}$



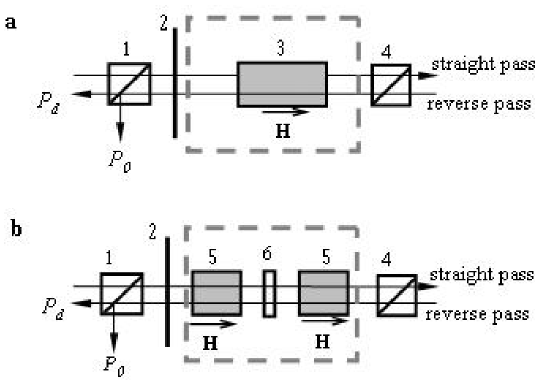


The limiting depolarization effect at high power can also be explained as a self induced Spin (SOM) to Orbital Angular Momentum (OAM) conversion [1].

[1] S. Mosca, B. Canuel, E. Karimi, B. Piccirillo, L. Marrucci, R. De Rosa, E. Genin, L. Milano, E. Santamato, Photon self-induced spin-to-orbital conversion in a terbium-gallium-garnet crystal at high laser power, *Phys. Rev. A* **82**, 043806 (2010)

Faraday isolator: Thermal depolarization

Thermal depolarization compensation scheme proposed by Khazanov et al.



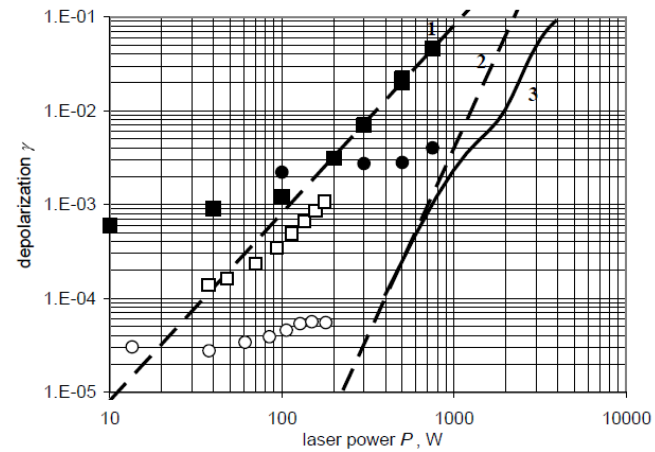
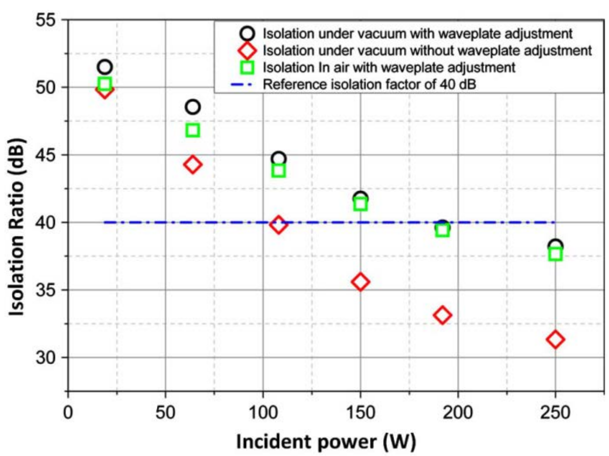


Fig.3. Depolarization versus heating radiation power in traditional FI without compensation (black squares, curve 1) and with compensation (black circles, curve 2, 3) of the depolarization; in FI with reinforced H with compensation (white circles) and without compensation (white squares) [4]. Curves 1, 2 were plotted by formulas, 3 – numerical computation result.



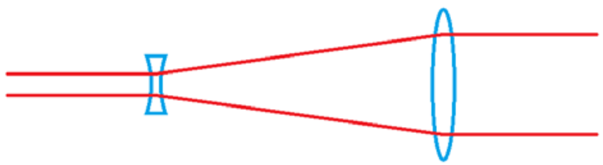
→ Isolation factor as high as 40 dB can be obtained at high average power.

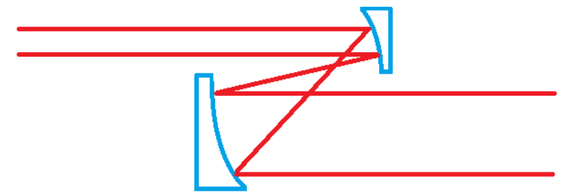
[1] E. Khazanov et al, Investigation of self-induced depolarization of laser radiation in terbium gallium garnet, IEEE Journ. Quant. Electr., 35 (8), (1999).

[2] O. Palashov, D. Zheleznov, A. Voitovich, V. Zelenogorsky, E. Kamenetsky, E. Khazanov, R. Martin, K. Dooley, L. Williams, A. Lucianetti, V. Quetschke, G. Mueller, D. Reitze, D. Tanner, E. Genin, B. Canuel, and J. Marque, High-vacuum compatible high-power Faraday isolators for gravitational-wave interferometers, JOSA B, Vol. 29, Issue 7, pp. 1784-1792 (2012).

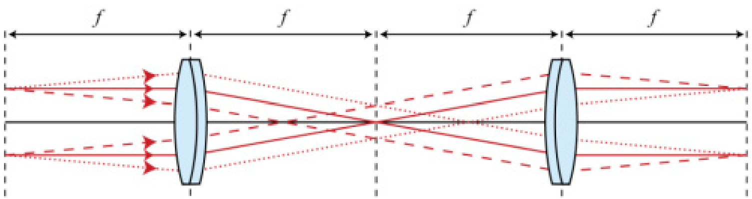
- **Telescopes**

Many telescopes are located on the benches in order to reach the beam size adapted for cavity matching or components aperture. Composed by two lenses or curved mirrors.





2 configurations for a laser beam expander are used the Keplerian one (no focal point between the optics) and the Galilean one (a focal point between the optics)



What is an afocal telescope? A telescope without a focus.
- No net convergence or divergence of the beam.
- In practice with an infinite effective focal length.
- Created with a pair of optical elements where the distance between the elements is equal to the sum of each element focal length.
- Simple example: optical telescope imaging the stars, both the object and the image are at infinity.
- Divergence of the beam is altered by the inverse of the telescope magnification.
- Width of the beam altered by the magnification.

Particular telescopes are especially designed to have aberration-free telescopes and be able to match more than 99% of the light in the Interferometer's cavities.

[1] C. Buy, E. Genin, M. Barsuglia, R. Gouaty, and M. Tacca, Design of a high-magnification and low-aberration compact catadioptric telescope for the Advanced Virgo gravitational-wave interferometric detector, *Class. Quantum Grav.,* 34 095011 (2017).
[2] M. Tacca, F. Sorrentino, C. Buy, M. Laporte, G. Pillant, E. Genin, P. La Penna, and M. Barsuglia, Tuning of a high magnification compact parabolic telescope for centimeter-scale laser beams, Applied Optics, Vol. 55, Issue 6, pp. 1275-1283 (2016).

- Deliver a stable laser beam @ 1064 nm with the requested power, frequency stability and with small power fluctuations. So that the interferometer sensitivity can be achieved.
- We are relying on continuous technologic developments which allow us to start with a 20 W injection locked laser. This laser system has been further improved to deliver 50 Watts.
- A new more powerful (able to deliver 100 W CW at 1064 nm) is being developed. Solid state laser or fiber technology being tested.
  → Challenging but seems to be able deliver the required power with the requested stability.

→ To get 200W two 100 W system will be summed coherently.

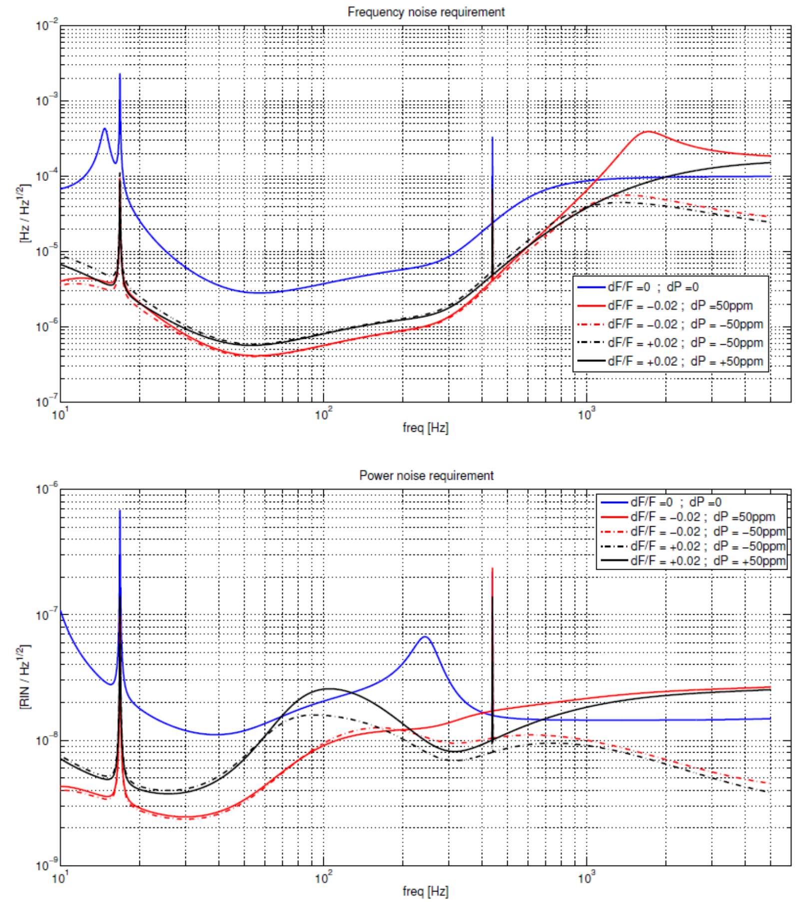


Figure 8.7: Dual recycled full power configuration, frequency and power noise requirements with a safety factor of ten used to draw the requirements from nominal sensitivity. Different values of finesse and loss asymmetries are used. Top: laser frequency noise at interferometer input. Bottom: laser intensity noise at the interferometer input. Blue curve: no defects. Red curves: dF/F = -2%; black curves: dF/F = +2%. Solid curves: dP = +50 ppm, dashed curves: dP = -50 ppm.

Requirements in term of frequency and power noise
Over the whole detector bandwidth

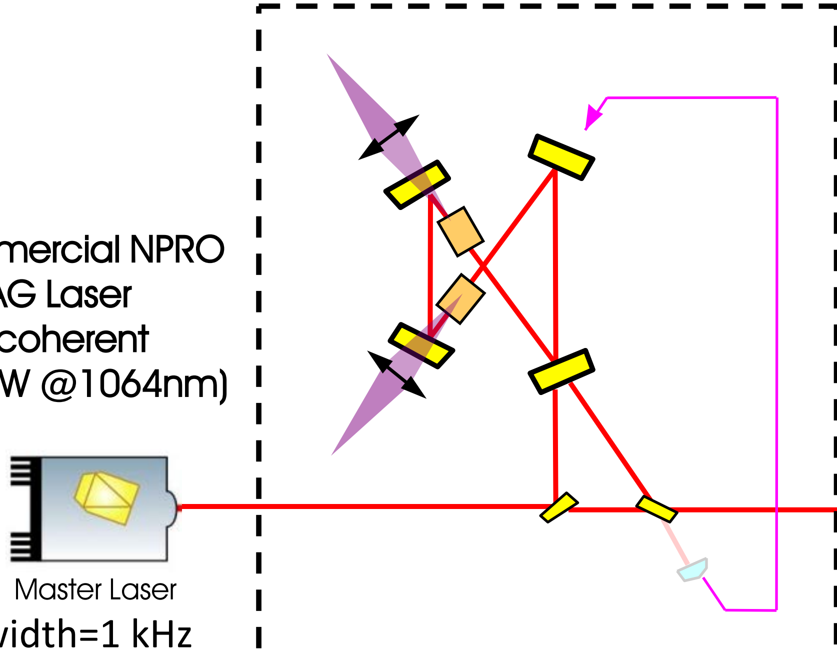
Laser frequency stability required for arm cavity locking: 1 Hz rms over 1 s.

