Input Optics for Gravitational Wave Detectors

P. Spinicelli*

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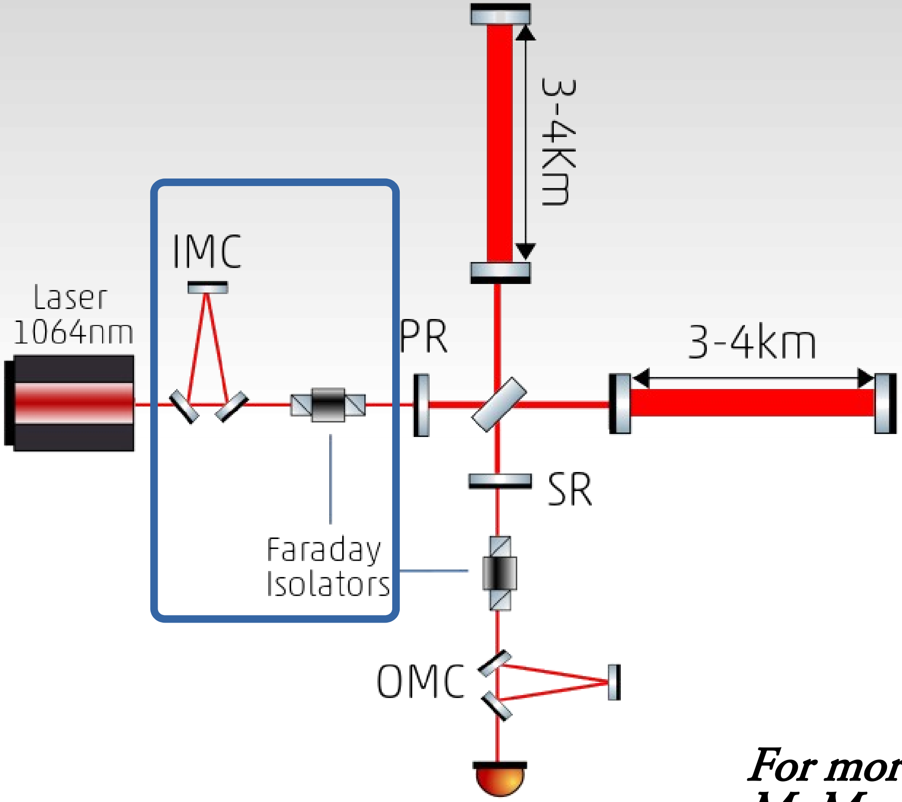
The Input Optics Subsystem



The Input Optic (IO) subsystem takes care of the laser beam downstream of the pre-stabilized high-power laser (PSL) and acts as interface between the interferometer and PSL

For more details on GW experiments and results see M. Mantovani's & D. Lumaca's talks today and F. Ricci's plenary talk on Friday morning

Main tasks of Input Optics System

The whole system must deliver :

- a laser beam at the interferometer (ITF) input port with the required power and size
- a good quality beam (filtered by IMC cavity)
- frequency and angular stability sufficient to reach the sensitivity goal

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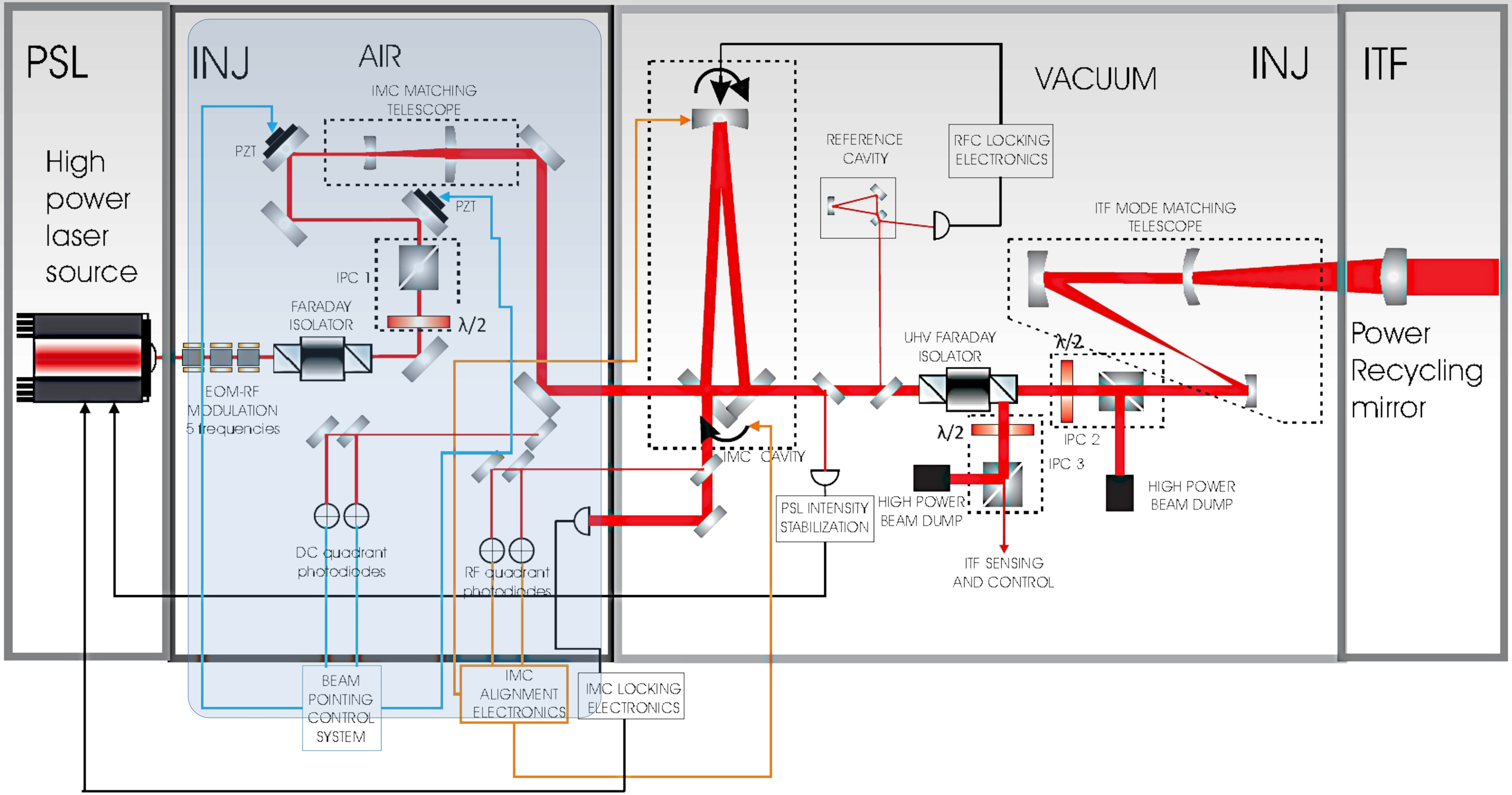
Its main components:

- **Electro optic modulation system (EOM)**: Phase modulation of the laser beam for ITF longitudinal and angular control
- **Input Mode Cleaner (IMC) cavity**: passively filter out amplitude, frequency and beam jitter noise
- **Faraday isolator (FI)**: isolates the Laser and the IMC 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
- **Good quality optics**: waveplates and polarizers able to withstand high laser power.

