Advanced Virgo INJ: Faraday isolator, Electro-optical modulator, high power beam dump and Input mode-cleaner

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VIR-0515A-10

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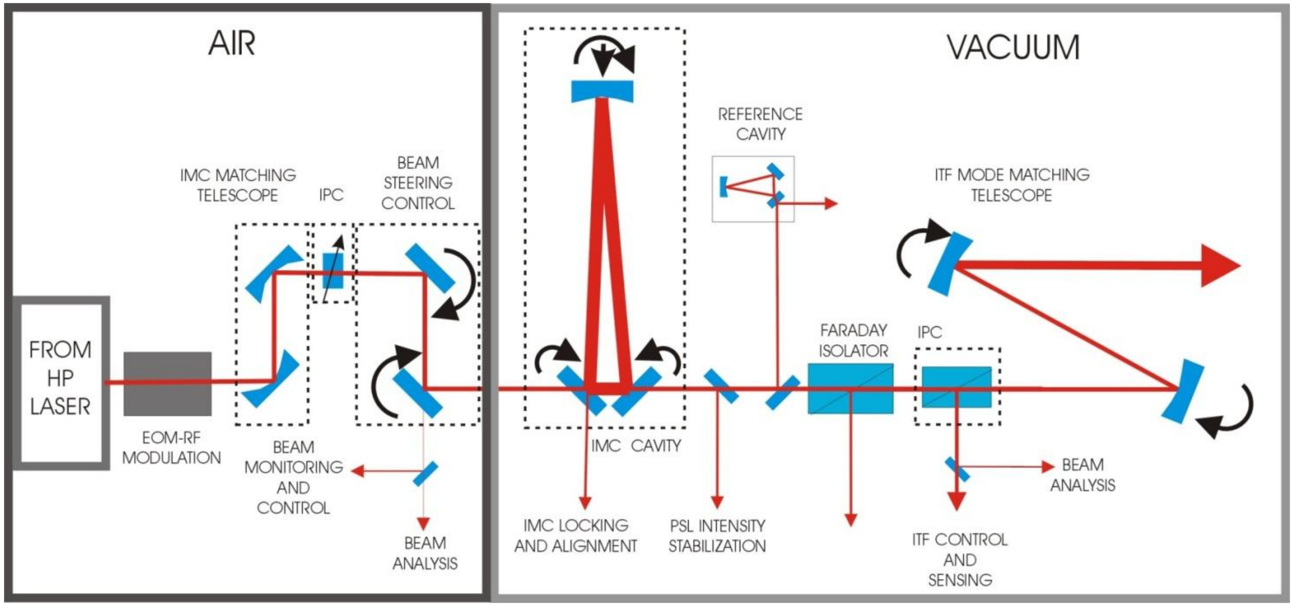
Outline

- Advanced INJ subsystem: overview.
- High power compatible components:
  - Faraday isolator for AdV
  - High power beam dumps
  - Electro Optical Modulator for AdV
- AdV Input Mode Cleaner: what to do to upgrade Virgo IMC for AdV.

AdV INJ Baseline design scheme



- In-air optics:
  - EOM system for IMC and ITF control
  - IMC mode-matching telescope.
  - Input Power Control system (IPC 1)
  - Beam pointing control system
  - Beam analysis system (cameras , Hartmann sensor,…)

- In-vacuum optics:
  - 144 m long Resonant Input Mode-Cleaner (IMC)
  - High power Faraday isolator
  - ITF Mode-Matching Telescope (MMT)
  - PSL intensity stabilization photodiode
  - Reference cavity (RFC)
  - Steering optics
  - Input Power Control system (IPC 2)

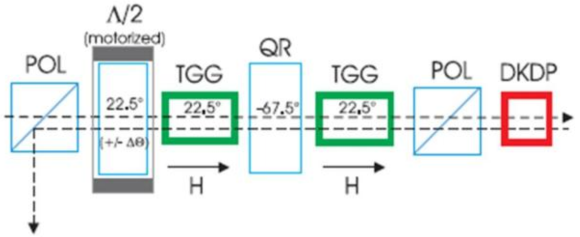
For more information on the subsystem:
- AdV INJ preliminary design study, VIR-0023A-09
- AdV INJ design requirements, VIR-0628A-09
- AdV baseline design, VIR-0027A-09

Faraday isolator for Advanced Virgo

- The requirements for the AdV Faraday isolator (FI) are:
  - Isolation factor > 40 dB with 250W laser power going through the FI.
  - Residual thermal focal lensing > 100 m.
  - Transmission > 95 %.
  - Be insensitive to thermal conditions changes going from air to vacuum.
  - UHV compatible: residual pressure ≤10^{-6} mbar.

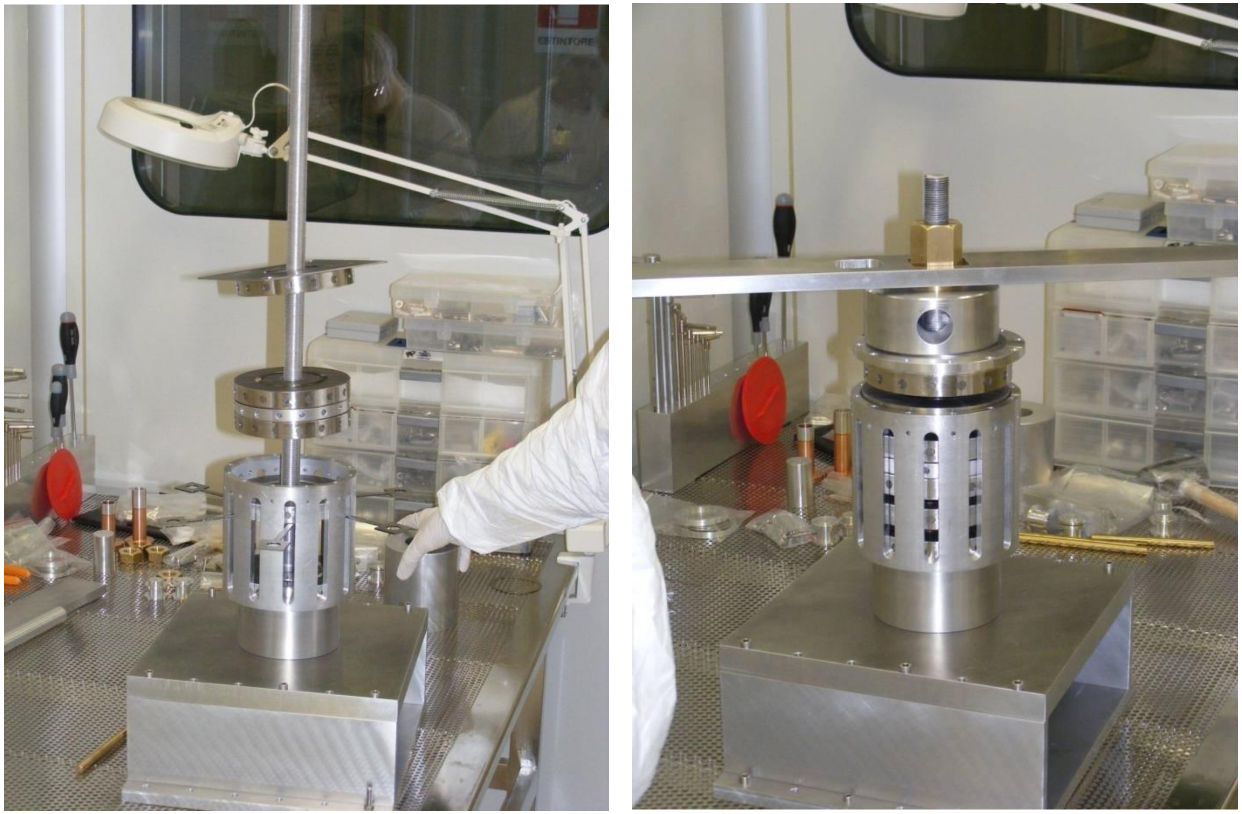
→ in order to reach these performances, we have contacted Efim Khazanov (IAP, Russia) who already produced HP-compatible FI for LIGO.