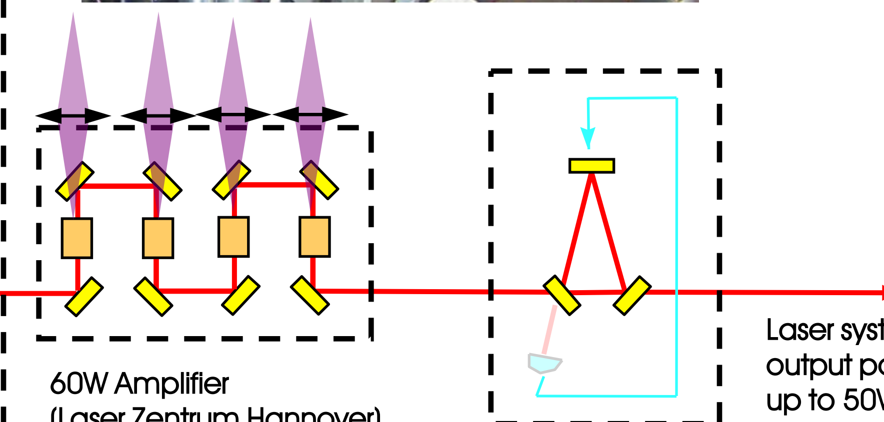
The Virgo/AdV (first phase) laser system

Four-stage end-pumped Nd:YVO4 60W amplifier

20 W Nd:YVO4 slave laser
(Laser Zentrum Hannover)
(injection-locked)

Commercial NPRO
Nd:YAG Laser
from coherent
(P=1 W @1064nm)





Laser system output power: up to 50W

Linewidth=1 kHz

Free running noise = $10^4/f$ Hz/sqrt(Hz)

Nd-YvO4 crystal

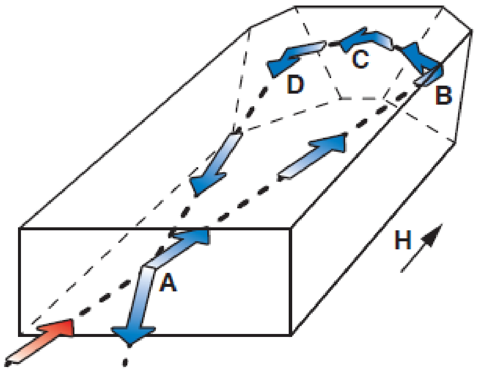
Crystal pumping module

The Pre Mode Cleaner is a triangular 13 cm long FP cavity (finesse=500), devoted to filter out the amplitude fluctuations of the laser (to be shot noise limited at the modulation frequency)

A 100 W laser system is being developed by the Virgo Artemis group (Nice, France).

The master laser

- The Master laser is a 1W Nd:YAG CW single mode @1064 nm Non Planar Ring Oscillator (from Coherent (formerly Innolight)).
- This technology has been developed in the 80s by Kane and Byer [1] and improved by Nilsson et al. [2]



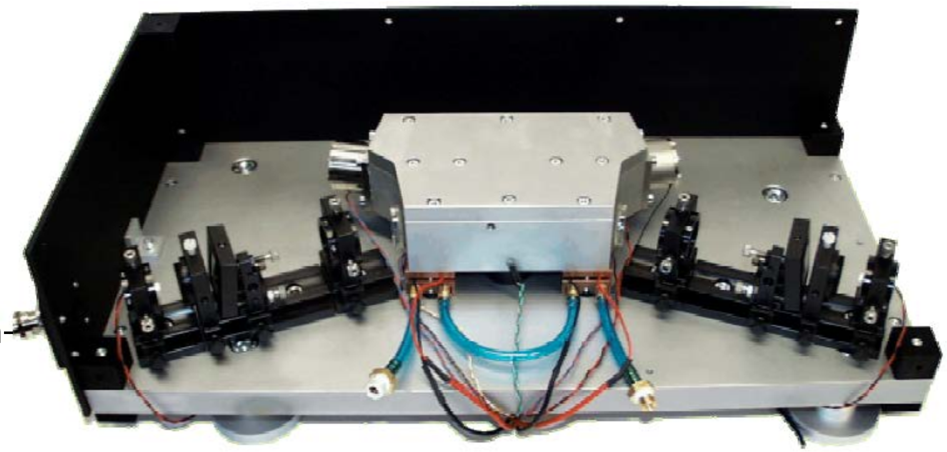
Credits: Coherent Ltd

[1] T.J. Kane, R.L. Byer: Opt. Lett. 10, 65 (1985).
[2] A.C. Nilsson, E.K. Gustafson, R.L. Byer: IEEE J. Quantum Electron. QE25, 767 (1989).
[3] Coherent white paper on NPRO lasers (https://www.coherent.com/assets/literature/white_papers/WP1_MephistoNPRO_Final.pdf#page=1)

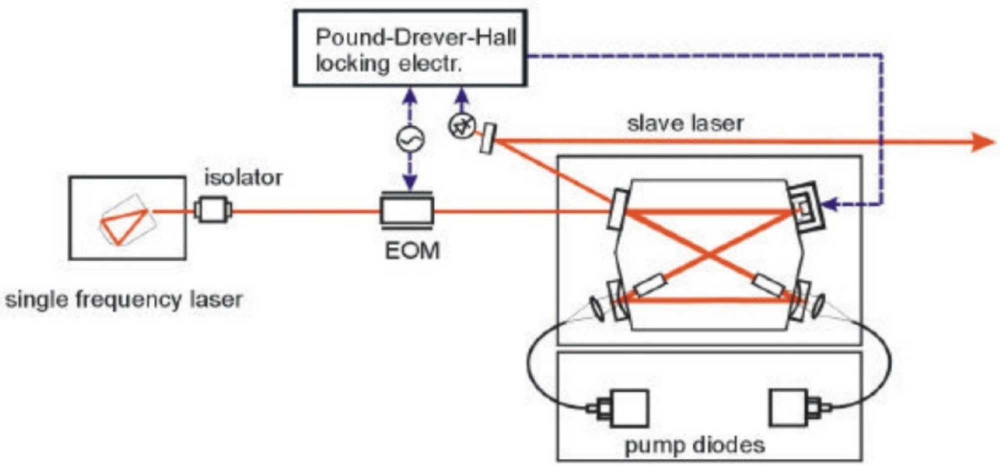
Injection locked laser

The Slave laser is a 20W ring cavity with 2 Nd:YVO4 fiber coupled pumping laser diodes (from LZH).
The output laser beam copies the master laser frequency and amplitude stability properties.

The injection locking technique:
The high output power is generated with a high-power laser system, called the ***slave laser***, the noise level of which is strongly reduced by injecting the output of a low-noise low-power **master laser** through a partially transparent resonator mirror. Provided that the frequencies of the master laser and the free-running slave laser are sufficiently close, the injection forces the slave laser to operate exactly on the injected frequency with relatively little noise. Close to quantum-limited intensity and phase noise can be achieved with this technique.

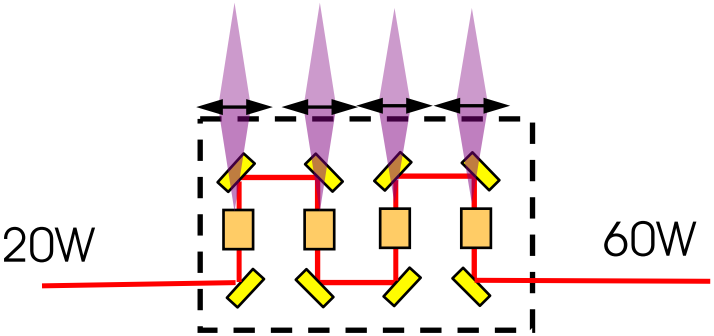


→The locking range depends on the master laser power. The higher the injected power is, the larger is the allowable frequency offset between the master laser and the slave laser's resonance.



The Laser amplifier

The amplifier is based on 4 Nd:YVO4-laser crystals. Each crystal is longitudinally pumped by a fiber-coupled laser diode with a maximum output power of 60 W @ 1064nm. This amplifier has been produced by LZH in Hannover and is used also in the LIGO laser system.

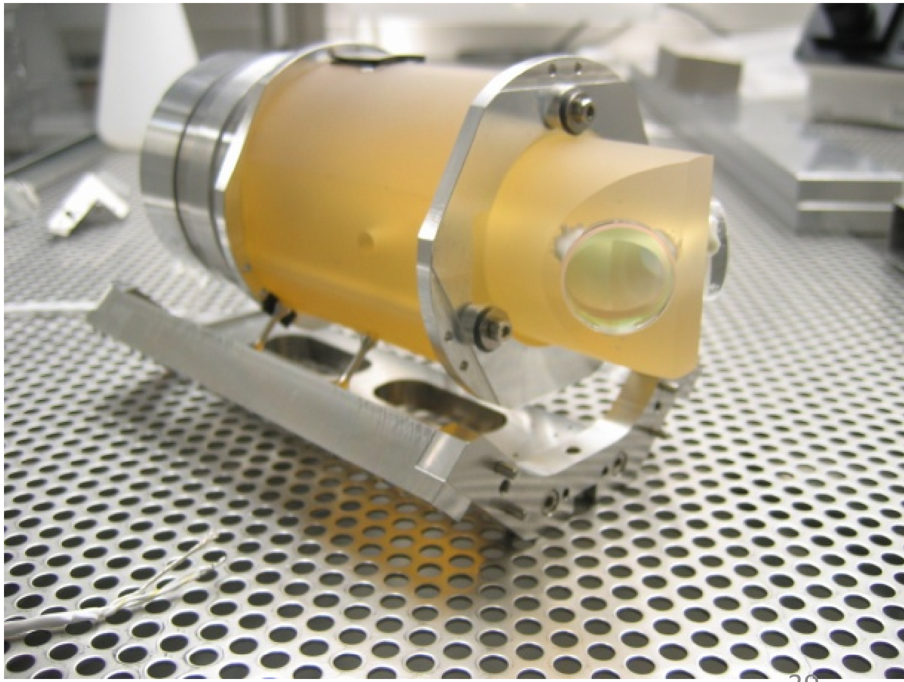


4-stages laser ampliifer

The Pre-Mode Cleaner

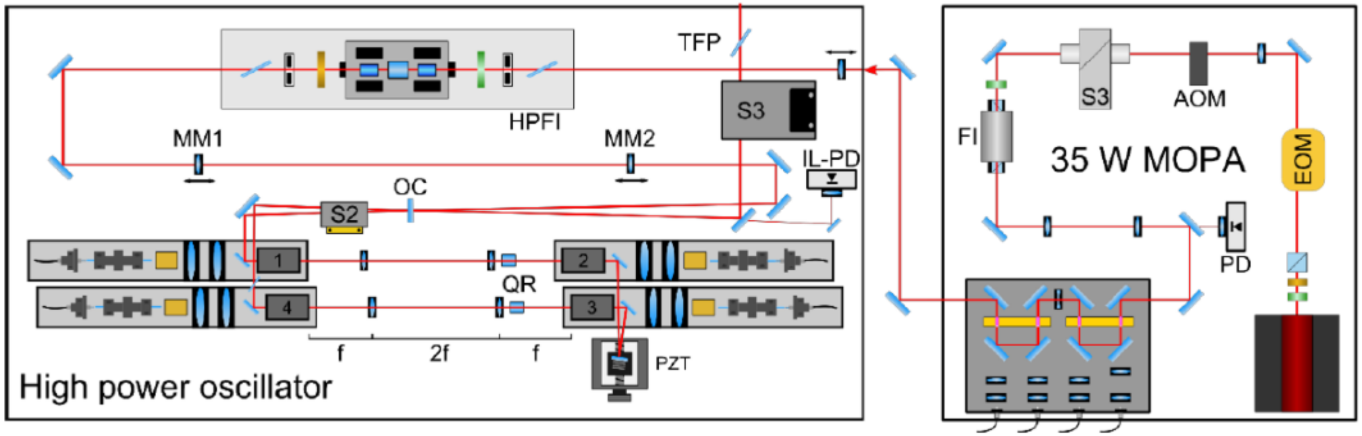
To obtain high performance from the modulation techniques, at the modulation frequency, the power fluctuations of the laser light must be shot noise limited in the amount of light detected at the interferometer output (typically up to a few tens of mWatts).
These high frequency power fluctuations are reduced by passing through a Pre Mode Cleaner cavity (a resonant triangular cavity). Above the corner frequency *fc* (FSR/2F) of the cavity, power and frequency fluctuations of the laser light are reduced by a factor *f*/*fc*.

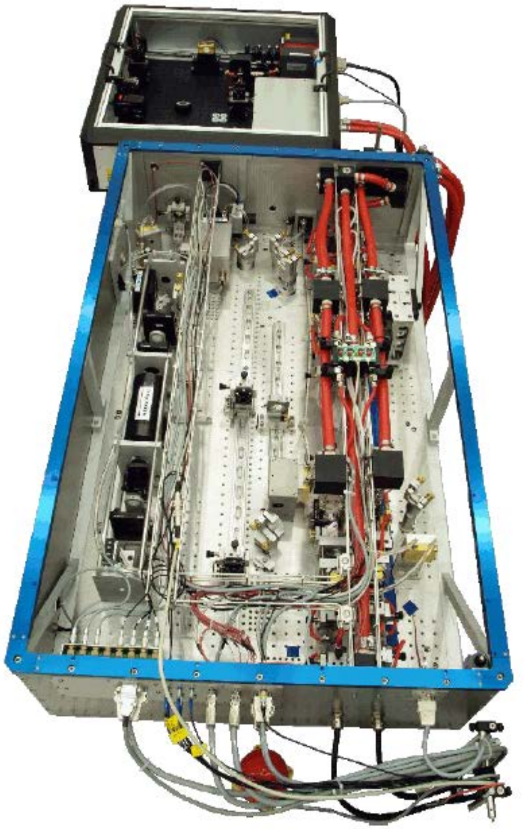
For this particular cavity, the Free spectral range is:
FSR=c/2*L with L=13cm
→ FSR=1.15 GHz.
The Finesse is 500.
Thus, the linewitdh is: 2.3 MHz and the cut-off Frequency fc=1.15 MHz. The filtering at 6 MHz (first Virgo modulation frequency) is: 1/30 and more for the higher frequency modulations.