IO: the case of Virgo detector



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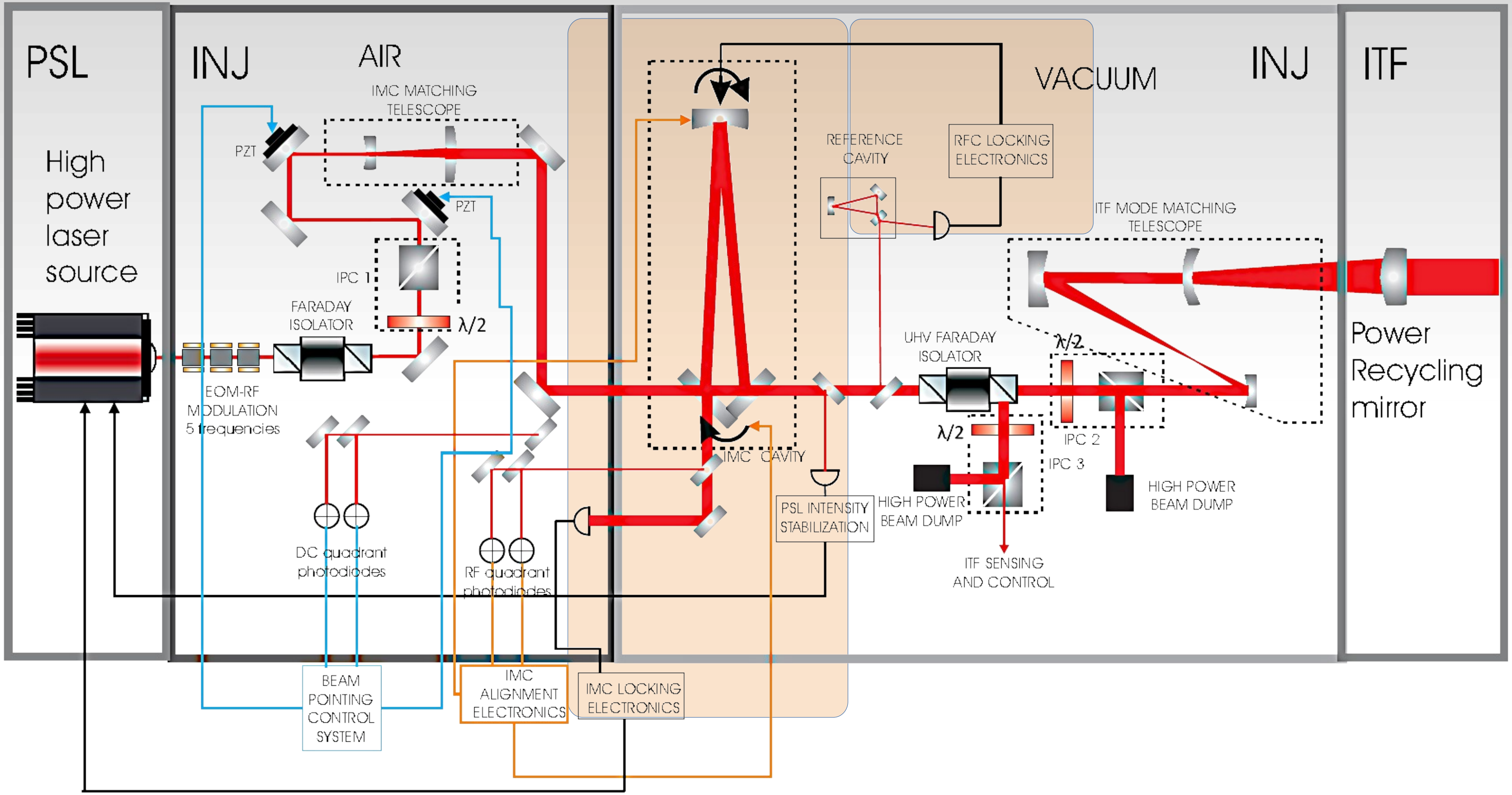