A collaboration between IAP and EGO started in July 2008 and a report on the study of different FI design with various aperture options delivered in March 2009 (See IAP report "AdV Faraday isolator design study", VIR-0245A-10).
→ we chose to produce a 20 mm aperture with reinforced magnetic field Faraday isolator, half waveplate for compensation of Verdet constant change with temperature and DKDP crystal for thermal lensing compensation.



High vacuum Faraday isolator for AdV: Magnetic system assembling.

- Prototype assembled by our colleagues of IAP (O. Palashov and D. Zheleznov) in January 2010 in Virgo clean rooms.


Faraday magnetic system during the assembling


TGG crystal installation in its copper holder

→ Assembly completed in March 2010 once the coated optics were available.

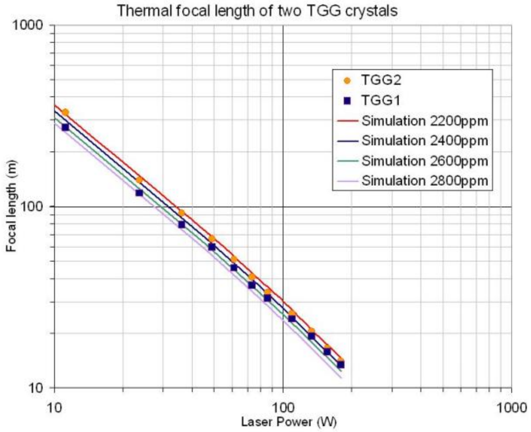
[1] The Faraday isolator prototype for Advanced Virgo Description and assembling procedure, Virgo internal note, VIR-0283A-10.

TGG crystals characterization and FI final assembling

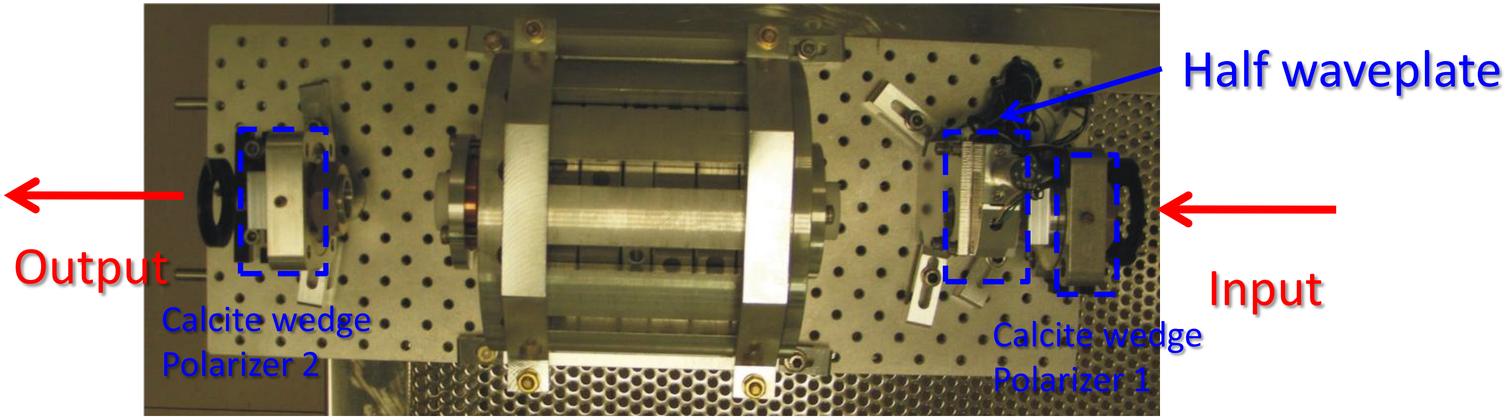
- TGG crystals characterized in the High Power facility.
  - Thermal lensing measurements:

    Absorption(TGG1) = 2300 ppm/cm (+-100ppm/cm)

    Absorption(TGG2) = 2600 ppm/cm (+-100ppm/cm)



  - Depolarization measurements: For each crystal, found the orientation of the crystals that produces the minimum of depolarization (required to have the depolarization optimally compensated).