The aLigo laser system

200 W Nd:YVO4 slave laser
(Laser Zentrum Hannover)
(injection-locked)





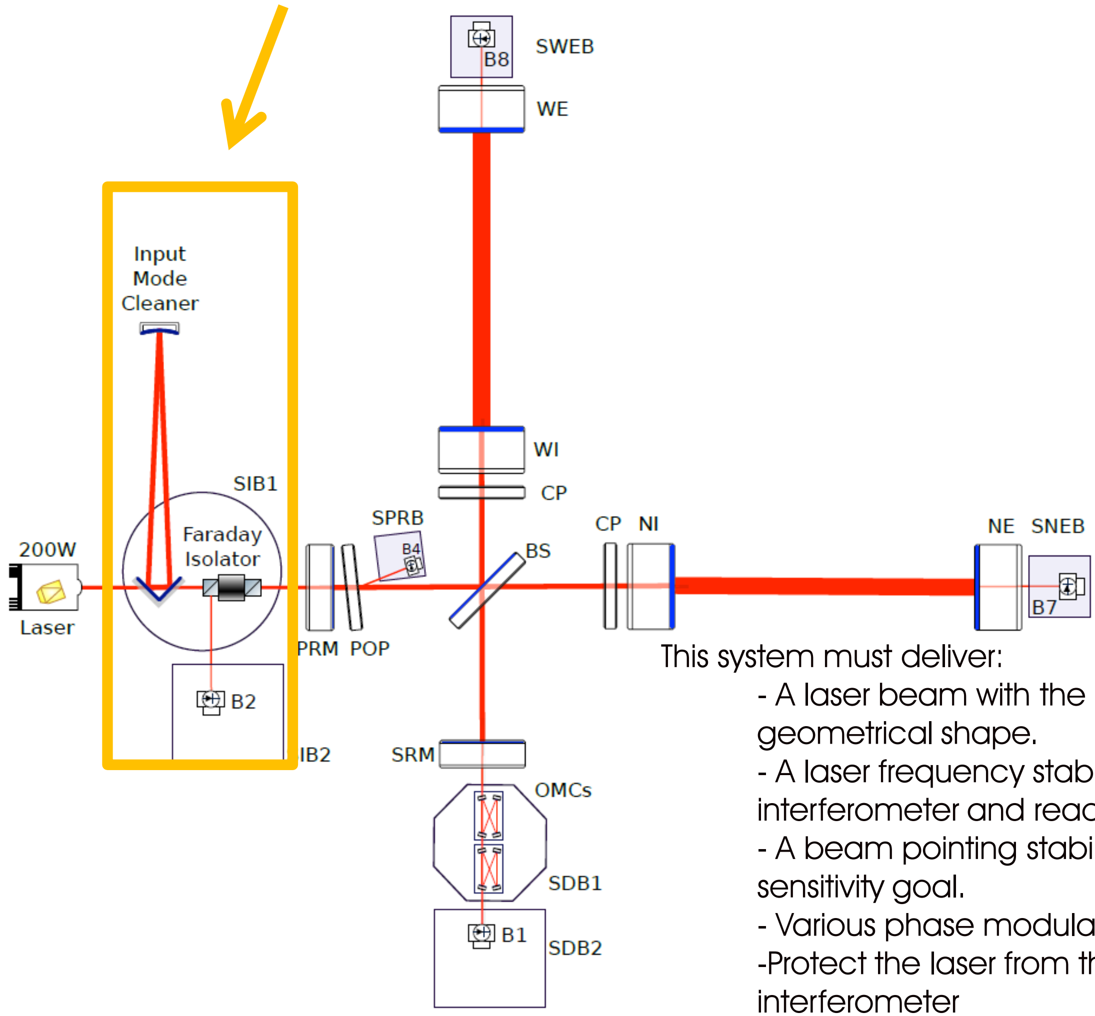
Credits: O. Puncken (LZH)

Laser Amplifier
(Laser Zentrum Hannover)

Commercial NPRO
Nd:YAG Laser
from coherent
(P=2 W @1064nm)
Linewidth=1 kHz
Free running
frequency noise = 10^4/f Hz/sqrt(Hz)

What is the Injection system?

Injection (input optics) system: optics located between the laser and the Interferometer

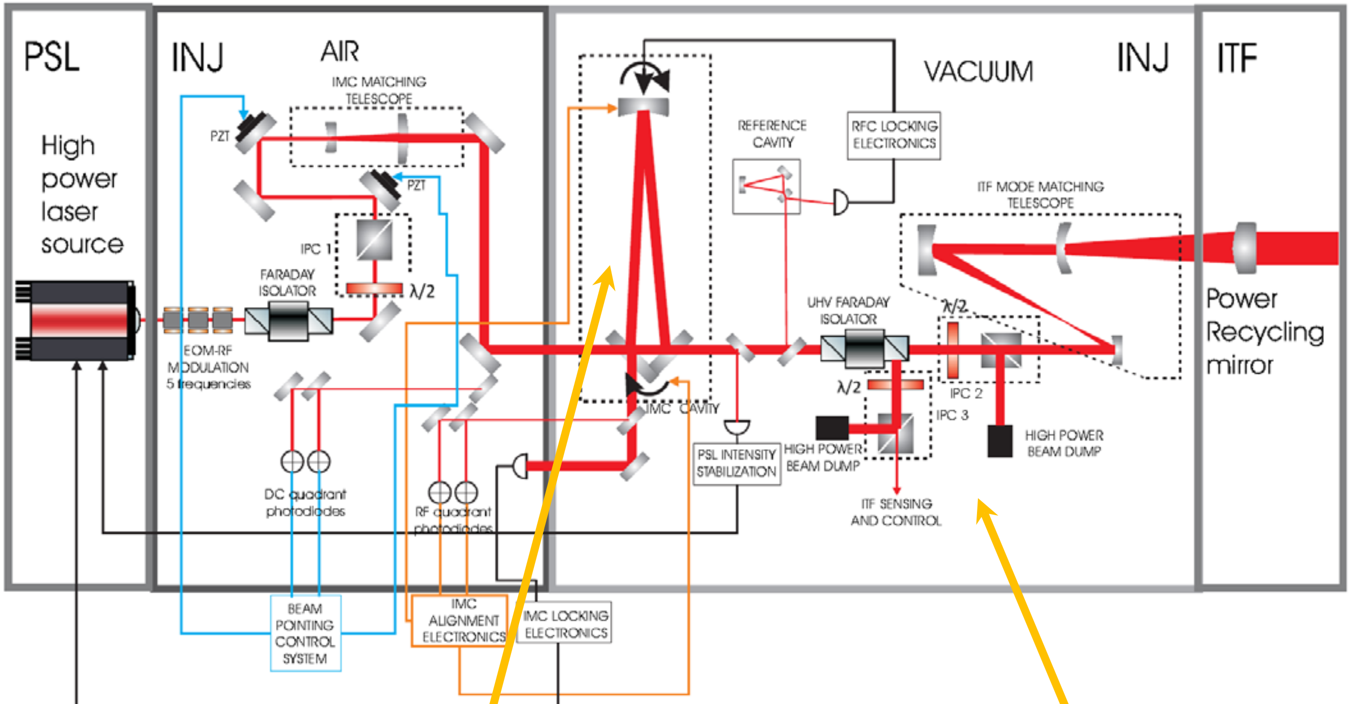


This system must deliver:

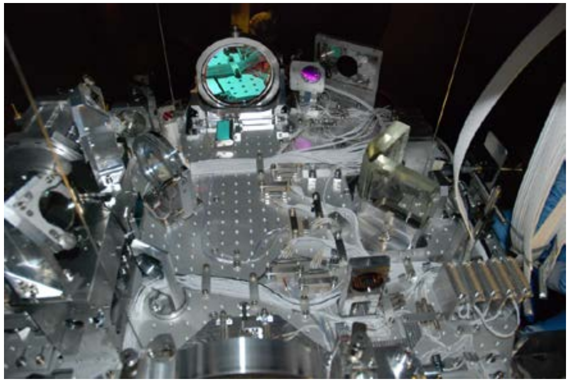
- A laser beam with the required power and geometrical shape.
- A laser frequency stability sufficient to lock the interferometer and reach the sensitivity goal.
- A beam pointing stability sufficient to reach the sensitivity goal.
- Various phase modulations of the laser beam.
- Protect the laser from the beam reflected by the interferometer

-The system should be able withstand high continuous laser power (up to 200W).

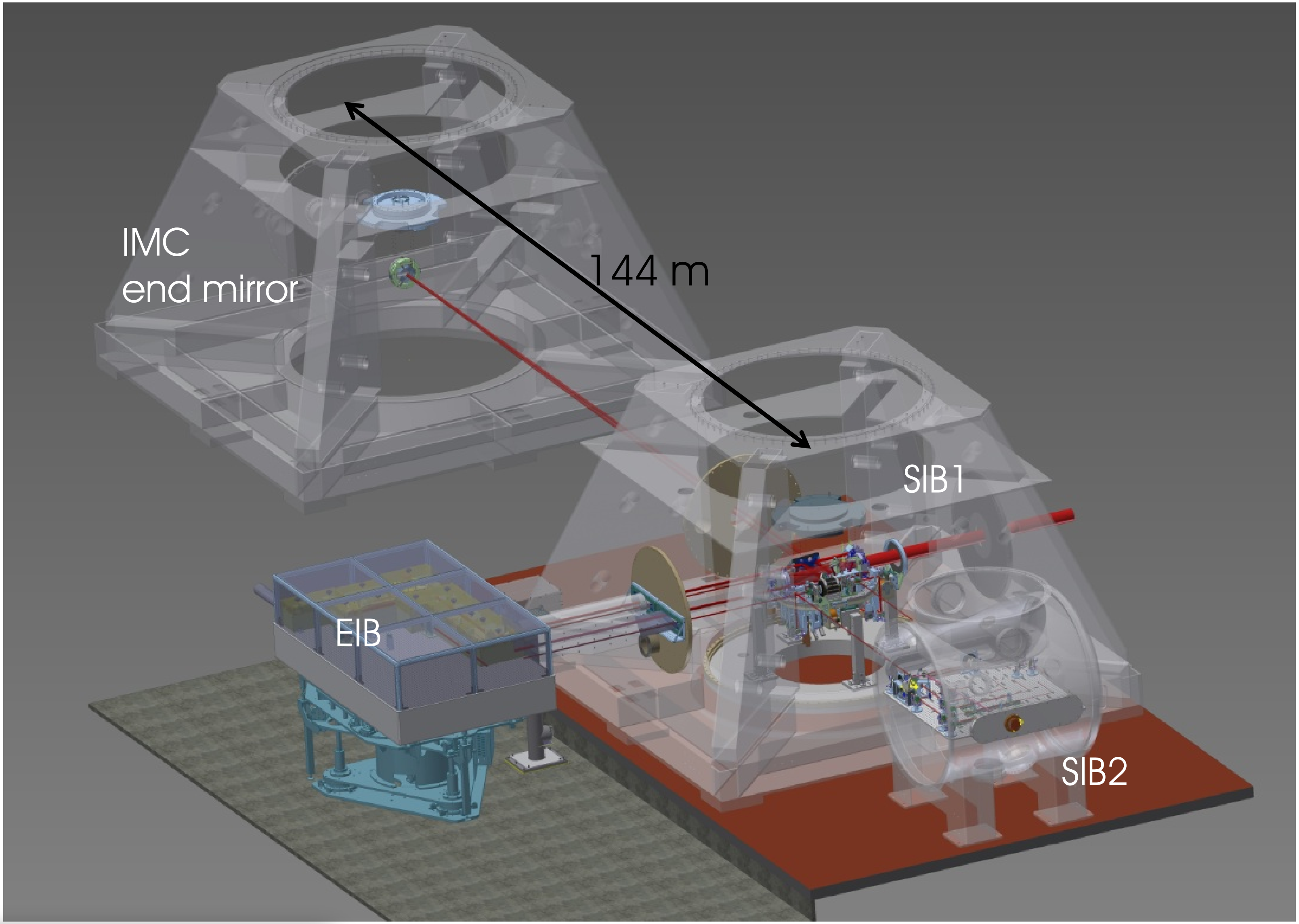
The injection (input optics) system



144m long filtering cavity



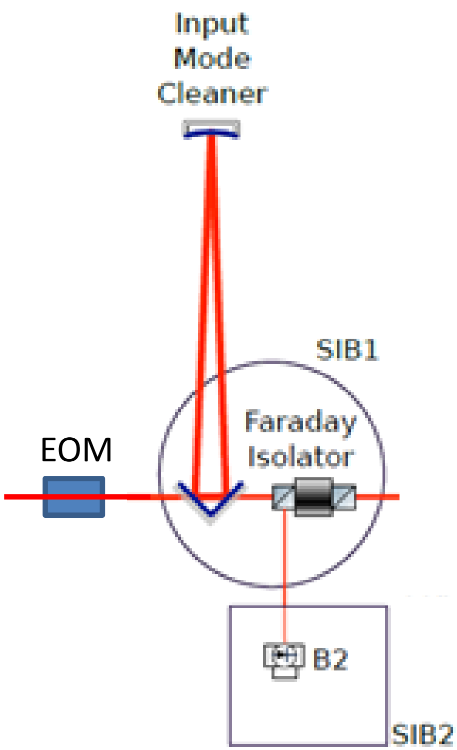
E. Genin


IMC
end mirror
144 m
SIB1
EIB
SIB2

The Injection system of AdV takes care of the optics downstream of the high power laser, and of the interface of these optics with the laser and the Interferometer.