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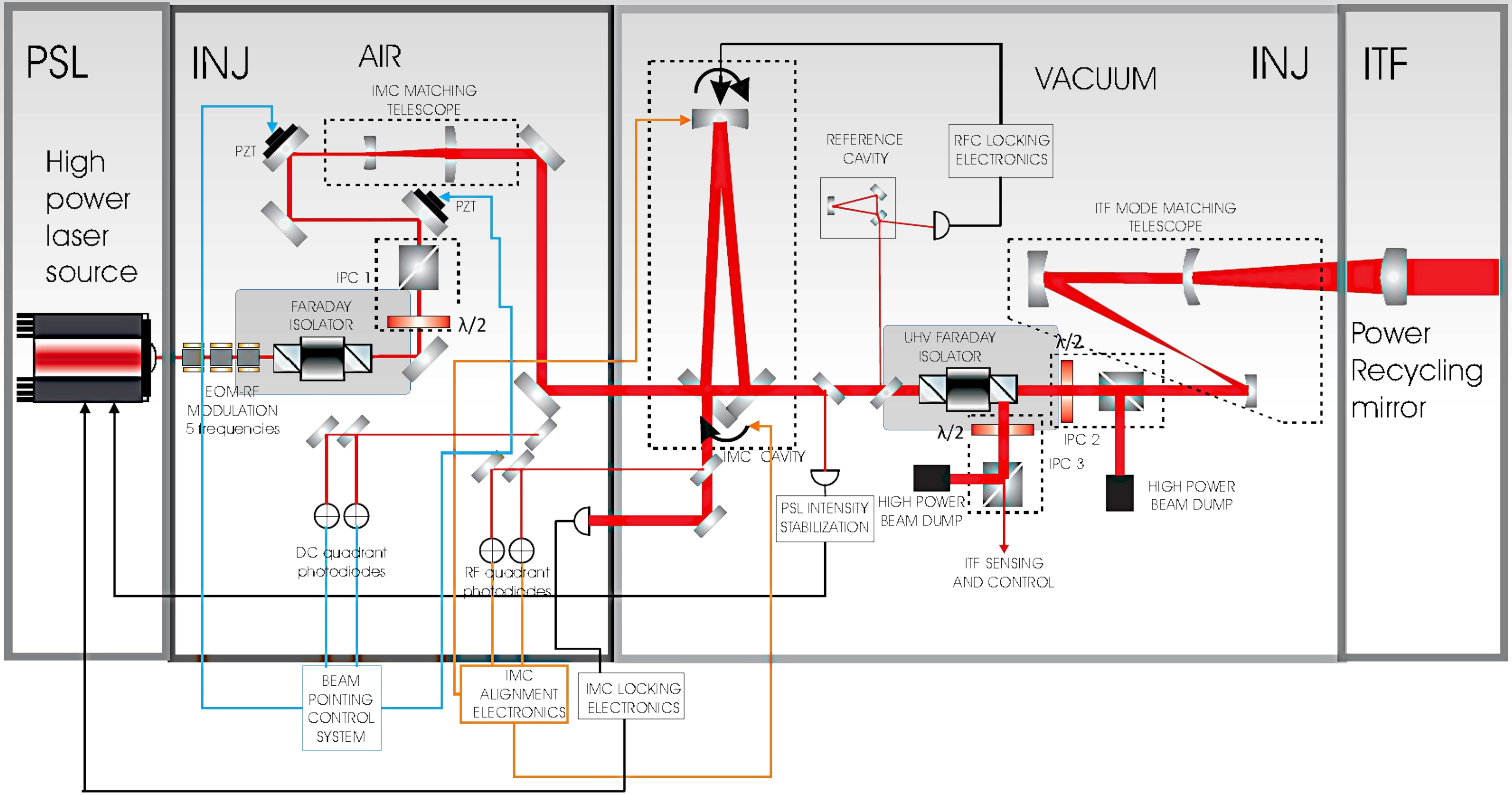

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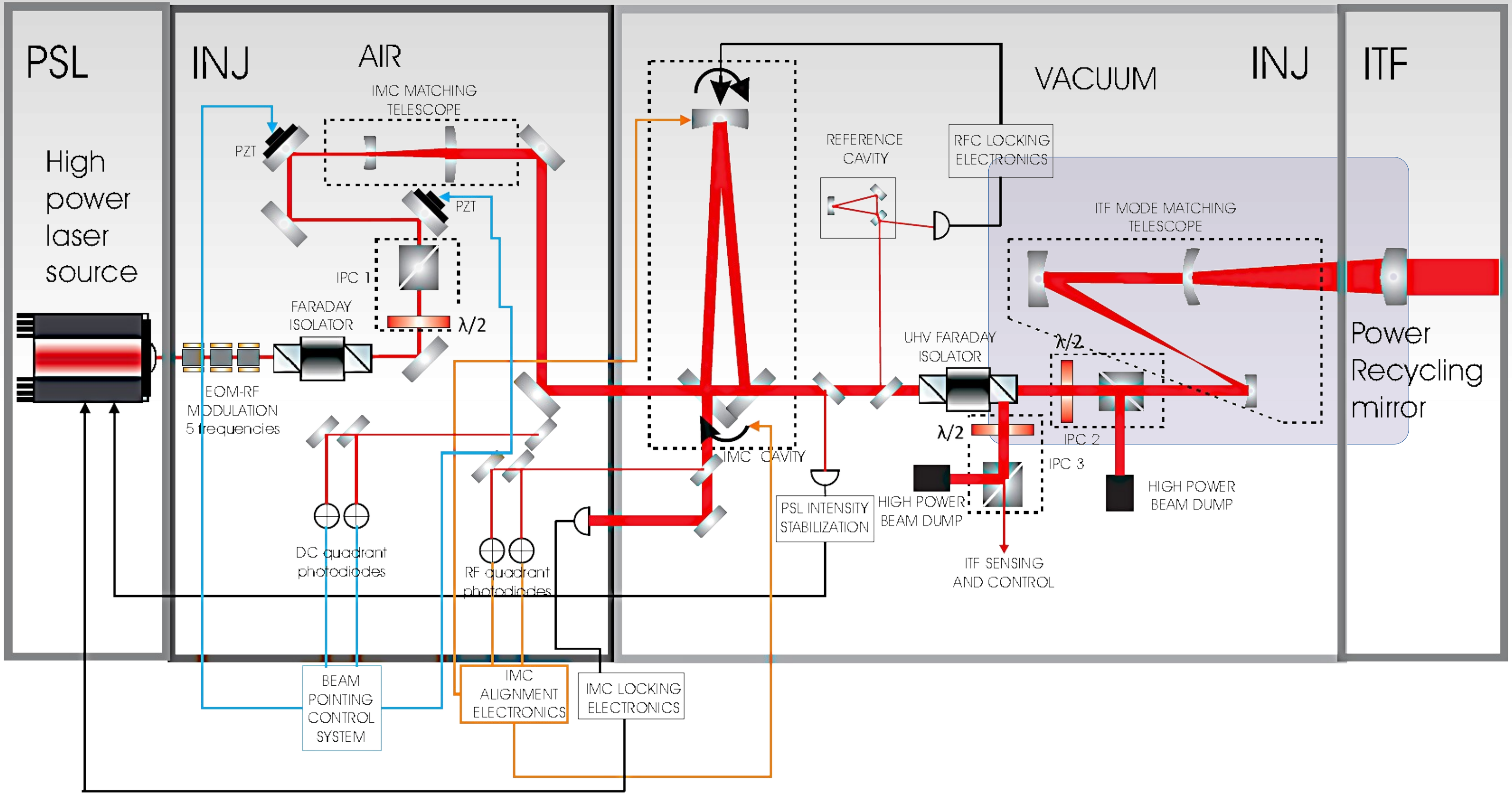
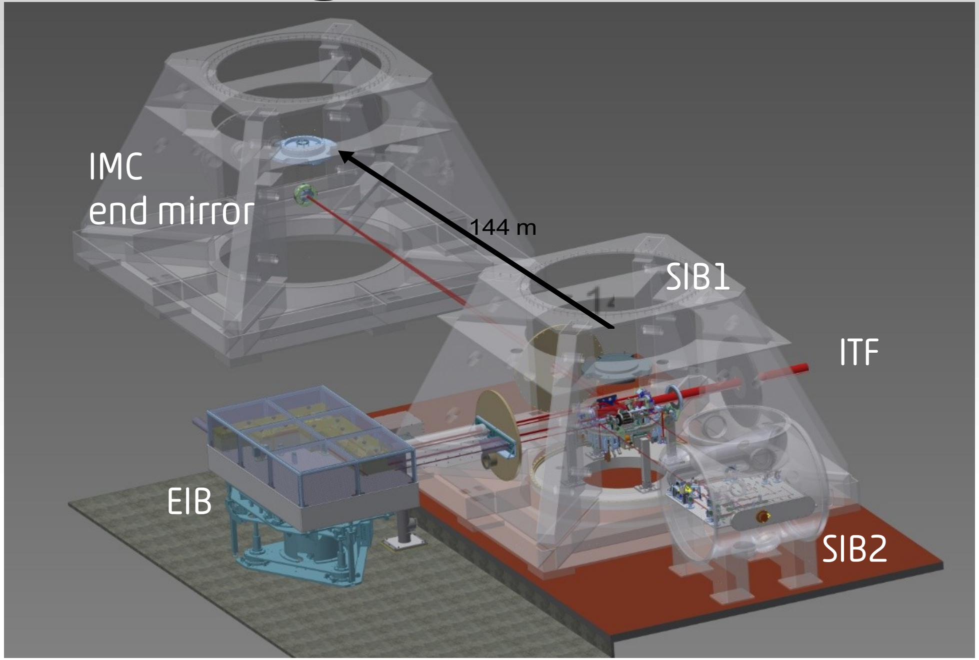