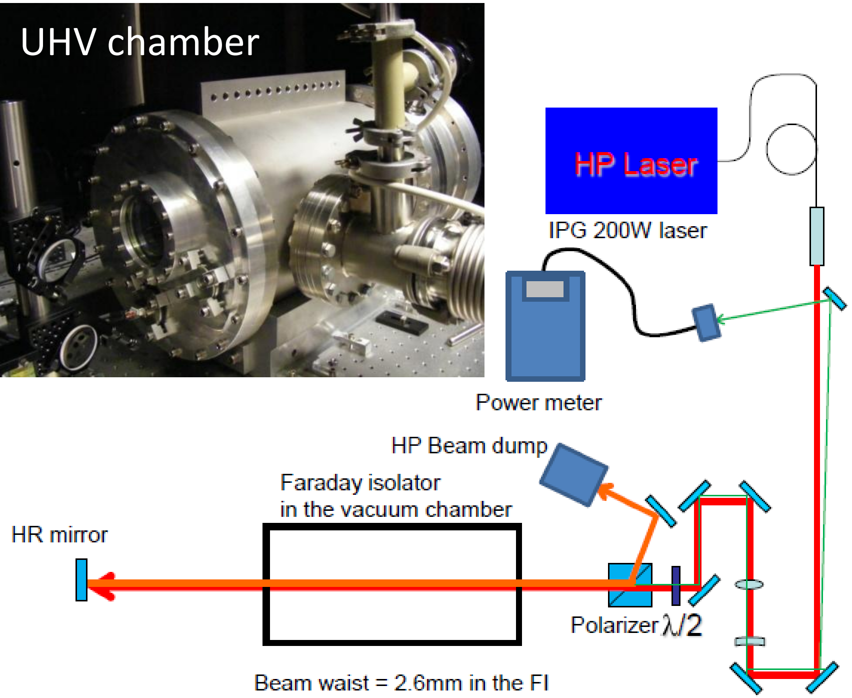


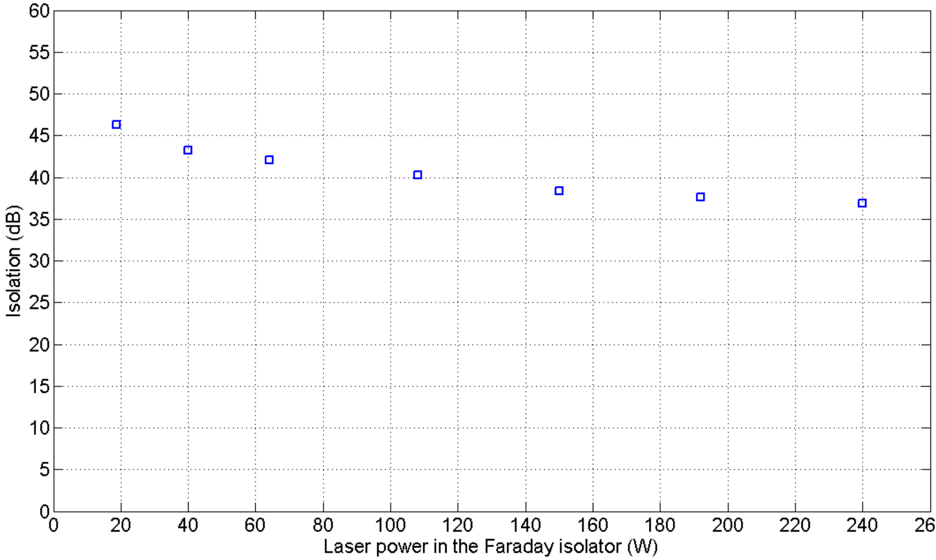
- All the optics of the Faraday isolator except DKDP crystals have been coated by LMA (to ensure a good transmission of the FI).

→ After assembling, we measured a transmission higher than 95% (within requirements) and an isolation factor higher than 45 dB at low power.

Faraday isolator for AdV: High power tests (July/August 2010).

- In-vacuum performances of the Faraday isolator (residual pressure = 2 .5. 10^{-6} mbar).



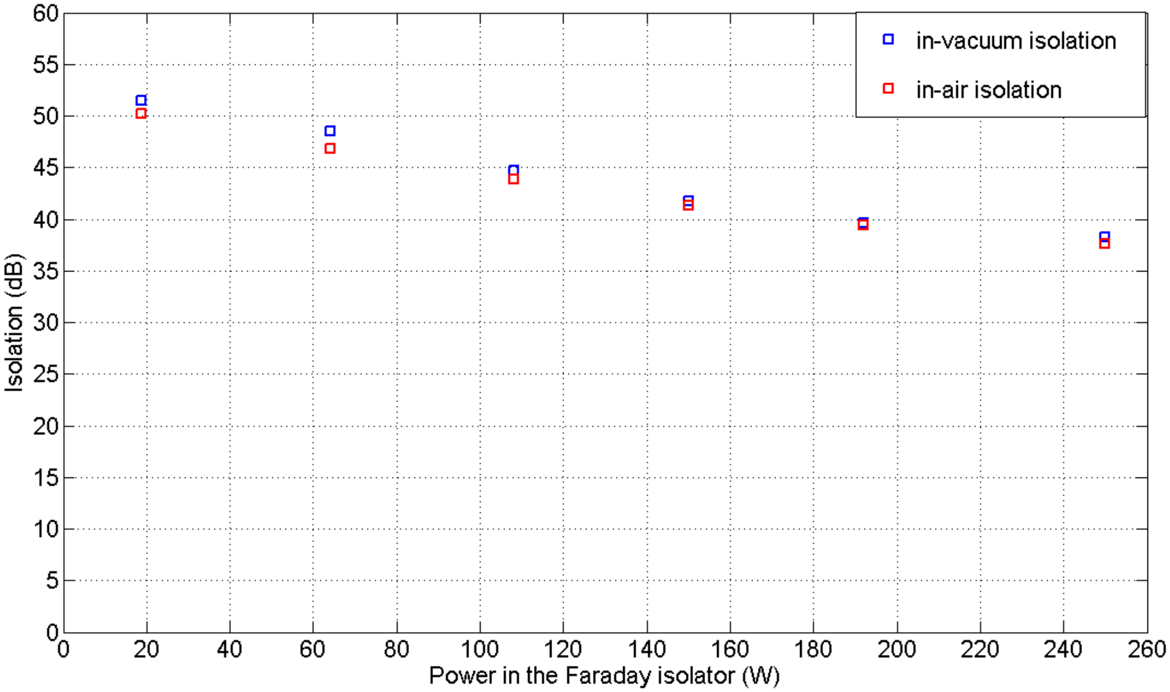


→ the isolation is about 36.5 dB with 240 W in the FI (120W+120W). We could reach 38 dB in particularly good alignment conditions.

Isolation could be further improved by a better adjustment of the axis of minimum depolarization of one TGG respect to the other.

Faraday isolator for AdV: High power tests (July/August 2010).

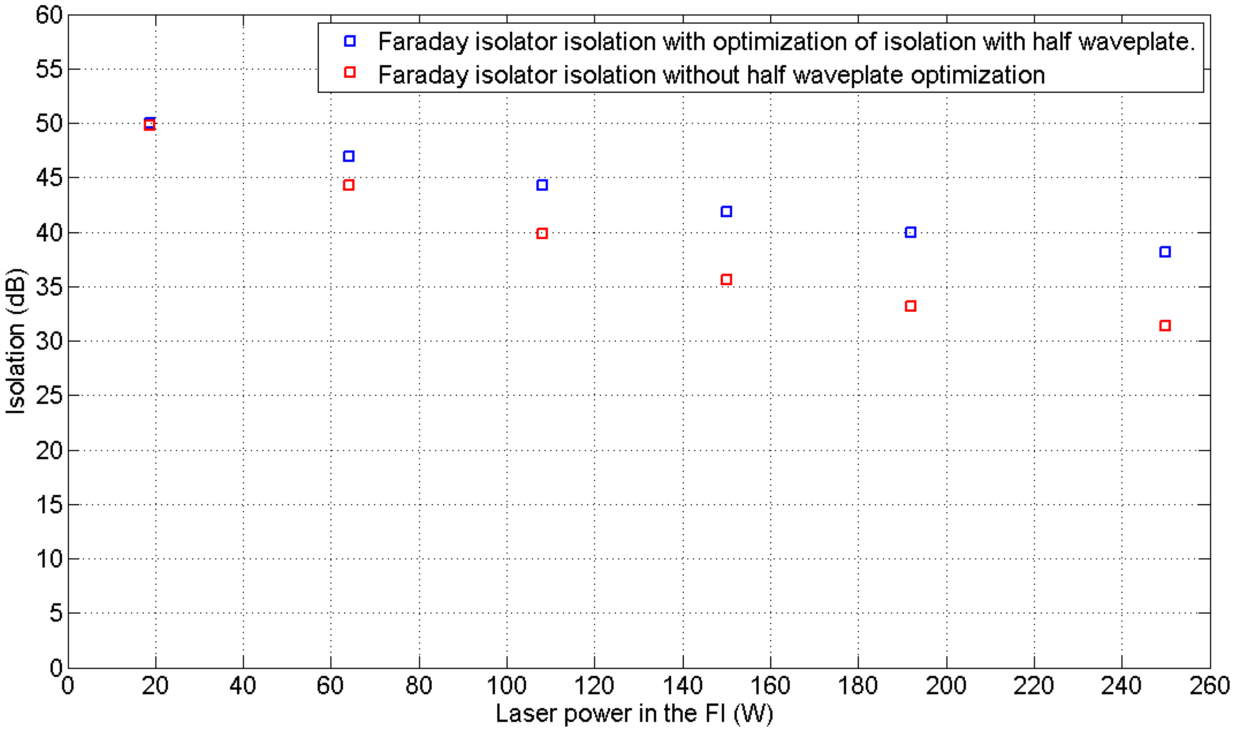
- Comparison of in-air and in-vacuum performances of the Faraday isolator (optimal isolation at each power after waveplate adjustment).