Main components:

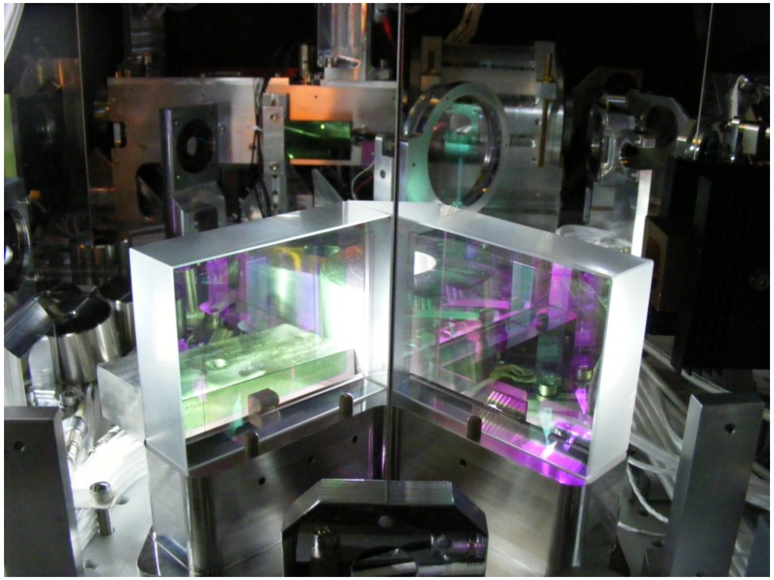
- Electro optic modulation system: Phase modulation of the laser beam to control the optical cavities and the interferometer.
- Input Mode Cleaner cavity: passively filter out amplitude, frequency and beam jitter noise. Laser frequency pre-stabilization.
- Faraday isolator: isolates the Laser from the back-reflected light of the interferometer.
- Mode matching optics: Adjust the beam dimension to properly match it on the interferometer to reduce as much as possible the light lost from the Laser bench to the ITF
- Reference cavity: Laser frequency pre-stabilization and in data-taking mode low frequency reference.

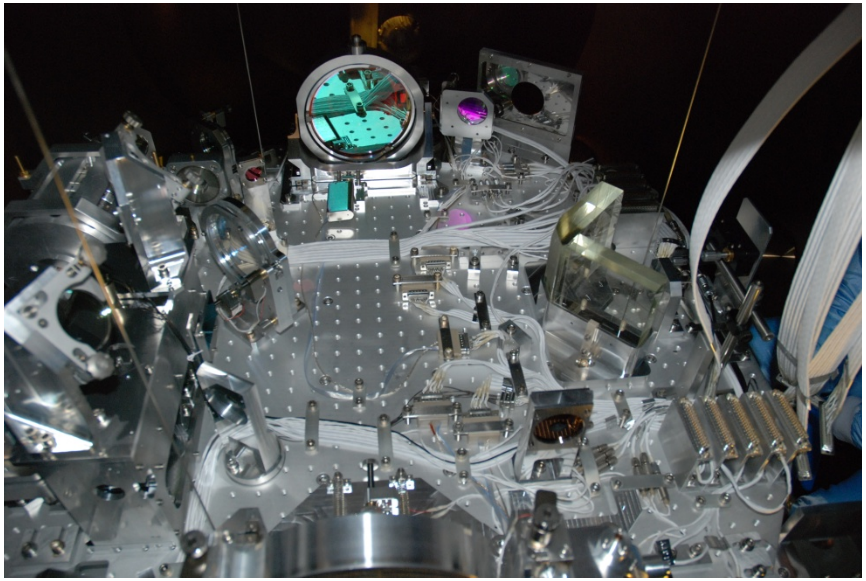


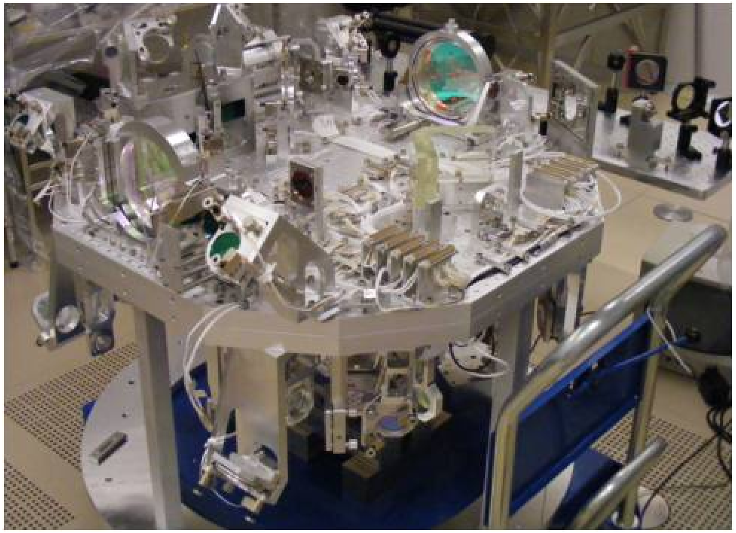
Parameter	Requirement
Transmission to the ITF	$> 70\%\ TEM_{00}$
Non-TEM_{00} power	$< 5\%$
Intensity noise	$2 \times 10^{-9}/\sqrt{(Hz)}$ at 10 Hz
Beam Jitter	$< 10^{-10}$ rad$/\sqrt{(Hz)}$ (f >10 Hz)
Frequency noise (for lock acquisition)	<1 Hz r.m.s

Requirements from the Technical report

Complex optical systems design and realization







→ Ultra high vacuum compatible optical table used to inject the Laser beam in the Virgo Interferometer.
Used also to pre-stabilize the laser frequency (a rigid cavity is hanged to this table)

Electro optic modulator

- Function: Phase modulate the laser beam at RF modulation frequencies needed for the control of the interferometer. We use the heterodyne detection technique which is commonly used to detect and analyze signals (radars, astronomy, telecommunications).
- Requirements:
  - Withstand 200W CW laser power @1064nm.
  - Limited thermal lensing effect (low absorption crystal used (RTP)).
  - Maximum modulation depth = 0.2 rad.
  - Low phase noise (mostly related to the RF oscillator).
  - Low Residual Amplitude modulation (RAM) noise.

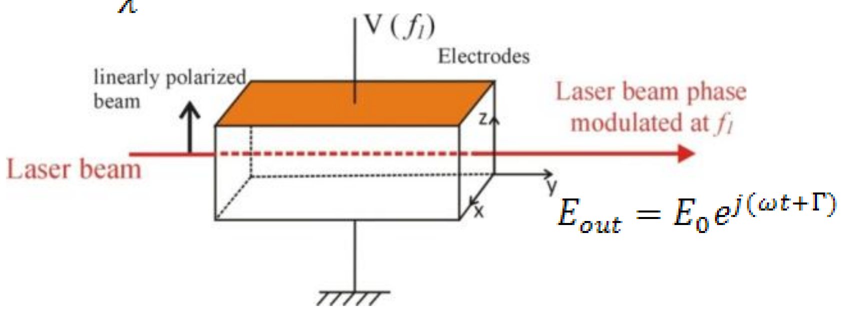
Applications:
- Optical cavities locking (heterodyne detection)
- Frequency- modulation spectroscopy (low RAM required)
- Telecommunications?

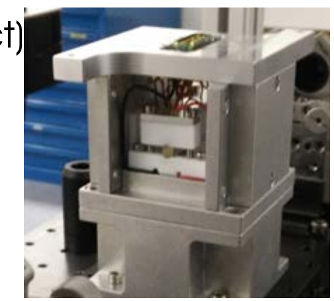
- Reminder:
  Phase shift induced by the electric field (Pockels effect)

$$\Gamma = \frac{2\pi}{\lambda} n_z L = \frac{2\pi}{\lambda} L(n_e - 0.5 n_e^3 r_{33} E_z) \qquad E_z = V/d$$

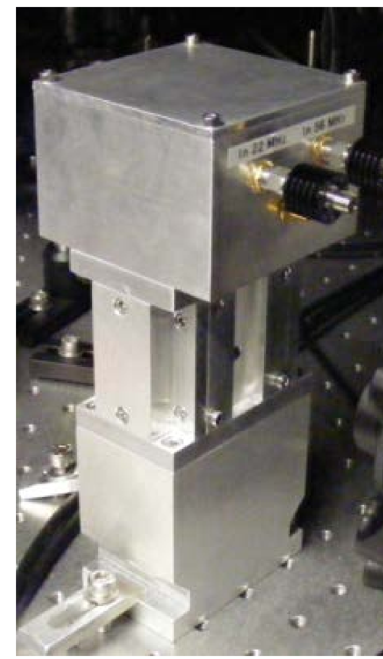
Modulation depth

$$\mathrm{m} = \frac{\pi}{\lambda} L(n_e^3 r_{33}) V_z/\mathrm{d}$$





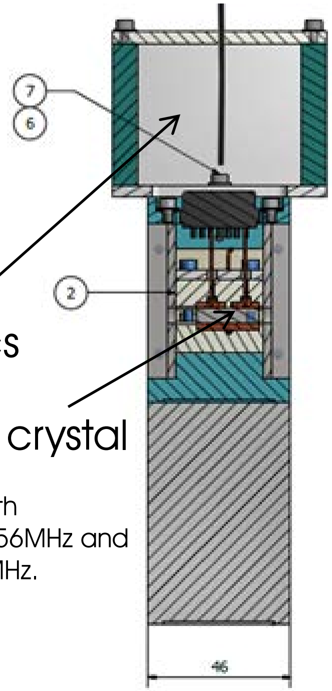
Electro optic material chosen:
Rubidium Titanyle Phosphate – RbTiOPO4



2-frequencies EOM

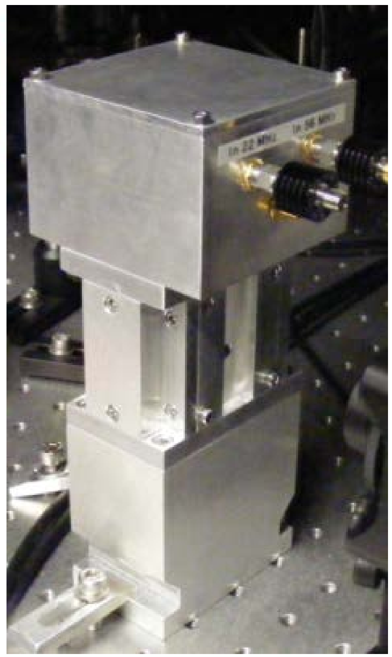
Electro optic modulator

In Virgo, 6 different modulation frequencies :
14.31 MHz (laser system), 6.27 MHz, 8.36 MHz, 22.304 MHz (IMC), 56.43 MHz, 119.144 MHz



Driving electronics

Electro-optic crystal



Maximum modulation depth achievable : m > 0.18 for 56MHz and m > 0.25 for 6, 8 and 22 MHz.