IO: the case of Virgo detector

- **External Injection Bench (EIB)**: RF generation, beam pointing control, IMC automatic alignment
- **Suspended Injection Bench (SIB) 1**: Reference cavity (RFC), Power stabilization sensor, Mode-matching telescope
- **SIB2**: RFC lock sensors, interferometer (angular and longitudinal) sensors
- **IMC**: mode cleaning, frequency stabilization



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

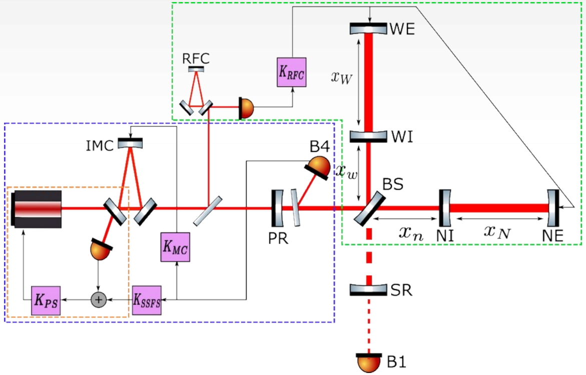
Example of IO requirements from AdV Technical Design Report

Main components: Input mode cleaner

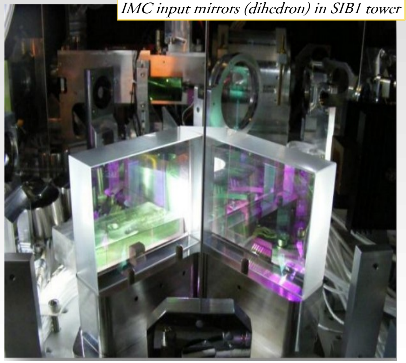
The IMC filters and stabilizes spatial mode and polarization of the laser before its injection in the interferometer

Laser frequency fluctuations are a common noise that should be cancelled out on the anti-symmetric port; due to unavoidable asymmetries though they couple with the GW detection channel

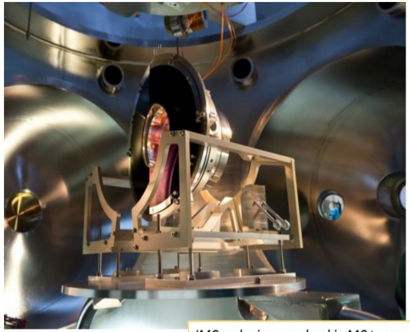
- Master laser frequency pre-stabilized on IMC length in order to allow the lock of the ITF
  - Bandwidth up to 110kHz
- Low-frequency stabilization (<10Hz) based on a monolithic reference cavity made with Ultra-Low-Expansion glass
- Once the ITF locked, the laser frequency stabilization is assured by the arms length (CARM signal) [1]



IMC input mirrors (dihedron) in SIB1 tower



~300m round-trip triangular cavity



IMC end mirror payload in MC tower

[1] M. van Dael, *et al*, Control of the laser frequency in the Virgo interferometer: Dynamic noise budgeting for controller optimization, Astropart. Phys, 164 (2025) 103028

Faraday isolators

Challenges :

- Withstand high continuous laser power on long periods (250W)
- Compensated in term of thermal lensing (residual thermal lensing > 100 m)
- Compensated in term of depolarization.
- Isolation factor >40 dB with high power laser
- UHV compatible: residual pressure $\leq 10^{-6}$ mbar
- Transmission > 95%

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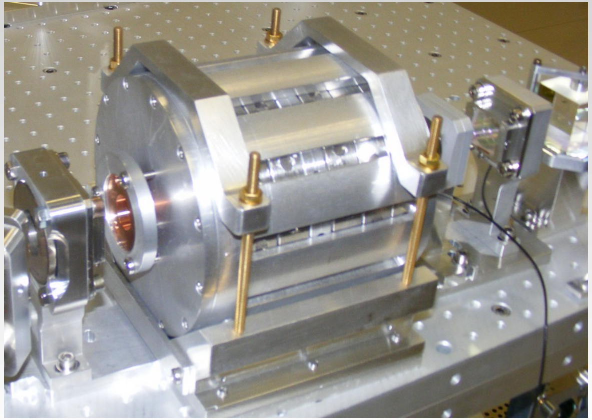