→ the measurements are very close. This is the proof that we are limited only by depolarization. Moreover the limited temperature increase of the TGG crystals (about 6 ^{o}C with 250W laser power in the FI) can guarantee that we will not loose too much power (due to the half waveplate adjustment).

Faraday isolator for AdV: High power tests (July/August 2010).

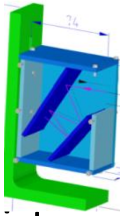
- Comparison of in-vacuum performances of the Faraday isolator with and without compensation of the Verdet constant change with temperature.



→ the isolation drop is about 6-7 dB at 250W (125+125W). This is quite limited and is consistent with the limited temperature increase measured before. Copper holders look to be very efficient to remove heat from the TGG crystals.

High Power low diffusing beam dump

- For AdV, we need high power, low diffusing beam dumps
  - Diffused light on optics of external benches can spoil the ITF sensitivity
  - Creates direct and up-converted noise (DL phase modulated by seismic noise).

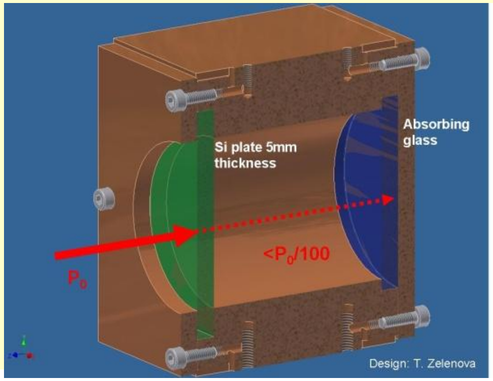


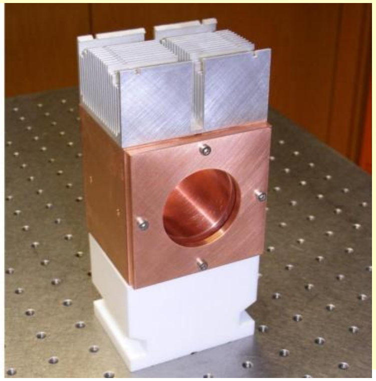
→ Mandatory for INJ (ITF and IMC reflections) but also for DET

→ Current solution : Absorbing glass (diffusion =10 ppm) but breaks at 2W with 1mm waist

- We tested the possibility of using Silicon Layers.
  - Good surface quality and diffusion comparable to absorbing glass
  - Very good thermal conductivity (150 W.m^{-1}.K^{-1}, to compare with glass: about 1 W.m^{-1}.K^{-1})
  - Large absorption at 1064 nm when temperature increases (transmitted beam can be dumped using absorbing glass).

New prototype with AR-coated thick plates of Si and improved heat removal is ready and should be tested soon in vacuum.

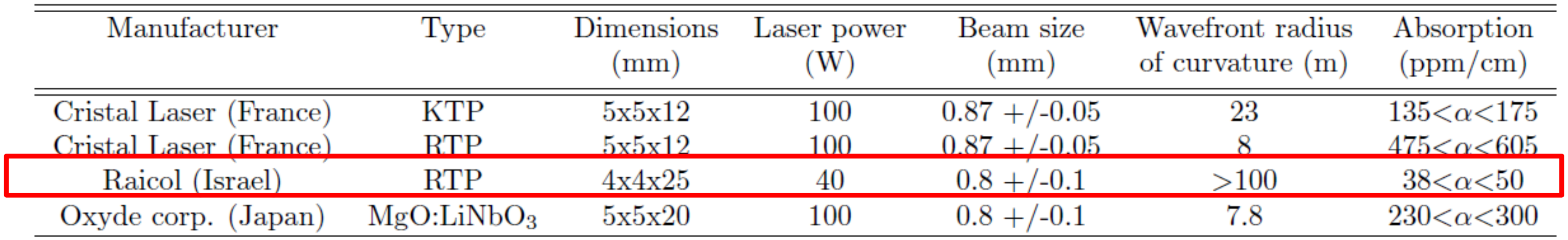




Phase modulators for AdV INJ

Preliminary requirements and guidelines for the design:

- Phase modulation of the beam at 4 different frequencies (3 for the ITF (max 70 MHz) and one for the IMC (22 MHz)).
- Phase noise requirements:< -100 dBc/Hz at 10 Hz and <-140dBc /Hz at 100 Hz (TBC by ISC subsystem).
- Reach a modulation depth higher than 0.1 at high frequency (> 60 MHz).
- Choose the lowest absorbing EO material: not only for thermal lensing problems (creates wave front aberrations) but also because it is a proof of local heating of the material. This heating can induce slow variation of the modulation index and disturb the ITF control.
- Minimize the number of optical interfaces: higher throughput of the EOM system and reduce the number of spurious beams to dump.
- Be able to easily dismount the crystal and the modulation electronics.



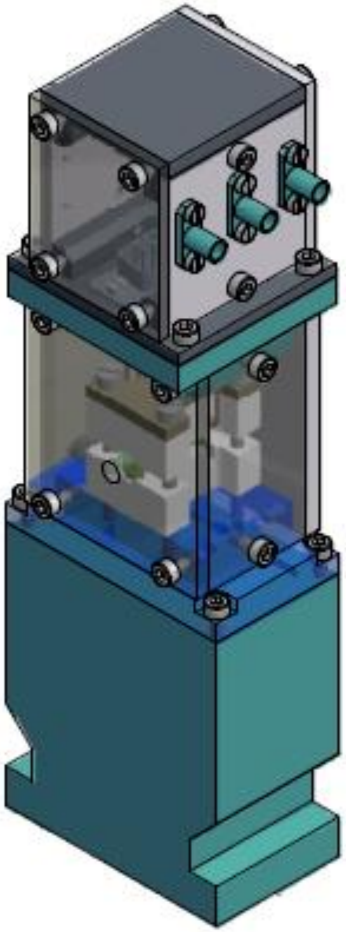
Manufacturer	Type	Dimensions (mm)	Laser power (W)	Beam size (mm)	Wavefront radius of curvature (m)	Absorption (ppm/cm)
Cristal Laser (France)	KTP	5x5x12	100	0.87 +/-0.05	23	$135<\alpha<175$
Cristal Laser (France)	RTP	5x5x12	100	0.87 +/-0.05	8	$475<\alpha<605$
Raicol (Israel)	RTP	4x4x25	40	0.8 +/-0.1	>100	$38<\alpha<50$
Oxyde corp. (Japan)	$MgO:LiNbO_3$	5x5x20	100	0.8 +/-0.1	7.8	$230<\alpha<300$

RTP from Raicol looks the most suitable material (identical conclusion for LIGO [2]).