2-frequencies EOM

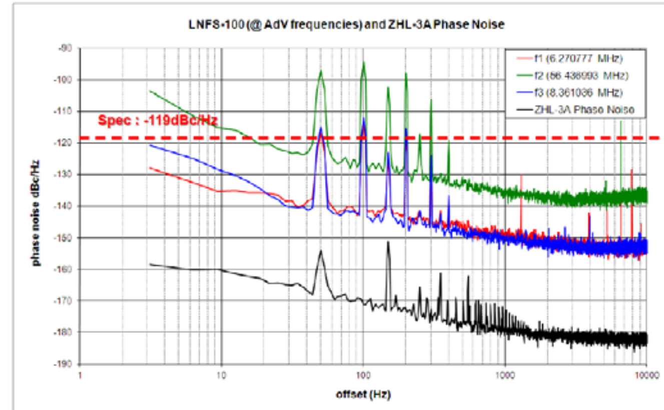
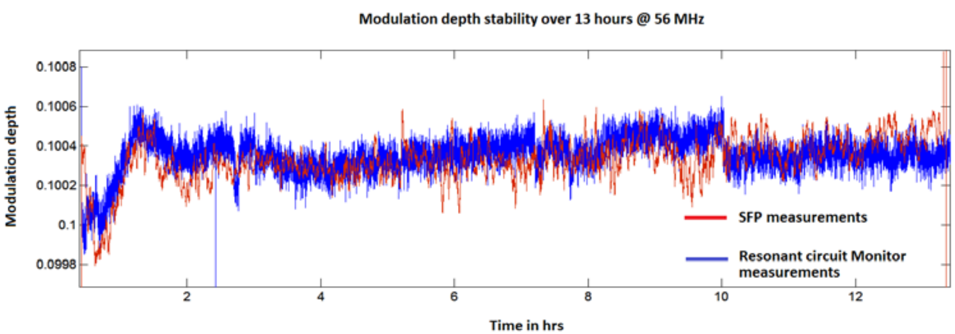


Figure 4.11: Measurement of the phase noise for f_1, f_2 and f_3 delivered by the LNFS-100 function generator. The black curve corresponds to the residual phase noise produced by ZHL-3A RF amplifier.

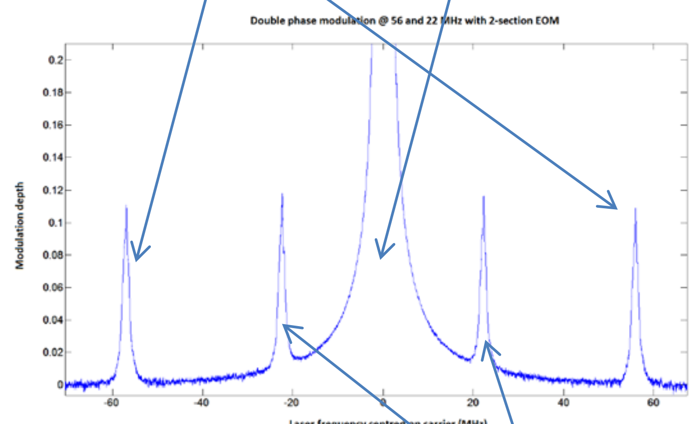
RF oscillator phase noise



Modulation index stability

Sidebands @56 MHz

carrier



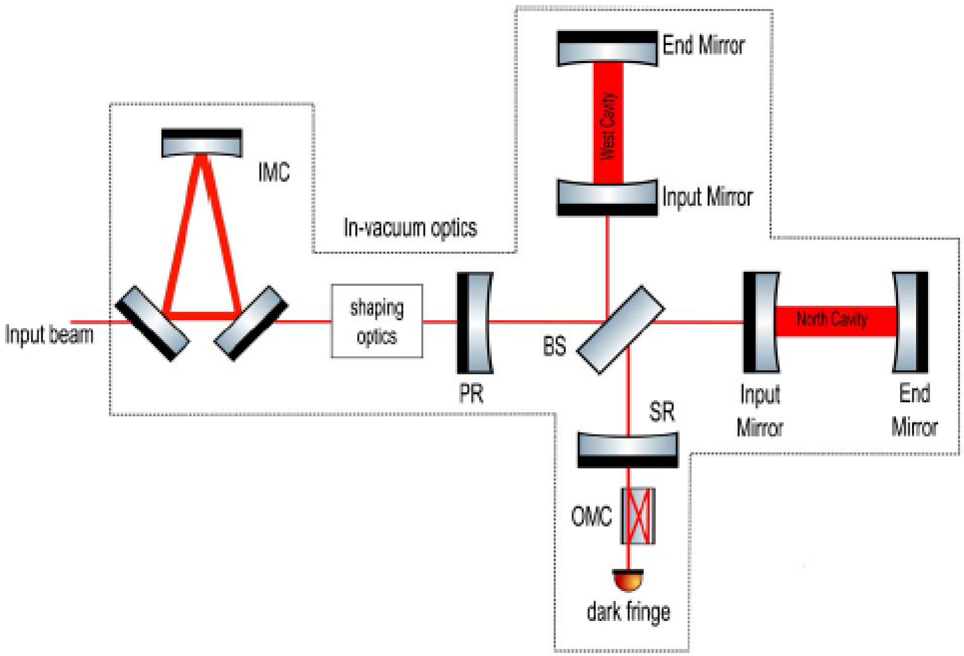
Modulation index measurement with scanning Fabry Perot (Optical spectrum analyzer)

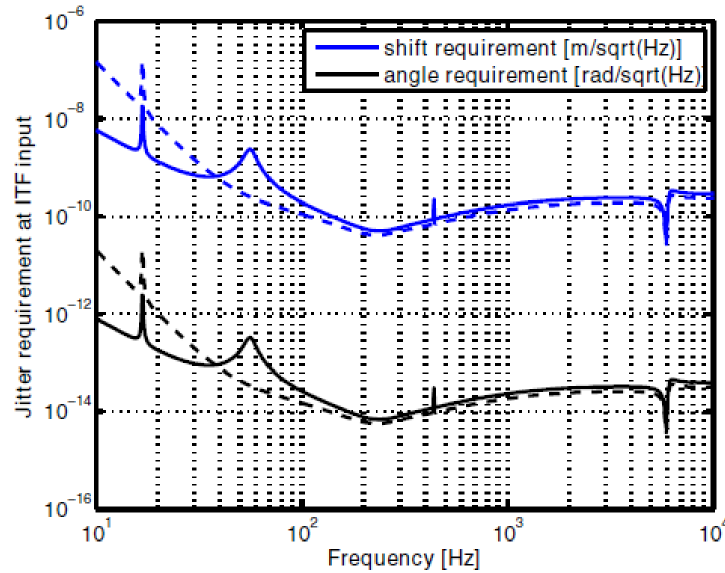
Sidebands @22 MHz

E. Genin

Beam jitter coupling into the interferometer

Beam pointing noise can spoil the ITF sensitivity





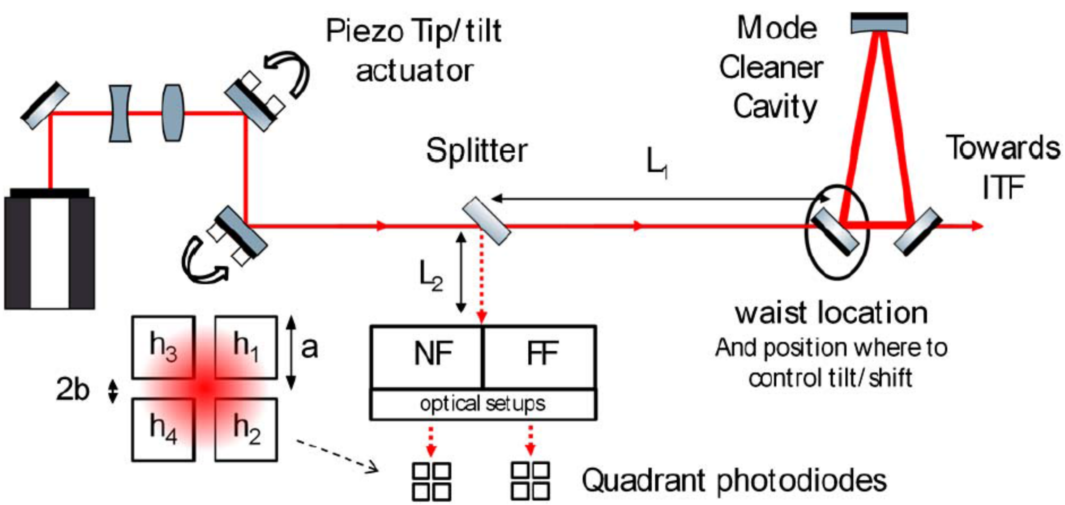
AdV specifications for the beam jitter

- The beam jitter, time dependent changes in the location of the impinging laser field originates from unsuspended optical components that steer the laser into the ITF or from active components such as laser/electrooptic components.
- Any jitter, angular or lateral, can be described as a pair of sidebands separated from the carrier by the jitter frequency.
- The spatial mode of these sidebands is the first order mode (TEM_{10}-TEM_{01} in Hermite-Gauss basis) propagating with the fundamental one (TEM_{00}).
- The complex amplitude $|a_1|$ of this mode can be evaluated from the displacement (y) and the tilt (β):

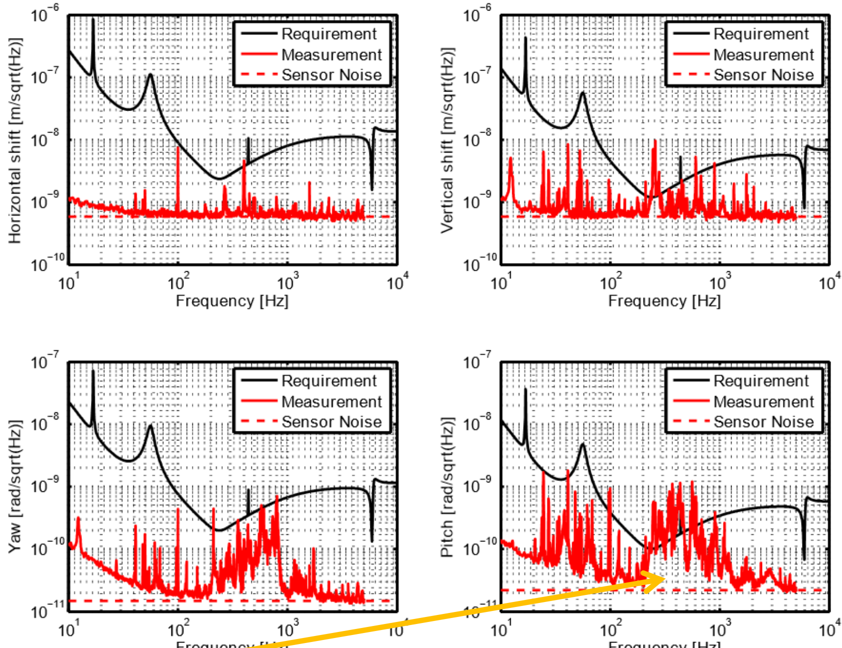
$$|a_1| = \sqrt{\left(\frac{\tilde{y}}{\omega}\right)^2 + \left(\tilde{\beta}\,\frac{\pi\omega}{\lambda}\right)^2}$$ Where ω, the beam waist and λ, the laser wavelength.

Why is a BPC system needed?

- The beam should always be stable at the right position at the input of the interferometer.
- The BPC (Beam Pointing Control system) system reads and adjusts the position of the beam at the input of the IMC and, in consequence, at the input of the interferometer.
- The BPC system monitors and stabilizes also the jitter (angular and lateral) of the input beam.