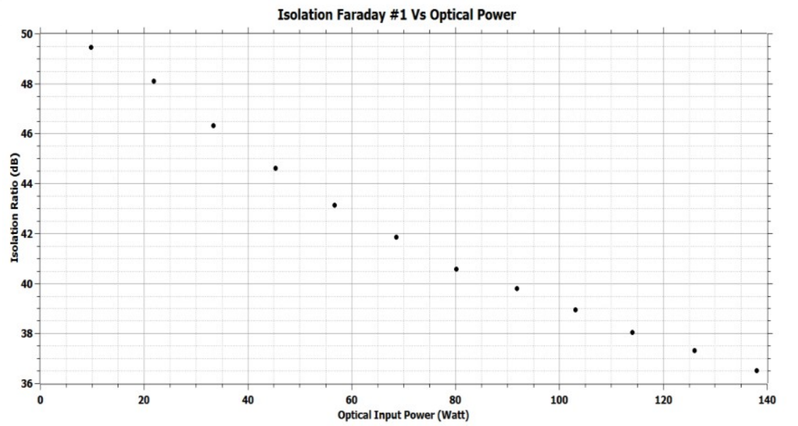

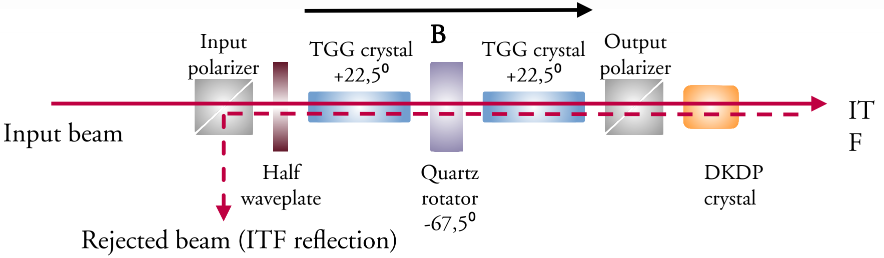

FI developed in collaboration with the Institute of Applied Physics (Russia) and the University of Florida (LIGO project) [1]

[1] O. Palashov, *et al*, High-vacuum compatible high-power Faraday isolators for gravitational-wave interferometers, JOSA B, Vol. 29, Issue 7, pp. 1784-1792 (2012)

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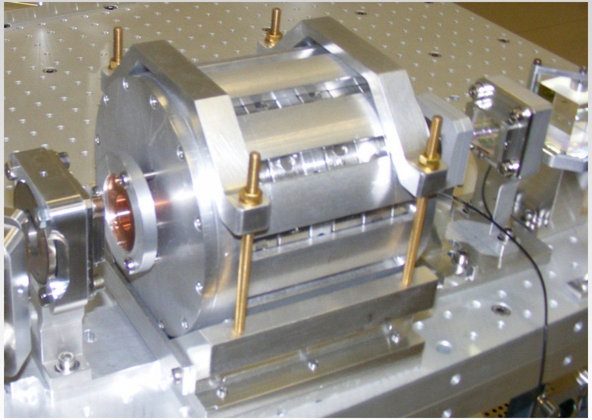
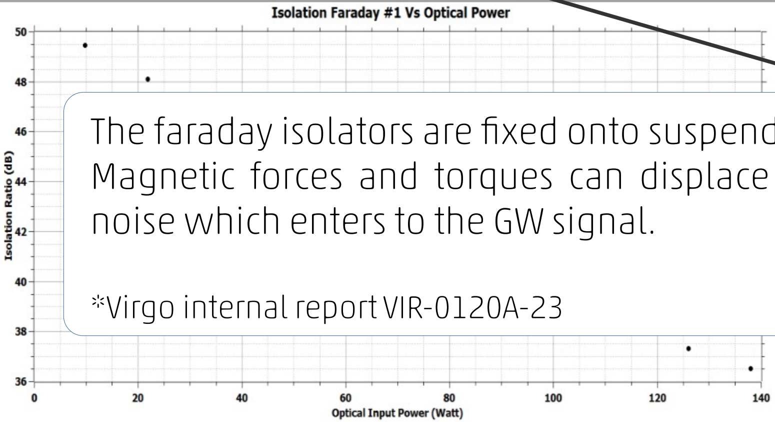
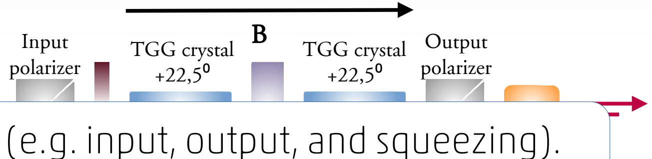
- ✘ 2T magnet couples with environmental magnetic fields







The faraday isolators are fixed onto suspended optical benches (e.g. input, output, and squeezing). Magnetic forces and torques can displace suspended benches ultimately causing a displacement noise which enters to the GW signal.

*Virgo internal report VIR-0120A-23

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Electro-optic modulators

High-power compatible electro-optic modulators (EOM) are used to phase-modulate the laser beam. This technique generates error signals which allow to control optical cavities

Requirements:

- Withstand 200W CW laser power @1064nm
- Limited thermal lensing effect (low absorption crystal used (RTP))
- Maximum modulation depth = 0.2
- Low phase noise (mostly related to the RF oscillator)
- Low Relative Amplitude modulation (RAM) noise

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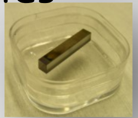