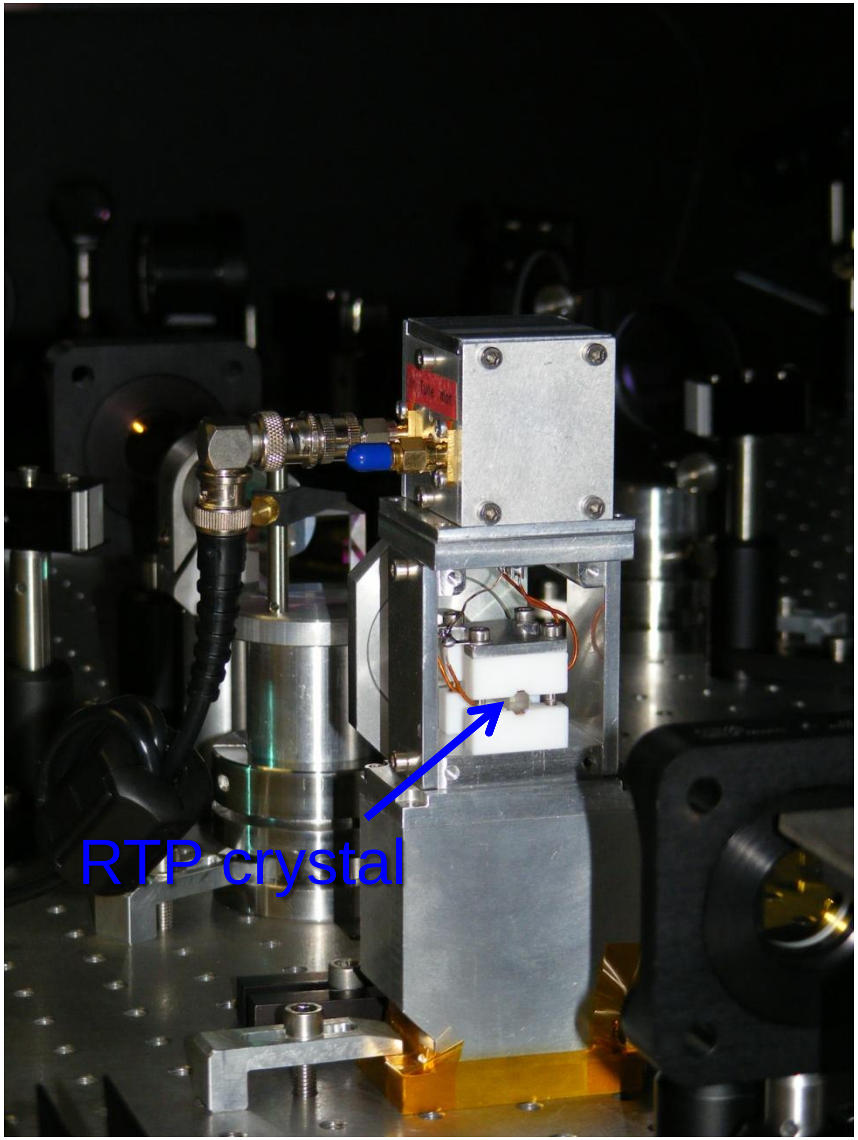
→ Prepared a prototype with 2 sections of modulations (10 MHz and 65MHz) designed to get the highest modulation index with the lowest possible RF power.

[2] UF LIGO group, IAP group, “Upgrading the Input Optics for High Power Operation”, Ligo internal note, LIGO- T060267-00-D.

EOM prototype views

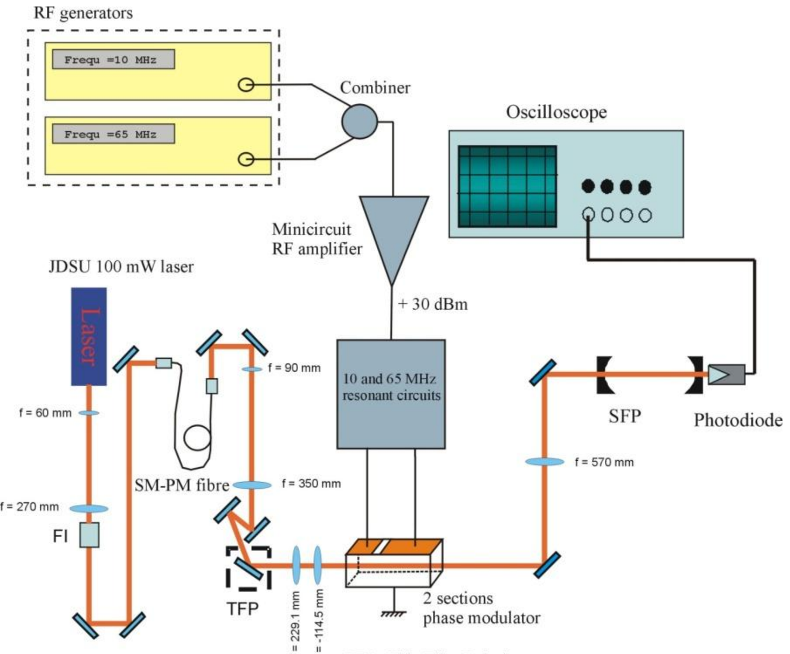


EOM prototype
(design EGO)

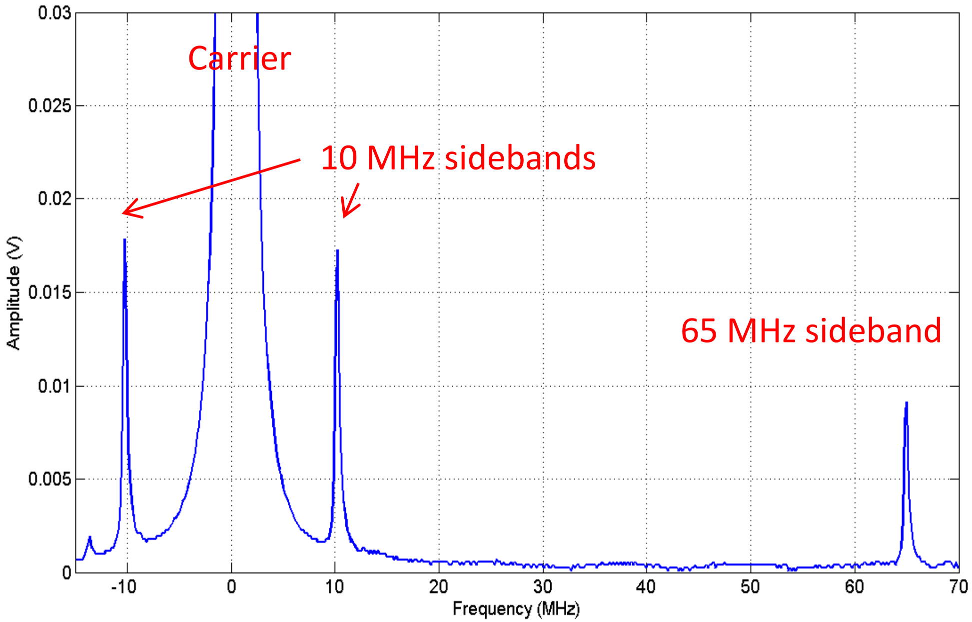


EOM prototype: Low power tests

Measurements performed with a scanning Fabry-Perot (FSR=300 MHz, F≈200).



TFP : Thin Film Polariser
FI : Faraday isolator
SM-PM fibre : Single mode polarisation maintaining fibre
SFP: Scanning Fabry-Perot



Modulation depth measurement:

$m_{10MHz} = 0.163$
$m_{65MHz} = 0.117$

With only 0.5W RF power for each frequency
before the resonant circuit

→ We have margin to increase the modulation depth if needed (play with electrodes length, RF amplifier output power can be increased, resonant circuits could be improved).