Scheme of the Beam Pointing Control system

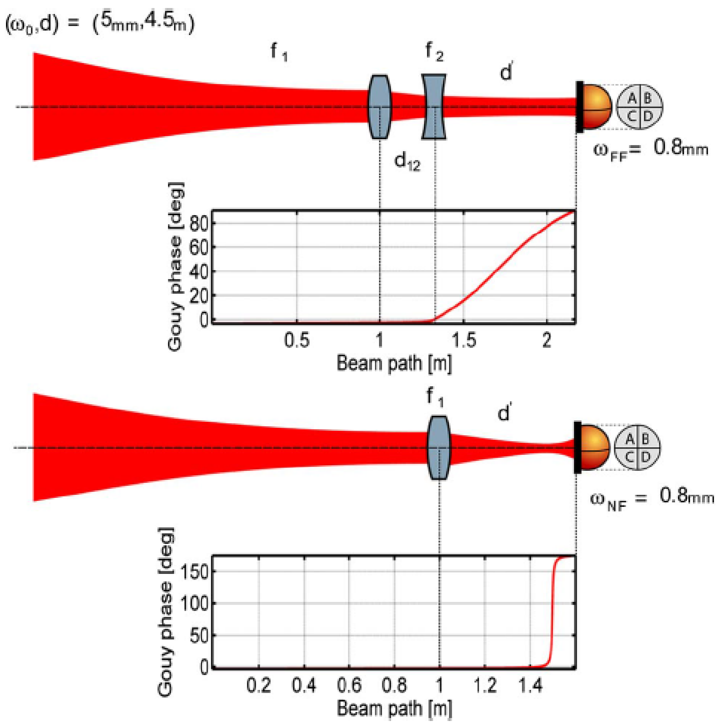


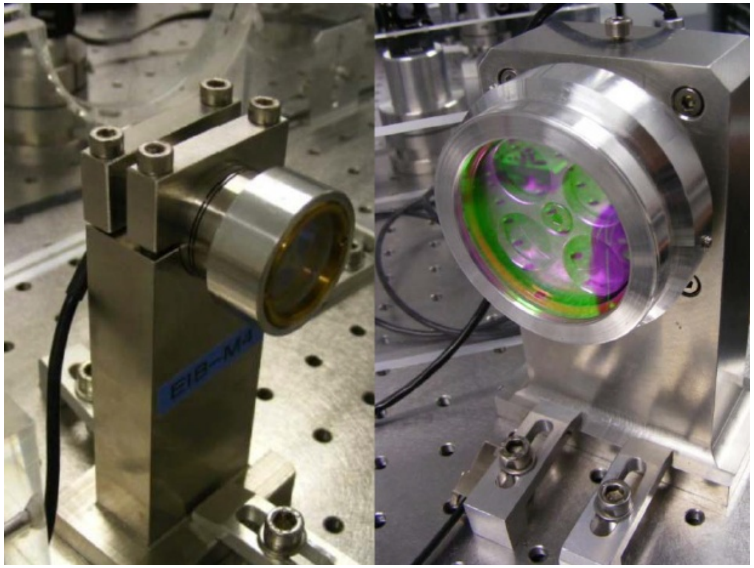
Those structures are excited by acoustic and seismic noise

Performances vs requirements (an example)

Beam jitter sensing and actuation

❑ To measure the beam jitter, quadrant photodiodes are used as sensors.
❑ One sensor is put in the Near Field and the other is put in the Far Field. The Gouy phase shift between NF and FF is 90º. It allows to decouple the measurement of beam direction and position.
→ Input beam jitter measured with the BPC quadrants can be used to estimate the angular and lateral jitter at the input of the interferometer.





The mirrors for actuation are mounted on tip/tilt piezoactuators.

Why an Input Mode Cleaner cavity is needed?

- The beam at the output of the laser can be characterized by the presence of some transversal higher-order modes.

- At the input of the interferometer a pure fundamental Gaussian mode beam is needed.

- Before entering in the interferometer the laser beam passes through a cavity whose role is to suppress all the higher-order mode other than the Gaussian one.

- Also the beam jitter of the laser beam must be filtered out

- The laser frequency must be very stable (avoid laser frequency jitter).

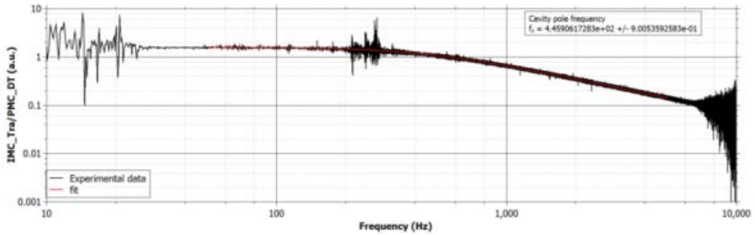
Input Mode Cleaner cavity

- Function: Beam spatial filtering, filter out beam jitter (1/*F*), to be used in Laser frequency stabilization loop, filter out frequency and power noise above its pole
- Main characteristics:
  - 144 m long suspended triangular resonant cavity (FSR=1.045 MHz)
  - *F* = 1000

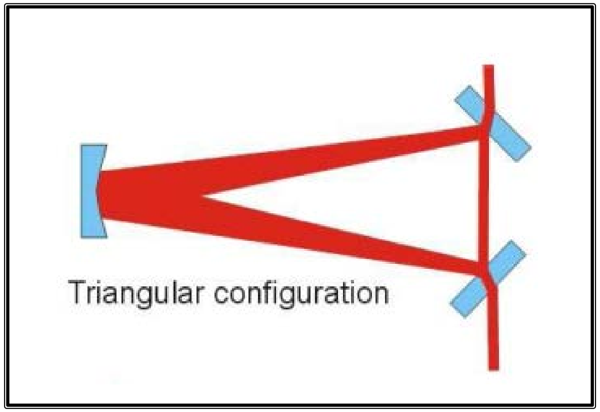
→ Cut-off frequency (cavity pole)≈ 500 Hz.

Parameter	Measured value
FSR	1045137 Hz +/- 0.5 Hz
IMC Length	143.4225 m
Pole	520Hz +/- 2 Hz
Finesse	1005 +/- 4
Round-Trip losses	222 ppm+/-24 ppm
IMC cavity throughput	92.9 % +/- 0.5%
Transmission (mirror #1)	T1=3015 +/-15 ppm
Transmission (mirror #2)	T2=3015 +/-15 ppm
Absorption flat mirrors	<1ppm / mirror
Absorption End mirror	3ppm

Applications:
- Laser Frequency stabilization
- Laser beam cleaning (M^2 close to 1)

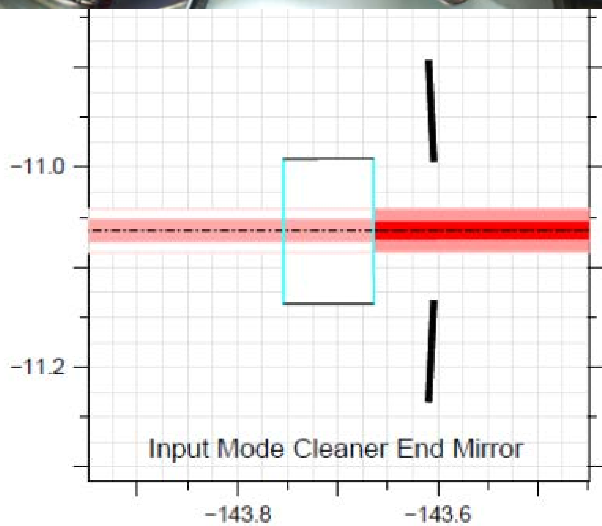


Example of IMC cavity pole measurement (injecting power noise before the cavity)

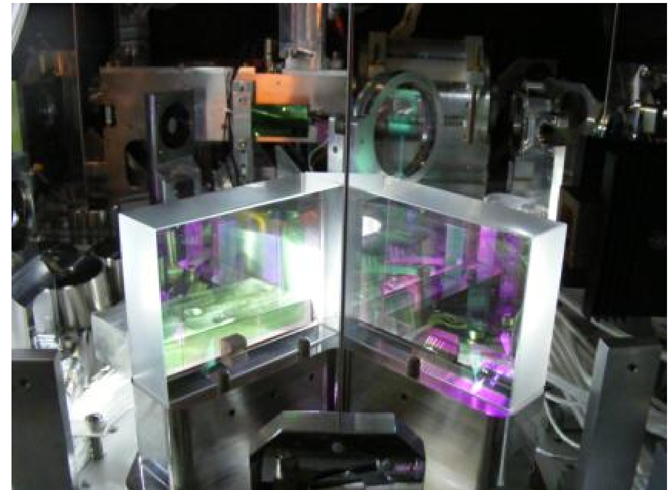


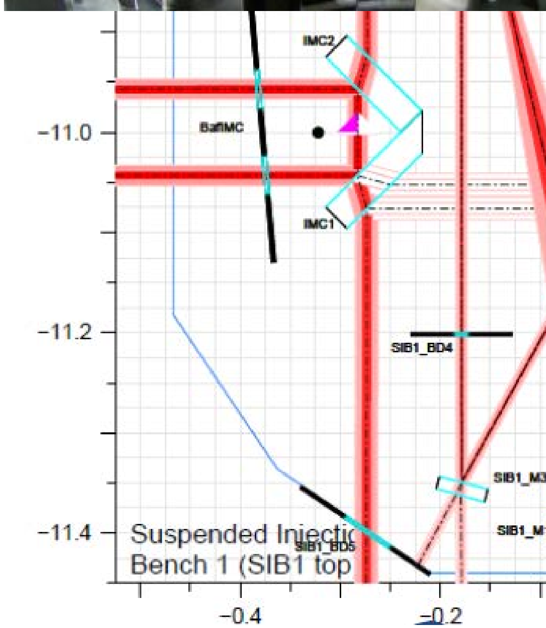
Input Mode Cleaner cavity: A few pictures

MC end mirror in MC tower

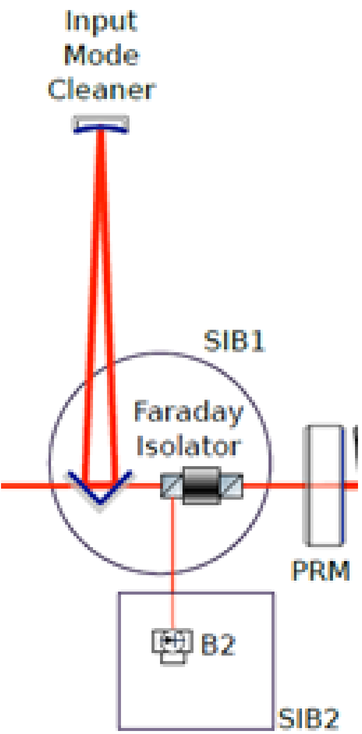


IMC dihedron (input and output flat mirrors optically contacted) on SIB1

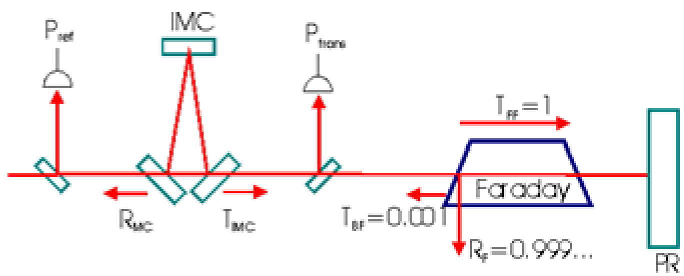


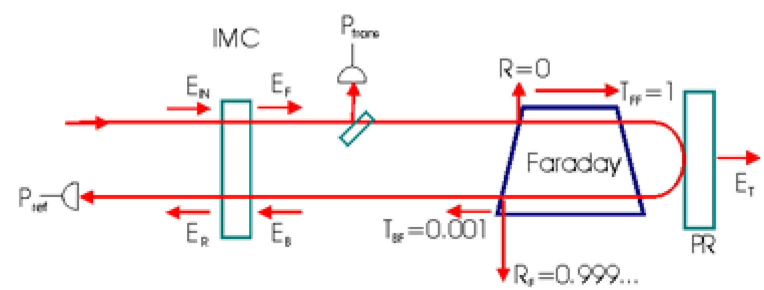


Vacuum compatible Faraday isolator



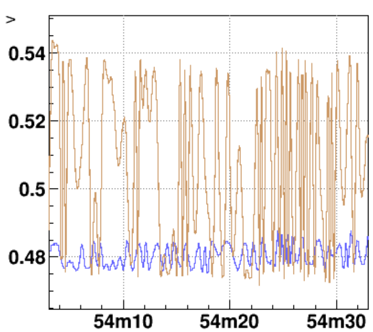
- Function:
  - avoid to create a spurious cavity Input Mode Cleaner/ Interferometer.
    Due to the fact that IMC cavity is long (144m), we have a small angle of incidence on 1 mirror of the cavity and the back-scattered light from this optics can easily be recoupled in the IMC cavity



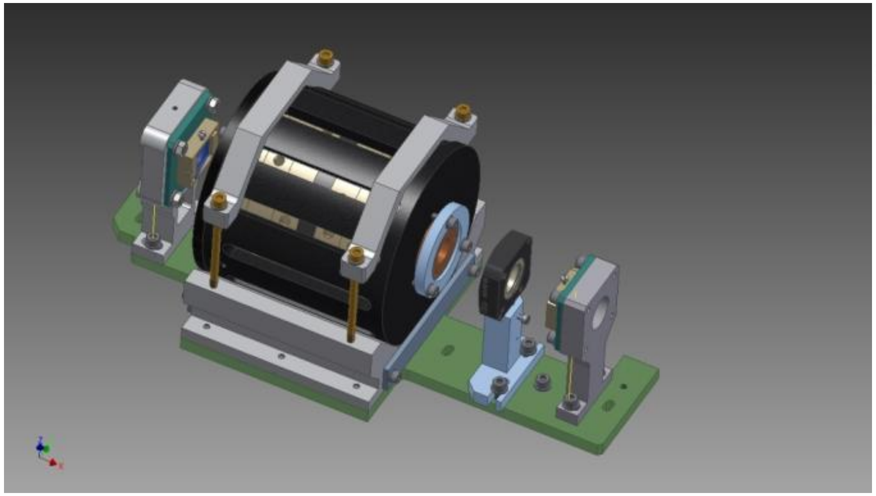


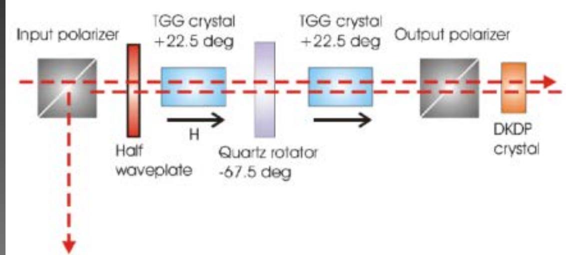
- have an easy way to get the interferometer reflection (to be used for the interferometer control).
- avoid to re-inject light in the laser system and damage it.