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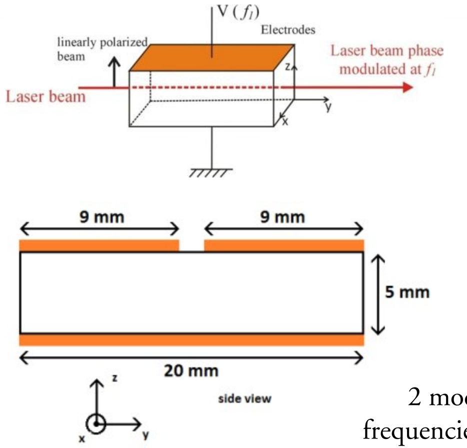
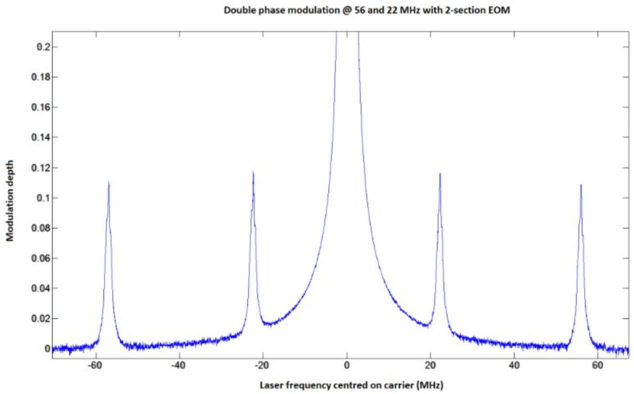
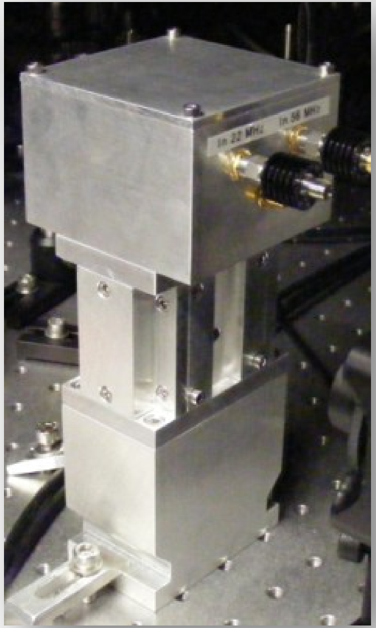
Electro optic material chosen:
Rubidium Titanyle Phosphate – RbTiOPO4



2 modulation frequencies per crystal





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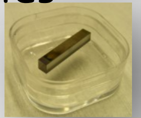

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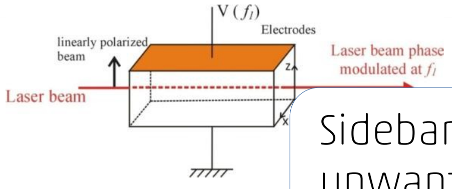
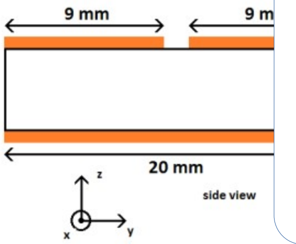
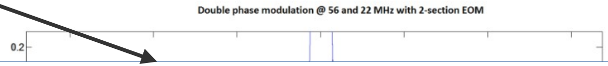


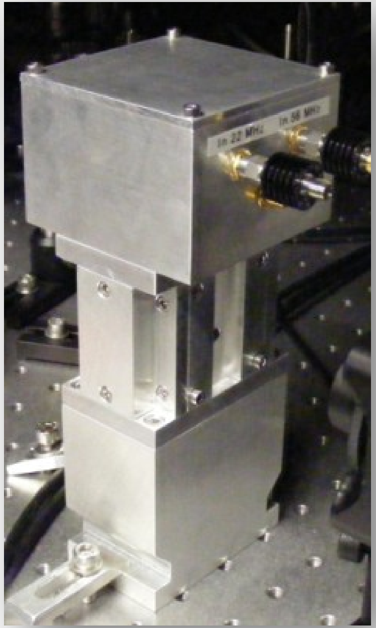




Sidebands amplitude fluctuations noise introduces a small unwanted beam amplitude modulation

Limitation for Virgo nominal sensitivity (80-100Mpc)

*Virgo internal note VIR-0630A-20

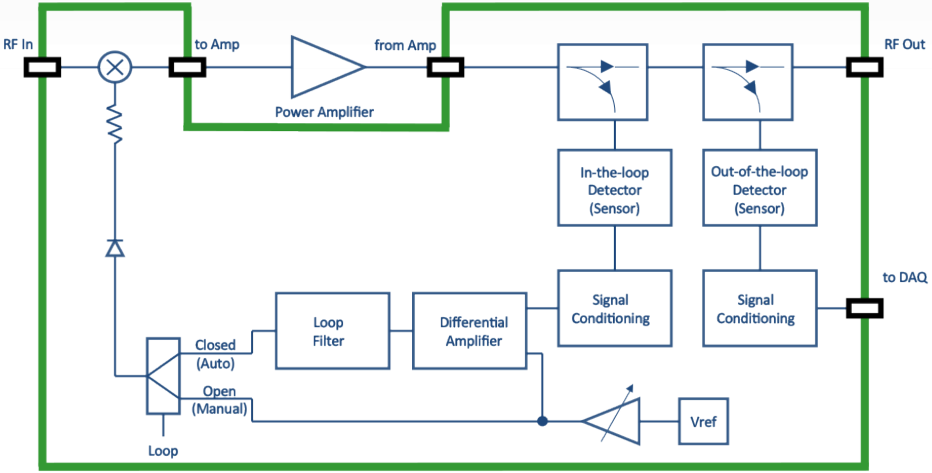


Relative Amplitude Modulation Stabilisation servo

- The Relative Amplitude Modulation Stabilisation (RAMS) Servo stabilizes the modulation *sidebands* before they are applied to the EOM
- The free-running noise of the modulation system is basically due to the RF Source, the LNFS-100 (chosen due to its good performance in terms of Phase Noise)
- Electronics downstream does not add amplitude noise contribution except in one case, the 56 MHz sideband, where we use a more powerful RF Amplifier

F. Nocera, B. Montanari, EGO electronics group

Virgo internal note VIR-1024C-20, VIR-0066A-24



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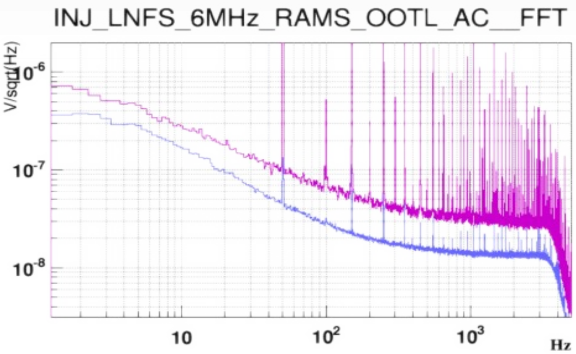
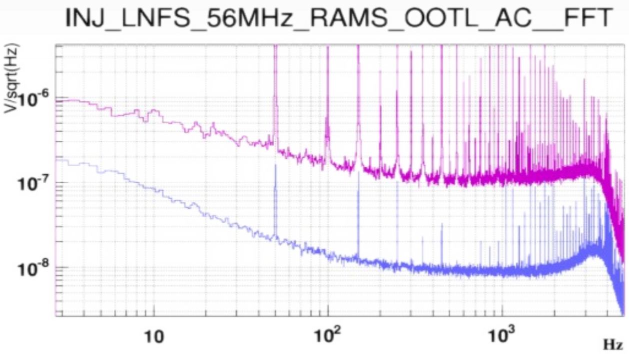