EOM prototype: RFAM measurements

m_{10MHz} =0.146 (from RF monitors)

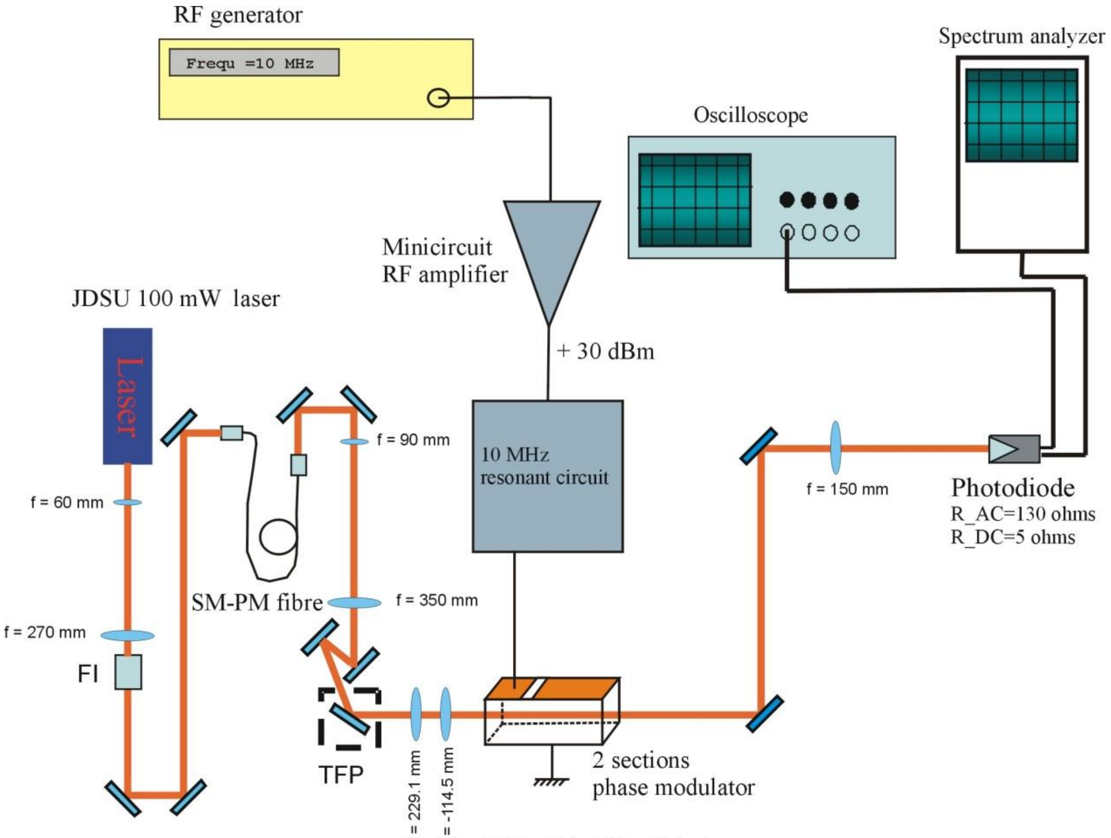
Preliminary result:

Pin=50 mW (V_DC=0.168V),

RFAM amplitude @ 10 MHz = 0.35 mV

→ RIN = 8 10^{-5}

In Virgo past measurements shown that RFAM at 6 MHz is about 10^{-3} but no associated noise could be found on the dark fringe (see logentry #22358).



TFP : Thin Film Polariser
FI : Faraday isolator
SM-PM fibre : Single mode polarisation maintaining fibre
SFP: Scanning Fabry-Perot

→ measurements at high laser power are starting.

AdV Input Mode-cleaner

- Input Mode-Cleaner cavity role:
  active: involved in the laser frequency stabilization loop.
  passive: spatial filtering of the laser beam.

- Requirements:
  - Beam jitter: $< 10^{-10}$ rad/√Hz (f>10Hz) after IMC (currently jitter specs definition are going on but we are still missing AdV final optical configuration before being able to give accurate numbers).
  - Throughput > 90%
- Main issues to be addressed
  - Geometry
  - Thermal effects
  - Losses
  - Back-scattering due to small angle of incidence on IMC end mirror.

IMC cavity geometry, thermal effects and losses

- **Compliance with ITF frequencies of modulation**
  144m long cavity => FSR=1MHz => all multiples of 1MHz can be used as modulation frequencies for ITF control. Having a shorter cavity may be a not so negligible constraint for ITF frequencies of modulation.
- **Back-scattering recoupling**
  Shortening the length of the IMC cavity should considerably reduce the problem of back-scattering of the IMC end mirror but this is very expensive and a good isolation of the Faraday is enough to overcome this problem.
- **Thermal effects**
  The thermal lensing induced in the input substrate affects the matching coupling of the input beam into the IMC cavity and into the interferometer.
  → For a finesse of 1000 and an input power of 180W, coating absorption ≤ 2ppm.
- **Radiation pressure**
  RP should not be a problem with current IMC end mirror (1.4 kg) but it would be better to increase a bit the mirror weight to be safe (3 kg) (see Virgo note on RP in AdV IMC VIR-0009B-09).
- **Throughput and losses**
  The throughput of the cavity is limited by the losses in the cavity (throughput > 90% for a finesse of 1000 with 300ppm losses)→ mirrors surface properties (roughness, radius of curvature, flatness) have to be well defined and checked before acceptation.

→ There are no strong arguments to change the geometry and the length of the cavity for Advanced Virgo.

Round-trip losses in IMC

- Round-trip losses caused by “rough” cavity mirrors.
- Studies made using FFT propagation to help provide accurate specifications for mirror roughness (VIR-0398A-10).
- Principle source of round-trip losses are due to clipping.
- There are two mechanisms:
  - Clipping of scattered light.
  - Clipping of resonant higher order modes (HOM’s)