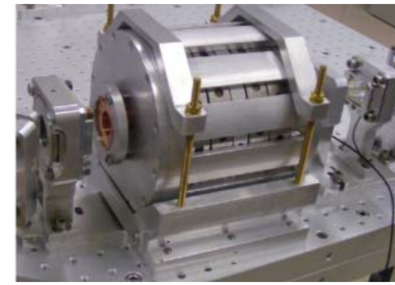
In order to reduce these effects, we have to install a Faraday isolator between the IMC and the interferometer.



- A vacuum compatible Faraday isolator has been developed in collaboration with the Institute of Applied Physics (Russia) and the University of Florida (LIGO group)

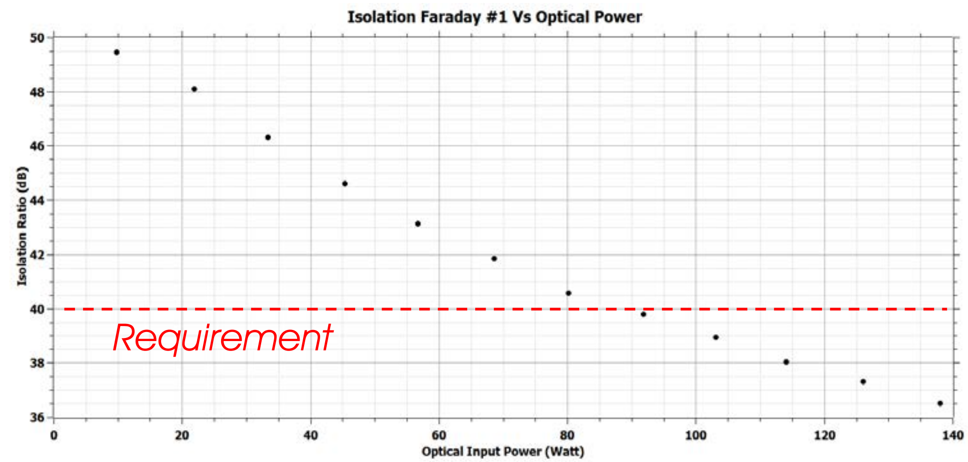






Parameter	Requirement
Isolation(low to 150 W)	$\geq$ 40 dB
Total throughput	$\geq 95\%$
Residual thermal lens	$>$ 100 m or $<$0.01 diopters at 150 W
Clear aperture	$\geq$ 20 mm
Vacuum compatibility	$< 10^{-6}$ mBar

UHV Faraday isolator requirements



Isolation ratio vs laser input power

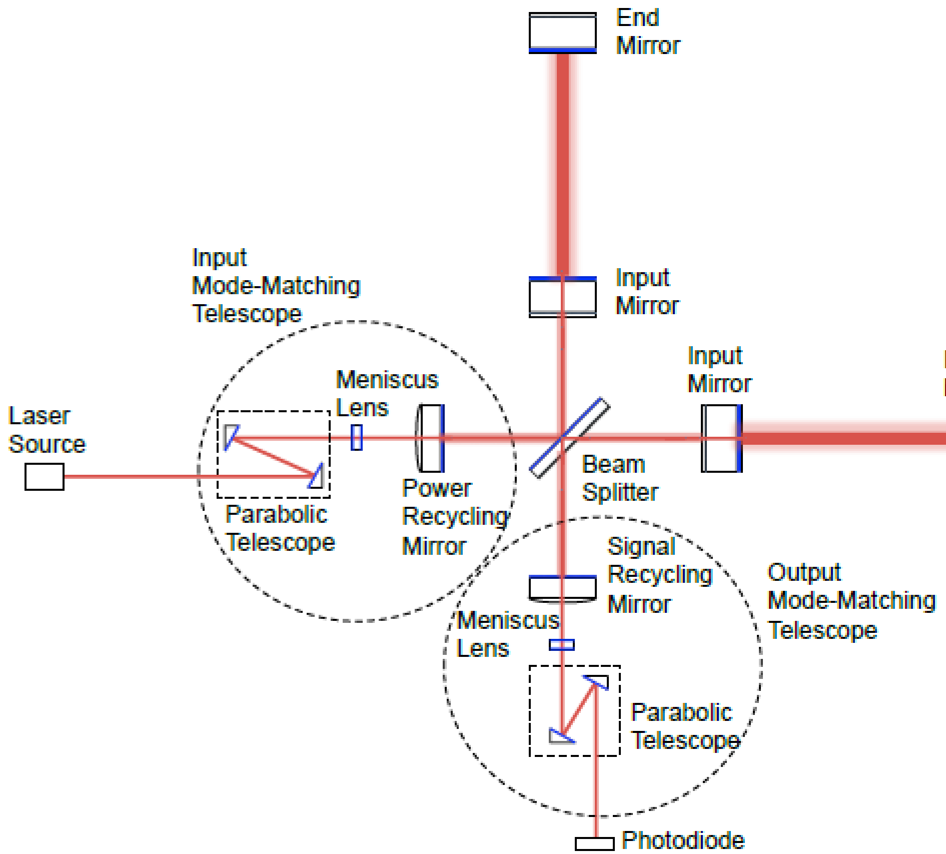
Reference:
[1] O. Palashov, D. Zheleznov, A. Voitovich, V. Zelenogorsky, E. Kamenetsky, E. Khazanov, R. Martin, K. Dooley, L. Williams, A. Lucianetti, V. Quetschke, G. Mueller, D. Reitze, D. Tanner, E. Genin, B. Canuel, and J. Marque, High-vacuum compatible high-power Faraday isolators for gravitational-wave interferometers, JOSA B, Vol. 29, Issue 7, pp. 1784-1792 (2012).

Why are Mode matching telescopes needed?

❑ The beam at the output of the laser is very different (for what concerns the dimension of the mode) from the one that resonates inside the cavities of the interferometer.

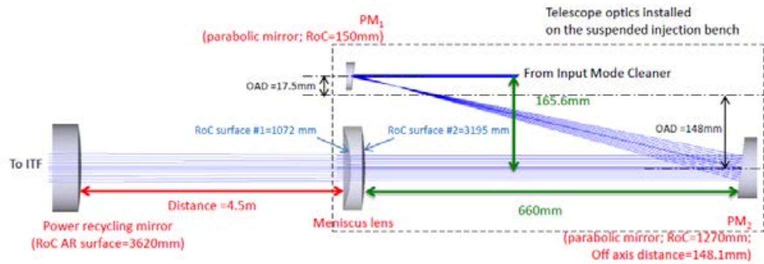
❑ Two mode matching telescopes (MMT) are part of the INJ system: one to match the beam onto lthe MC, the other to match the beam onto the interferometer. Those devices should be remotely adjustable.

❑ Requirements of the ITF MMT:
- ❑ mode matching > 99 %.
- ❑ low noise coming from the scattered and back-reflected light.
- ❑ magnification sufficient to separate the secondary beams.
- ❑ quite small dimensions (space constraints on SIB1).
- ❑ very low aberrations.



High magnification beam expander/reducer

- Due to the large laser beam and the limited space available, we had to design an original and compact design for the launching telescope for Advanced Virgo. This is a catadioptric system.



Applications:
- Astronomy (Laser guide stars)
- Whatever experiment which need a high magnification compact laser beam expander

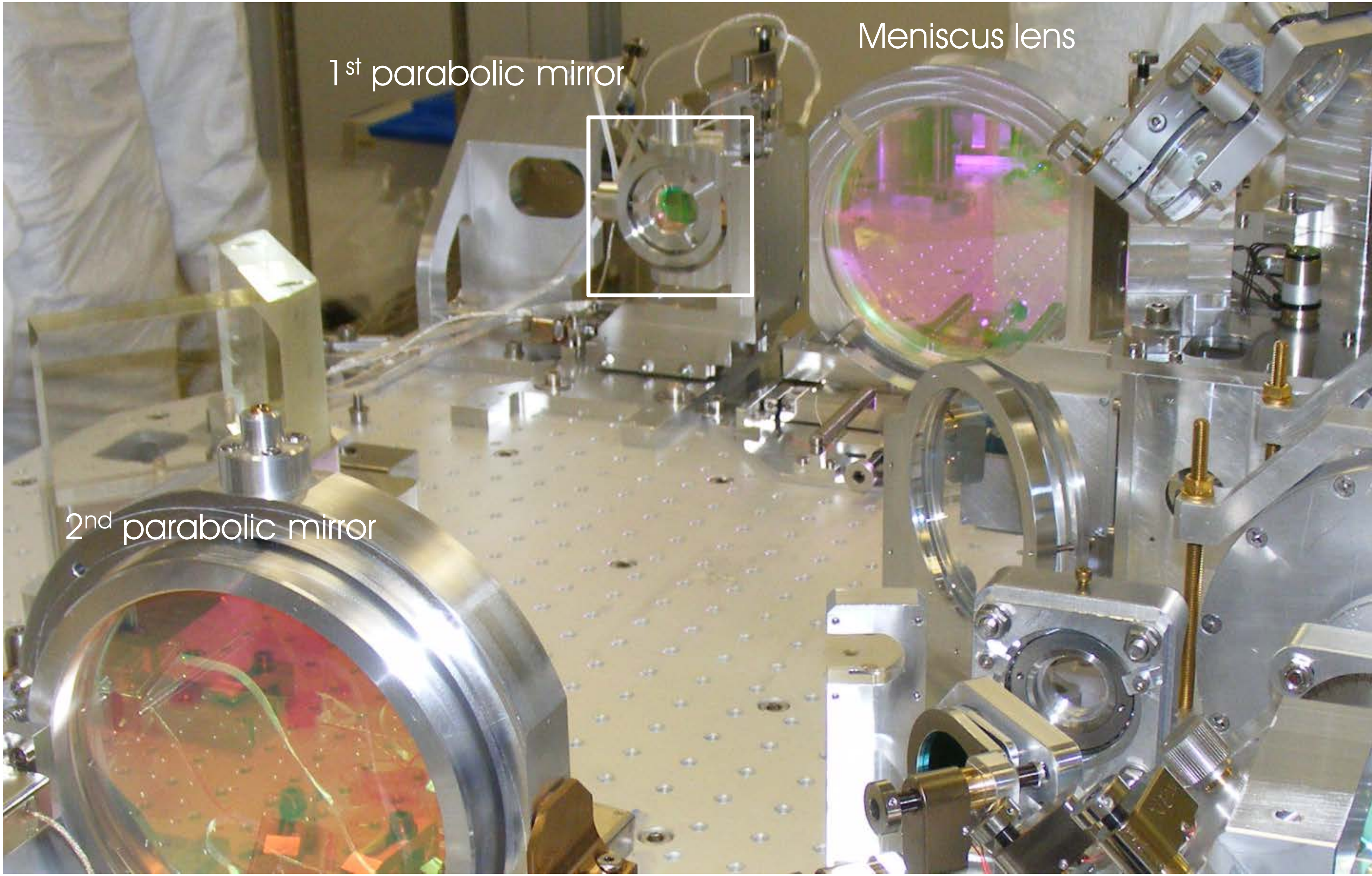
→ This design has been chosen by the AdV Project for the interferometer input and output telescopes.

- Optimization has been made keeping in mind the compactness and the lowest possible aberrations (in particular spherical aberrations compensation was required as well as low astigmatism).
- Scattered light has been studied to determine the requirements on optics surface errors and on baffling.

→ modematching higher than 98.4% has been measured on both arm cavities.