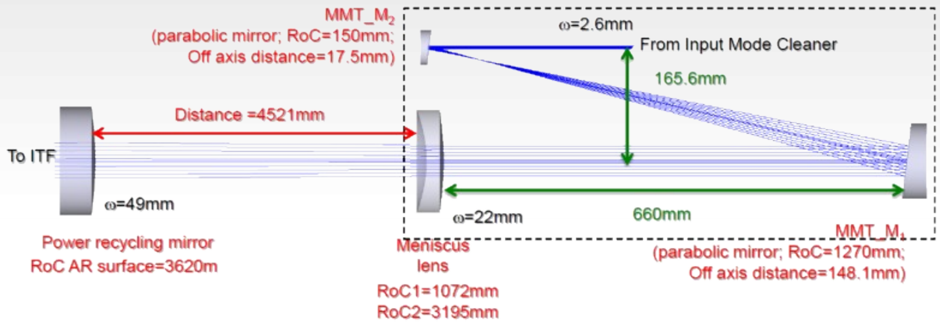
RAMS loop OFF
RAMS loop ON

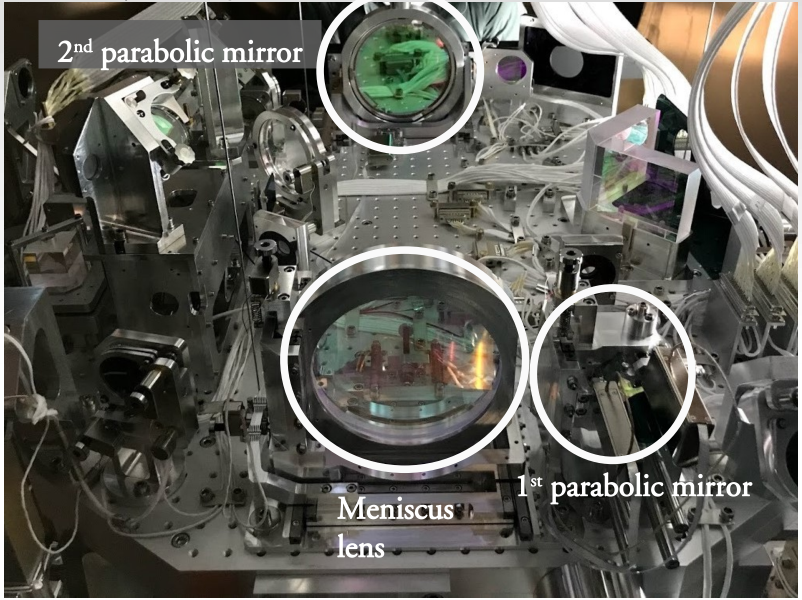
Virgo internal note VIR-0066A-24

RAMS servo works as expected on the two modulation frequency used for the ITF, even though, Virgo sensitivity is not limited yet by RAM noise

High magnification mode-matching telescope

Due to the large laser beam and the limited space available, an original and compact design has been designed for the input telescope for the Virgo detector: a catadioptric system





[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).

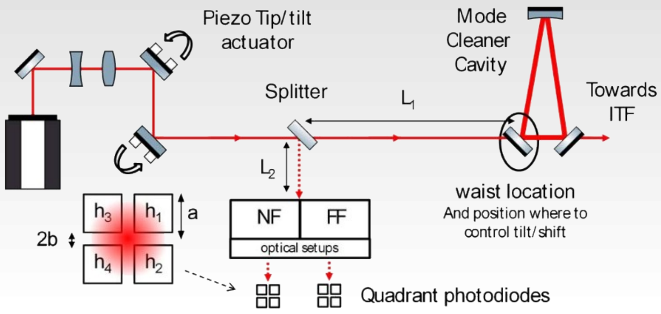
[3] B. Canuel, E. Genin, G. Vajente, J. Marque, Displacement noise from back scattering and specular reflection of input and output optics in advanced GW detectors, Optics Express, Vol. 21, Issue 9, pp. 10546-10562 (2013).

Future evolutions

Future evolution: Improvement of the IMC control and alignment loops

Current situation

- SIB1 used as an pointing actuator towards the ITF at low frequency
- Home-made Beam Pointing Control (BPC) is used to align beam from EIB on the IMC cavity [1]



Principle of the BPC:
The beam coming from the laser is shaped to the IMC input by using a telescope. The input beam jitter is then controlled by two piezo tip/tilt actuators and sensed by two quadrant split photodetectors.

[1] B. Canuel, E. Genin, M. Mantovani, J. Marque, P. Ruggi, and M. Tacca, "Sub-nanoradiant beam pointing monitoring and stabilization system for controlling input beam jitter in gravitational wave interferometers," Appl. Opt. 53, 2906-2916 (2014)

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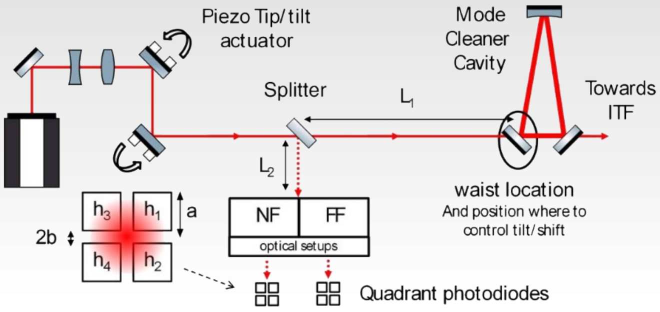

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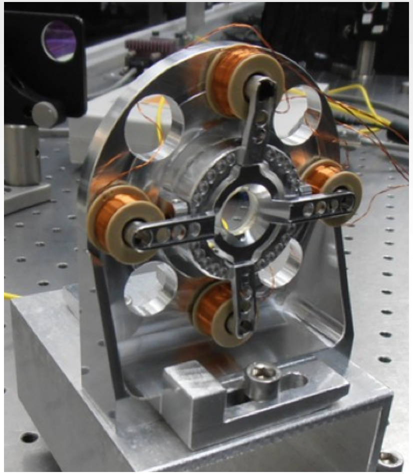


Galvo actuators, Nikhef prototype

The idea would be to not use the benches as actuators but to have dedicated pointing sensors/actuators on the benches :