- Quantity of scattered light is directly related to mirror roughness

rms^2

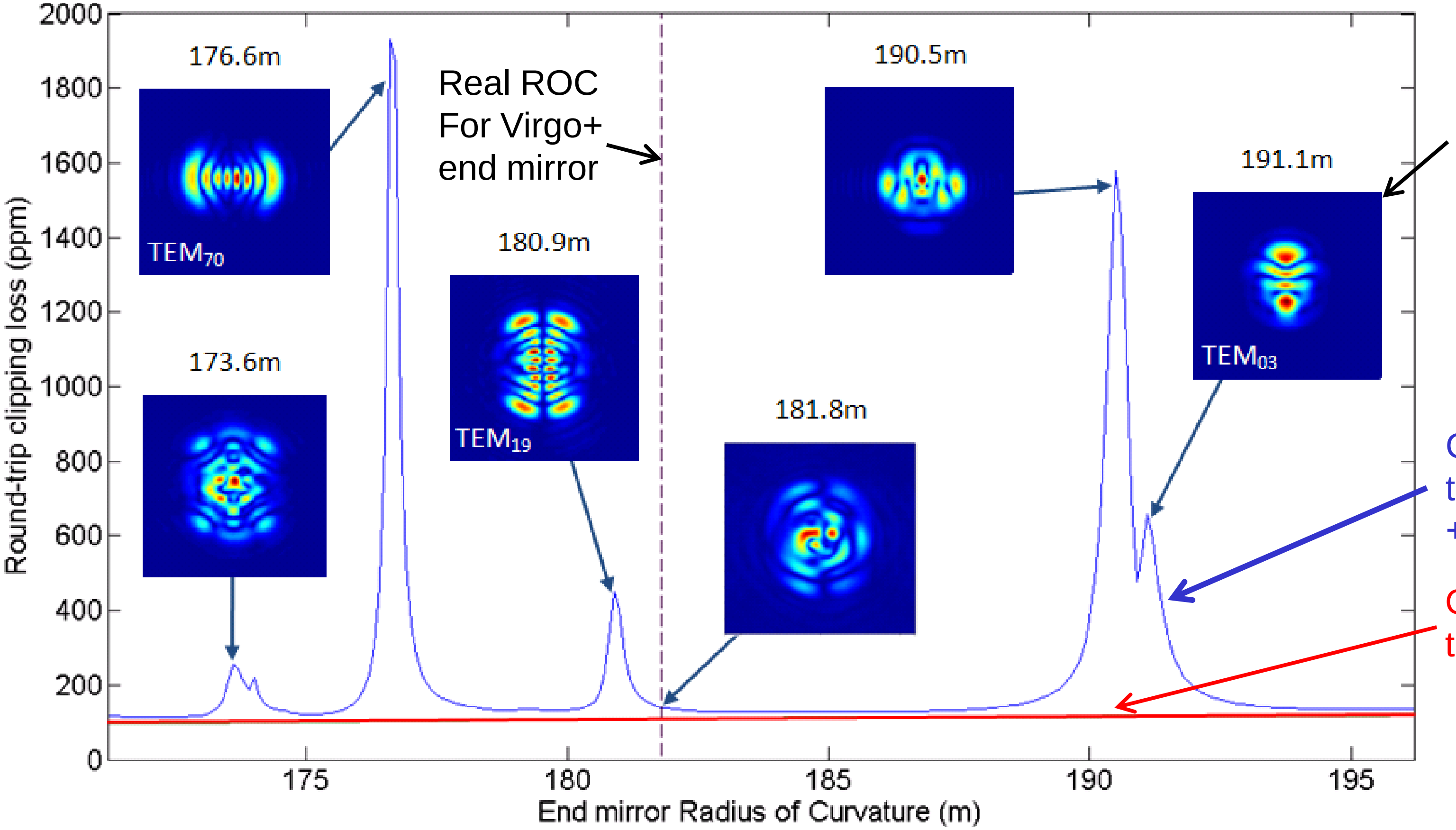
Magic number 140ppm/nm^2

$$\alpha = \left(\frac{4\pi}{\lambda}\right)^2 \int PSD(\rho)\, d\rho$$

Spatial frequency

Round-trip losses in Virgo IMC

- Mirror roughness can also excite Higher Order Modes.
- HOM resonance depends on end mirror Radius Of Curvature



Images of HOM component

Clipping loss due to scattering + HOM's

Clipping loss due to scattering

- HOM's can become dominant source of round-trip losses.

Round-trip losses in IMC: experimental tests

- Test carried out in transmission of IMC end mirror
- Mask placed to obscure the TEM00 mode thereby revealing HOM's

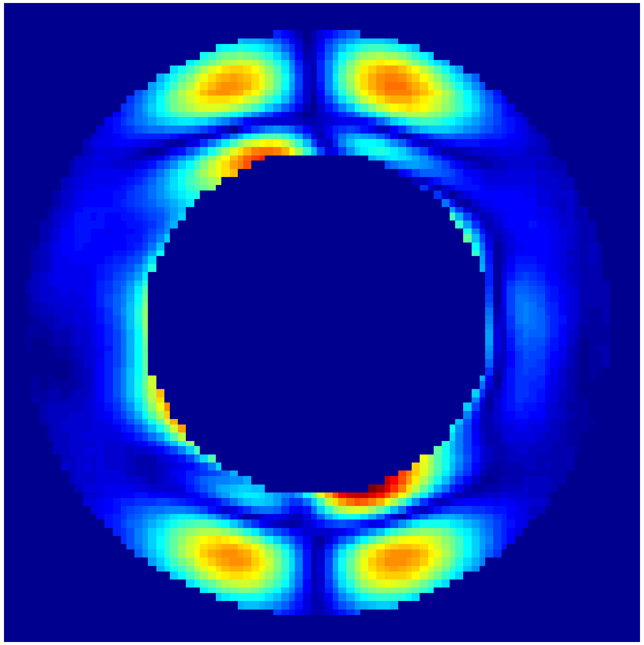


Image from simulation

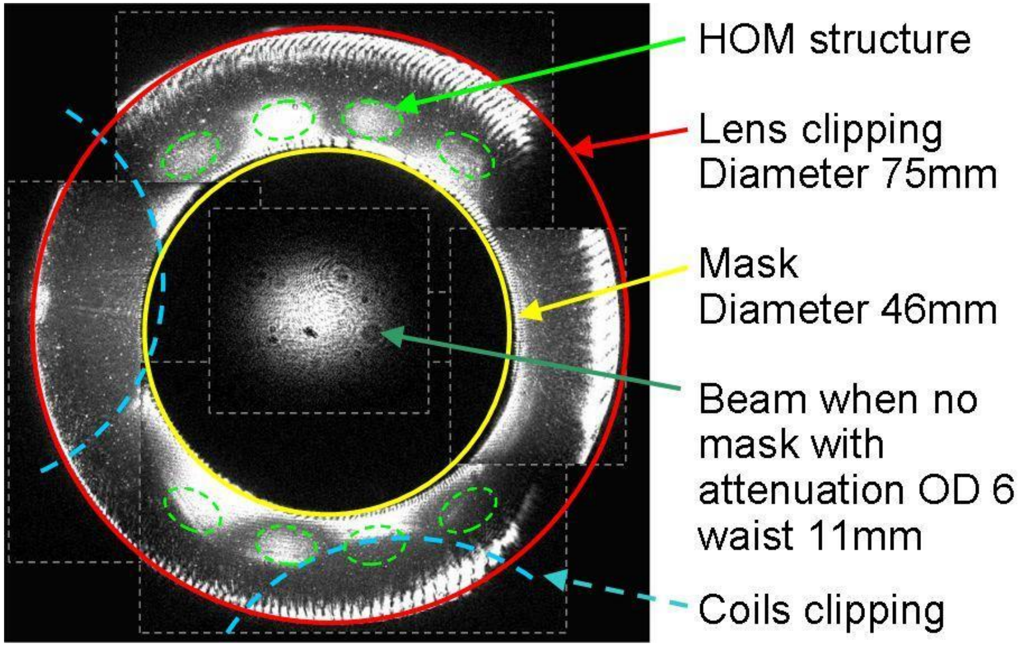


Image from experiment

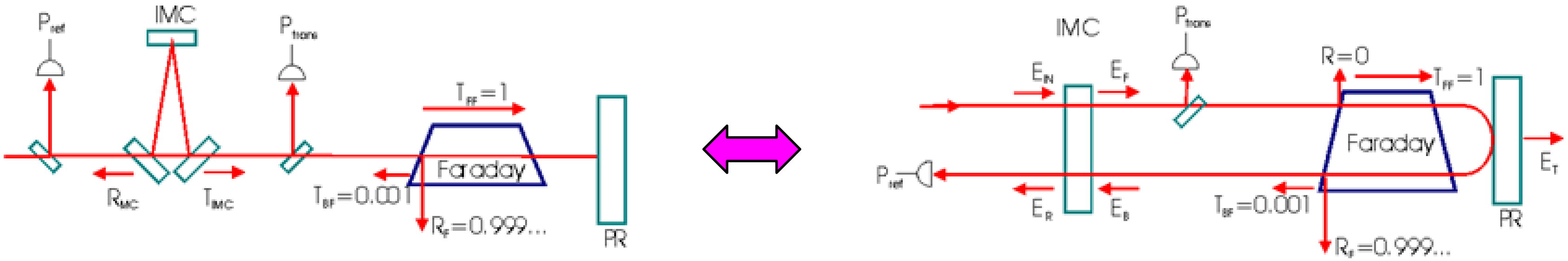
- HOM's clearly visible although does not agree well with simulation.