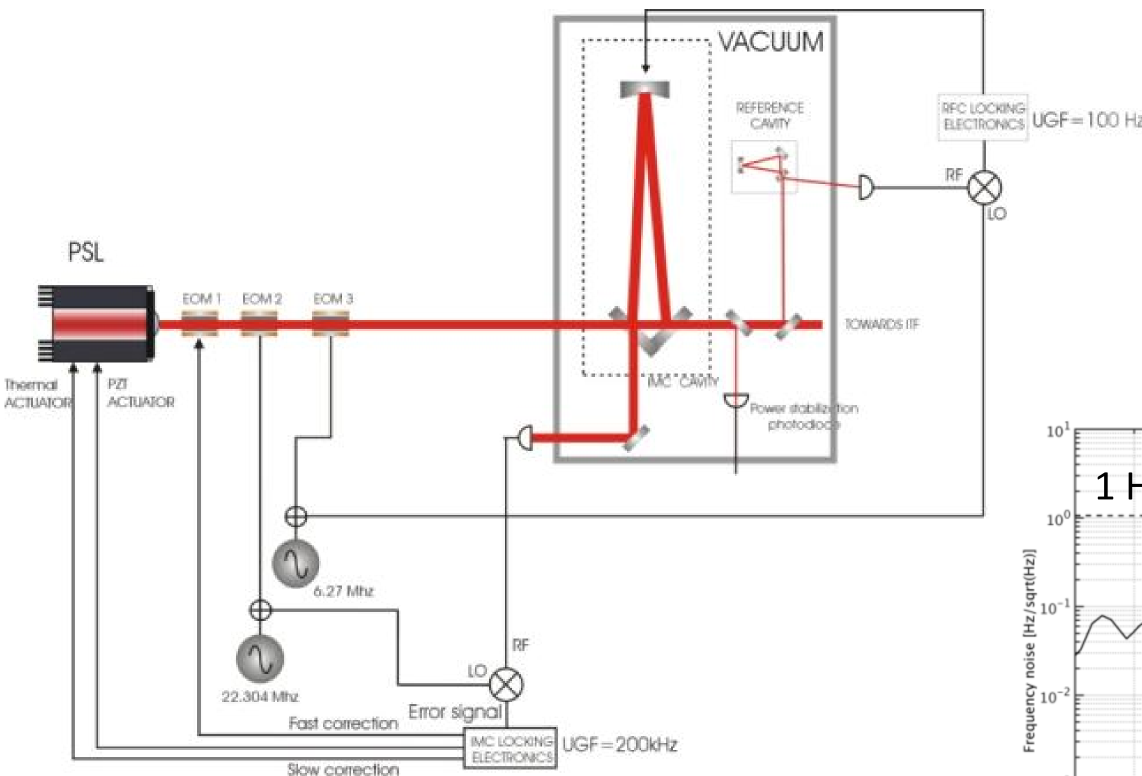
[1] B. Canuel, E. Genin, G. Vajente, J. Marque, Displacement noise from back scattering and specular reflection of input and output optics in advanced GW detectors, Optics Express, Vol. 21, Issue 9, pp. 10546-10562 (2013).
[2] M. Tacca, F. Sorrentino, C. Buy, M. Laporte, G. Pillant, E. Genin, P. La Penna, and M. Barsuglia, Tuning of a high magnification compact parabolic telescope for centimeter-scale laser beams, Applied Optics, Vol. 55, Issue 6, pp. 1275-1283 (2016).
[3] C. Buy, E. Genin, M. Barsuglia, R. Gouaty, and M. Tacca, Design of a high-magnification and low-aberration compact catadioptric telescope for the Advanced Virgo gravitational-wave interferometric detector, *Class. Quantum Grav.,* 34 095011 (2017).

AdV launching telescope

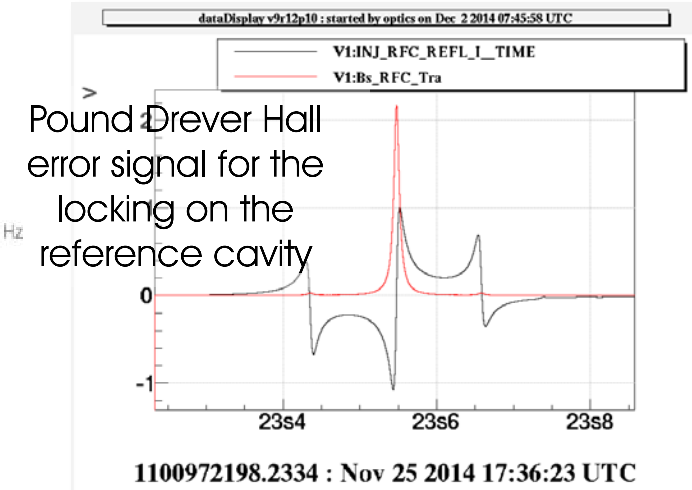


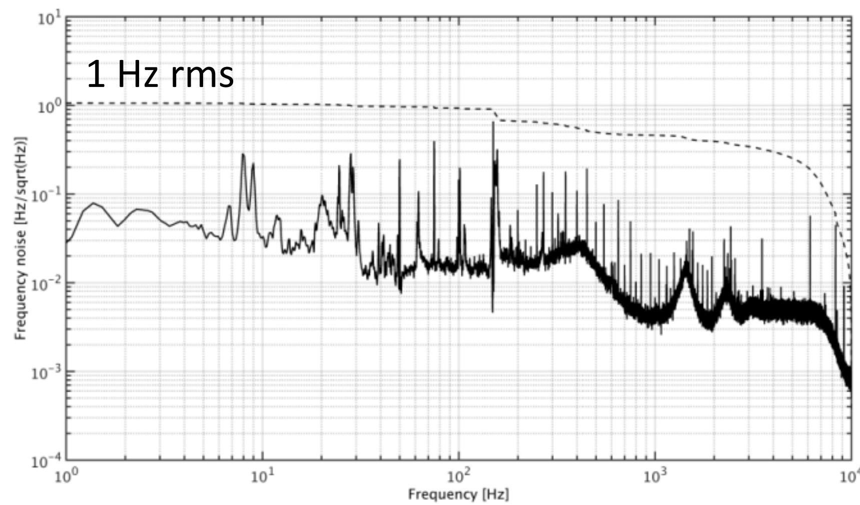
Laser frequency pre-stabilization

- In order to lock, the 3km long arm cavities, we have to pre-stabilize the laser frequency. In this loop the IMC cavity and a reference cavity (made of ULE) are used to achieve the required 1 Hz rms.



Laser frequency pre-stabilization scheme



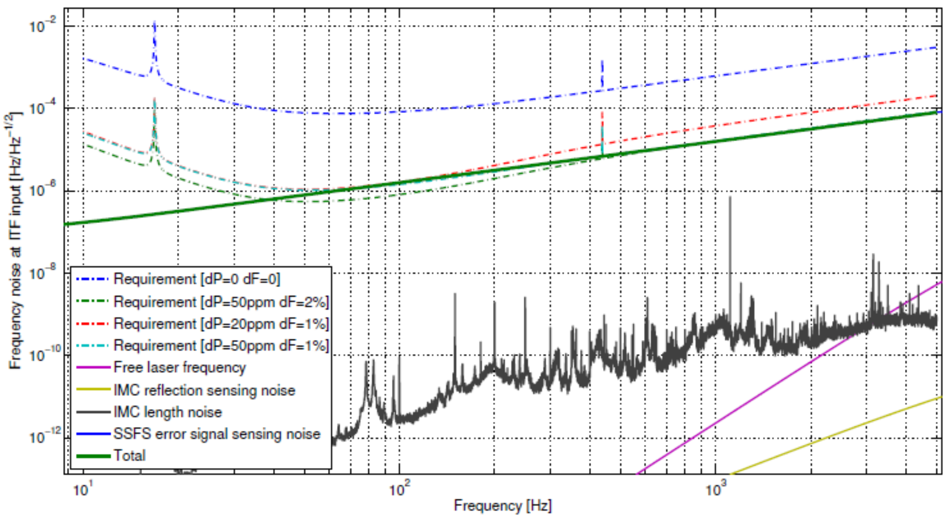


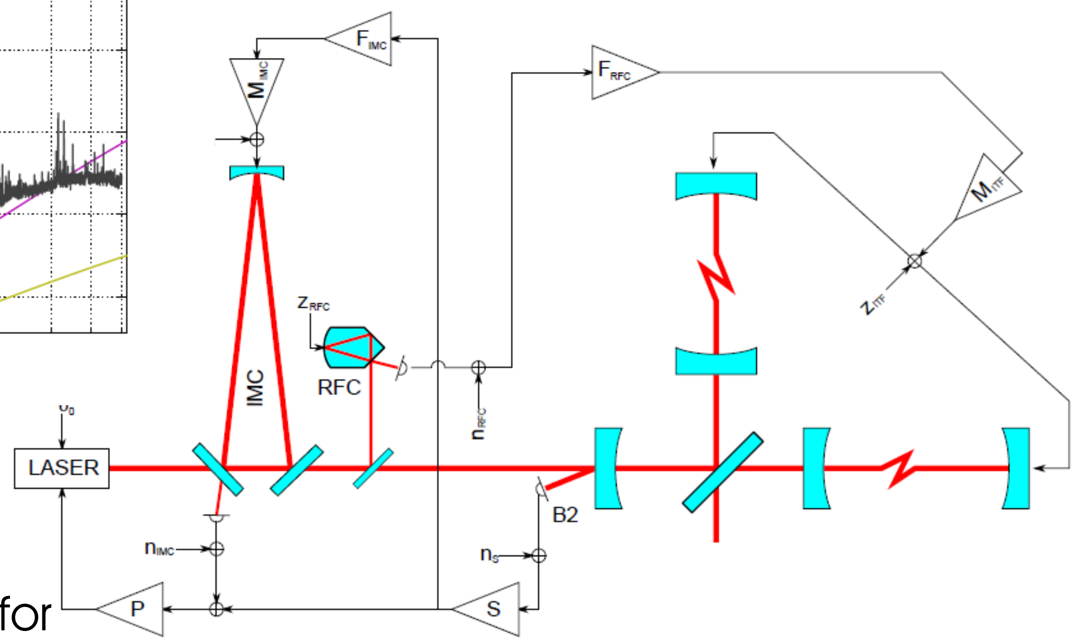
Residual frequency noise of the Pre-stabilized laser

Laser frequency second stage of frequency stabilization

- To achieve the sensitivity required, we should get a relative stability of the laser frequency better δν/ν than 10^{-21} (the long term drift of the frequency is not that important for us). (ν=300 THz)

IMC: Input Mode Cleaner
RFC: Reference cavity
B2 beam: interferometer reflection





→ another error signal is extracted from the interferometer itself.
We use the arm cavity as a reference for this second stage of frequency stabilization.

Laser frequency stabilization scheme

Reference:
The Virgo collaboration, Laser with an in-loop relative frequency stability of 10^{-21} on a 100-ms time scale, PHYSICAL REVIEW A 79, 053824 , 2008.

Useful links

Optical simulations used for the design of GW detectors

- Modal codes:
  - FINESSE (Frequency domain INterferomEter Simulation SoftwarE), Developed at GEO600 by Andreas Freise. http://www.gwoptics.org/finesse/.
  - MIST, developed at Virgo/Ligo by Gabriele Vajente https://sourceforge.net/projects/optics-mist/files/

- FFT-based codes:
  - SIS (with FOG inside), developed at Ligo/Virgo by Hiro Yamamoto and Richard day
  - OSCAR, developed at GEO by Jerome Degallaix http://www.mathworks.com/matlabcentral/fileexchange/20607-oscar

→ Those simulation tools are useful for the design of optical cavities and inteferometers.

Virgo technical documentation system: some technical notes are publicly accessible.

https://tds.ego-gw.it/itf/tds/index.php?callContent=1&startPage=

Virgo logbook

https://logbook.virgo-gw.eu/virgo/

Useful references

- Lasers and optical resonators:
  - A.E. Siegman, Lasers, link
  - W. Koechner, Solid-state laser engineering, Springer.
  - H. Kogelnick and T. Li, Laser beams and resonators, link

- Faraday isolator:
  - E. Khazanov, Faraday isolators for high average power lasers, link

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Visit Virgo website
https://www.virgo-gw.eu/


Thank you for your attention!

Rubidium Titanyl Phosphate *crystal properties*

Properties	Units/conditions	RTP
Damage Threshold	MW/cm2, (10ns, 1064 nm)	>600 (AR coated)
nx	1064nm	1.7652
ny	1064nm	1.7751
nz	1064nm	1.8536
Absorption coefficient	cm-1 (1064 nm)	< 0.0005
$r33$	pm/V	39.6
$r23$	pm/V	17.1
$r13$	pm/V	12.5
$r42$	pm/V	?
$r51$	pm/V	?
$r22$	pm/V	?
$n_z{}^3\ r33$	pm/V	252.2
Dielectric const., ϵ_{eff}	500 kHz, 22 °C	13
Conductivity, σ_z	$\Omega^{-1}.cm^{-1}$	~10-11-10-12
Thermal conductivity	$W.m^{-1}.K^{-1}$	k=3
Thermo-optic coefficient	/K	dnx/dT=? $dny/dT=0.279.10^{-5}$ $dnz/dT=0.924.10^{-5}$
Thermal Expansion	/K	$ax=1.01.10^{-5}$ $ay=1.37.10^{-5}$ $az=-4.17.10^{-6}$
Density	g/cm3	3.6
Specific Heat	J/kg.K	363