- Pointing loop towards the ITF with an increased control bandwidth (up to 100Hz)
- New pointing actuators required (collaboration with A. Bertolini, Nikhef)

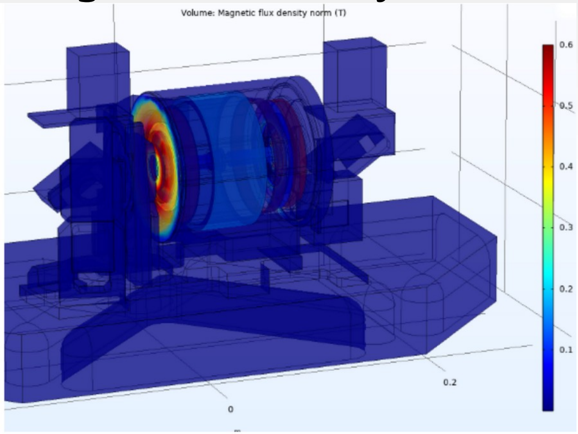
[1] B. Canuel, E. Genin, M. Mantovani, J. Marque, P. Ruggi, and M. Tacca, "Sub-nanoradiant beam pointing monitoring and stabilization system for controlling input beam jitter in gravitational wave interferometers," Appl. Opt. 53, 2906-2916 (2014)

Future evolution: Magnetic shielding for Faraday Isolators

A mitigation solution for the FI magnetic coupling is the installation of a magnetic shield which be needed to:

- Improve isolation of suspended bench (Input and output optics benches) from magnetic perturbation
- Ensure the good functioning of the galvo actuators

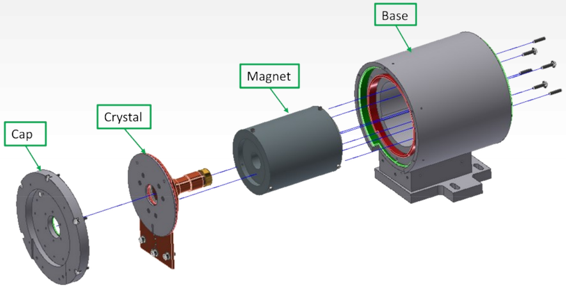
Modelling of the Faraday isolator magnet

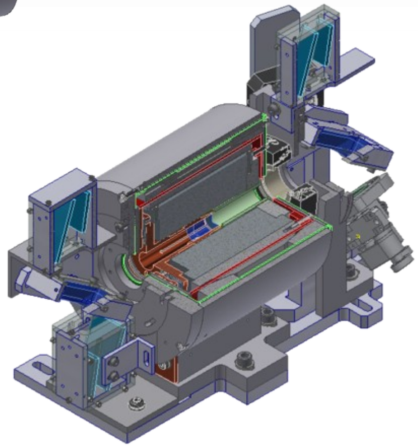


J.-L. Raymond, ParisTech
G. Quéméner, IN2P3 - LPC Caen

Virgo internal note VIR-0120A-23

Design and prototyping

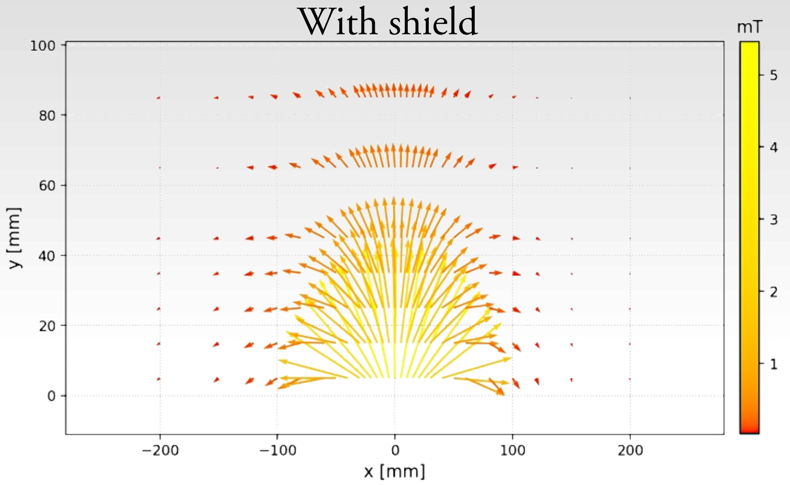


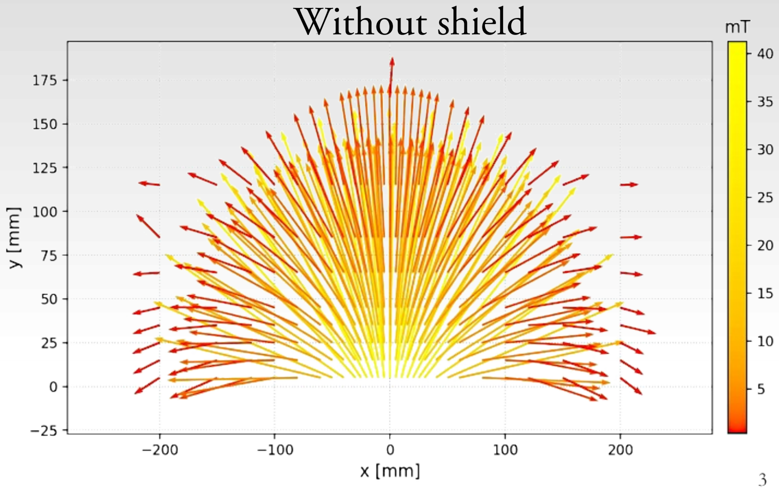


A. Buggiani, EGO

Future evolution: Magnetic shielding for Faraday Isolators

Experimental ongoing results





B. D’Angelo, INFN Genova
I. Fiori, M.C. Tringali, M. Gosselin, EGO
G. Quéméner, IN2P3 - LPC Caen
F. Paoletti, INFN Pisa

Conclusions

The Input Optics is one of the critical systems of GW detectors, with the aim to provide a low-noise and stable laser field for the interferometer.

Principal components of this system are:

- Electro optic modulation system
- Input Mode Cleaner cavity
- Faraday isolator
- Mode matching optics

In the case of Virgo detector, strong effort has been done on improving some critical aspect, in view of further detector upgrade, mainly on reducing magnetic coupling and relative amplitude modulation noise.

So long, and thanks for all the fish

Anything that can go wrong, will go wrong.
Murphy's Law