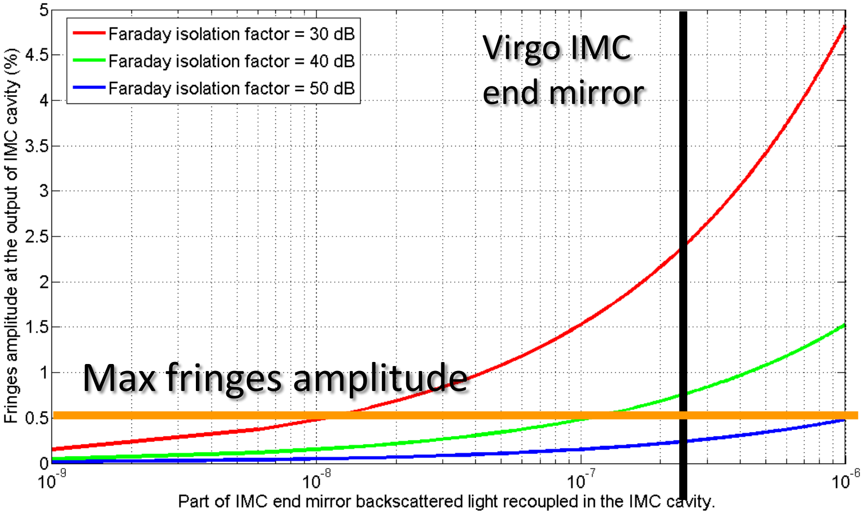
→mandatory to change the radius of curvature of IMC end mirror in AdV if we want to reduce the round-trip losses. A ring heater could help us to accurately tune the radius of curvature in case we are close to a HOM.

Back-scattering effect

- This problem can be modelled by a spurious cavity IMC-PR

The effective reflectivity of the IMC goes as the square of the finesse and the backscattered coupling factor. It can be reduced by improving the Faraday isolator isolation factor.
Final effective reflectivity should be lower than 0.1ppm to have negligible fringes on the sensors used to control the IMC.





- Amplitude of the fringes appearing at the ITF input: **specs <0.5% (TBC)**

IMC Finesse=1000 (to guarantee a good filtering of Input beam jitter)
Faraday isolator isolation is 40dB at full power.
→ we should change the IMC end mirror to reduce the amount of fringes (surface error should be improved).

Conclusion & next steps

- Faraday isolator:
  - The FI prototype looks very promising: fulfills almost all our requirements up to 250W.
  - Next steps:
    - Optimize the isolation tuning at high power by optimizing the angle of one TGG respect to the other.
    - Measure residual thermal lensing after compensation (waiting for the DKDP crystal from IAP).
- EOM:
  - An EOM prototype was realized with a very low absorbing crystal (RTP).
  - A modulation depth larger than 0.1 @ 65 MHz has been measured (fulfills current ISC specs) using 0.5W RF → 0.2 or 0.3 should be reachable by playing with the electrodes length, improving a bit the modulation electronics and/or applying RF power up to 1W.
  - Next steps:
    - Complete the RFAM tests (high power tests).
    - Waiting for the decision on AdV modulation frequencies to prepare the final version of the modulators.
- IMC:
  - We should keep Virgo IMC geometry (triangular) and length (144 m).
  - A Finesse of 1000 could help us to filter out jitter noise and reach AdV requirements.
  - Virgo IMC end mirror should be changed for AdV to improve the cavity throughput.
  - Next steps:
    - Define IMC end mirror radius of curvature and specs on surface error.
    - Waiting for input beam jitter specs to confirm the cavity Finesse.
- INJ subsystem:
  - The release of the Final Design Report is expected for spring 2011.

- Questions?
- For more information, please contact us:
  - General information on INJ subsystem:

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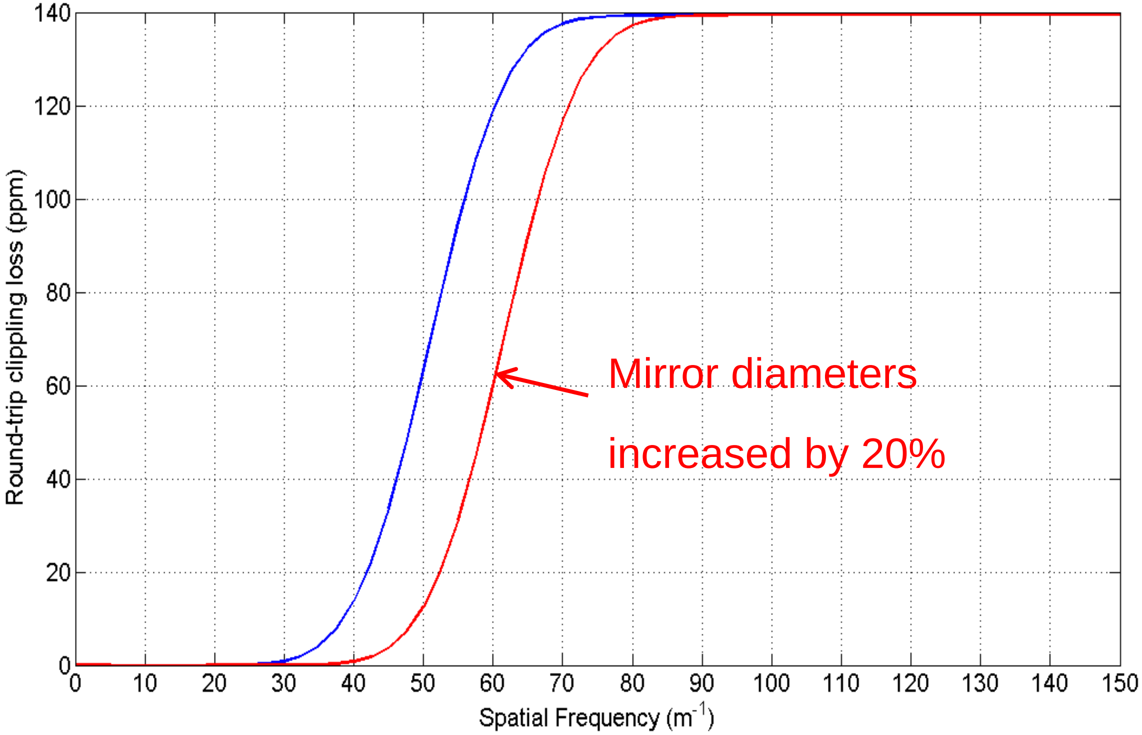
Extra slide: Round-trip losses in IMC

- Only scattered light that is clipped by mirror apertures contributes to round-trip losses.
- Direction of scattered light depends on roughness spatial frequency.

→ $\sin\theta = \lambda\rho$



Mirror diameters increased by 20%

- Spatial frequencies above a cutoff contribute to round-trip losses.
- Cutoff frequency depends on cavity geometry.

→this simulation work helped us a lot to define specs for new IMC flat mirrors (currently produced in Holland in collaboration with Nikhef group).