VIRGO

Optical simulations of stray light on instrumented baffles surrounding Virgo end mirrors during O5

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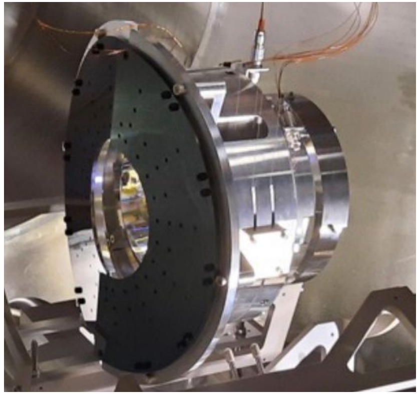
Context and motivation

- **Stray light is an important source of noise in Virgo**
- **Baffles to reduce scattered light in mirrors / core optics / arm tubes**
  - Absorb 99.5% of diffused light
  - No active monitoring of stray light
- **Instrumented baffles equipped with photodetectors to monitor scattered light**
  - Help with laser alignment
  - Dynamic mapping of mirror surface
  - Monitor development of higher order modes in the beam



IMC baffle - Credit: IFAE

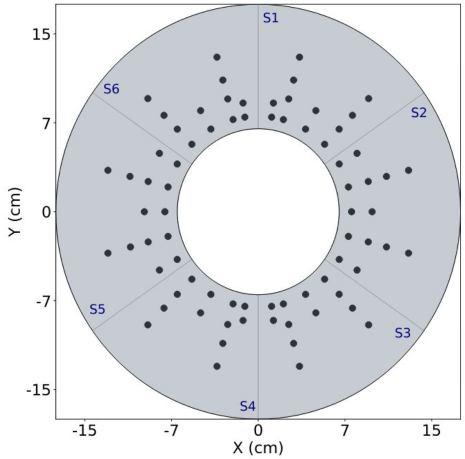
➔ Phase I - Instrumented baffle around IMC end mirror (done)

➔ Phase II - Instrumented baffles around end mirrors (EM) in main arms (being executed)

Instrumented baffle around IMC end mirror

See poster: *Stray Light Measurements With an Instrumented Baffle in the Advanced Virgo Input Mode Cleaner Cavity* by Machiel Kolstein

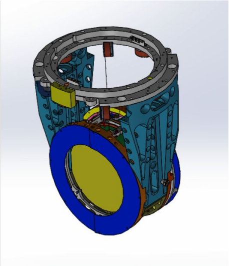
- A first instrumented baffle was installed in April 2021 around the IMC end mirror as a demonstrator for the technology
    - 76 photosensors + 16 temperature sensors
    - Currently operational
    - Good agreement between measurements and simulations



O.Ballester et al., CQG, 2022

➔ Monitor misalignment and mirror defects in IMC cavity
➔ Help to calibrate future optical simulations
➔ Design new instrumented baffles for Virgo main mirrors

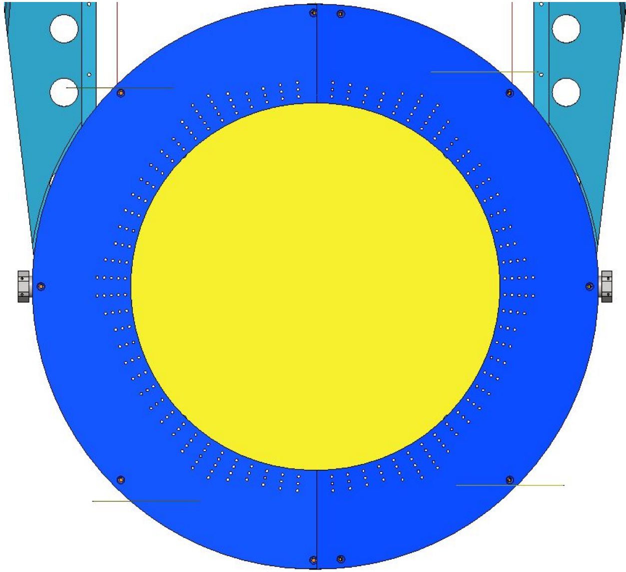
Planned design of EM instrumented baffle



- Baffle: r = 26 cm to 40 cm
- 5 rings of sensors (active area 0.49 cm^2)
  - 72 sensors at r = 27 / 28 / 29 cm
  - 24 at r = 30 cm, 12 at r = 31 cm
- Final layout subject to modifications
  - Impact of sensors' reflectivity
  - Readout speed

Goals of simulations:

- Demonstrate benefits of instrumented baffles
- Find optimal design / dynamic range / resolution for sensors

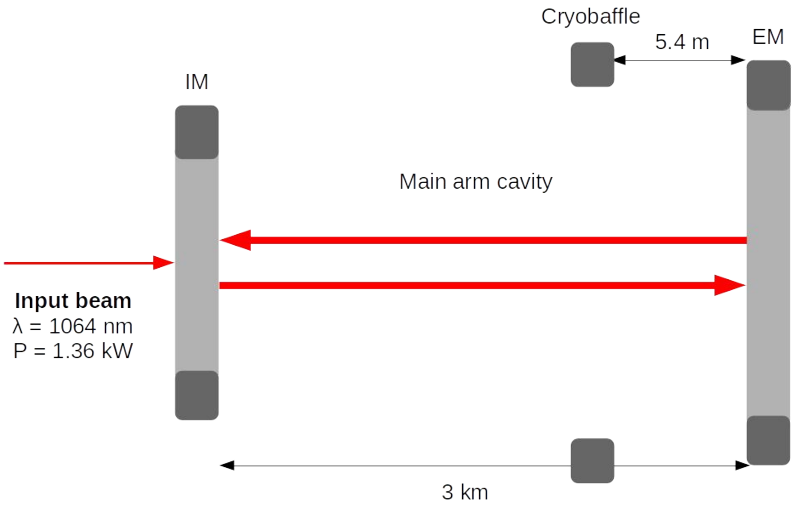


Planned layout of sensors

Simulations of light distribution in Virgo main arms

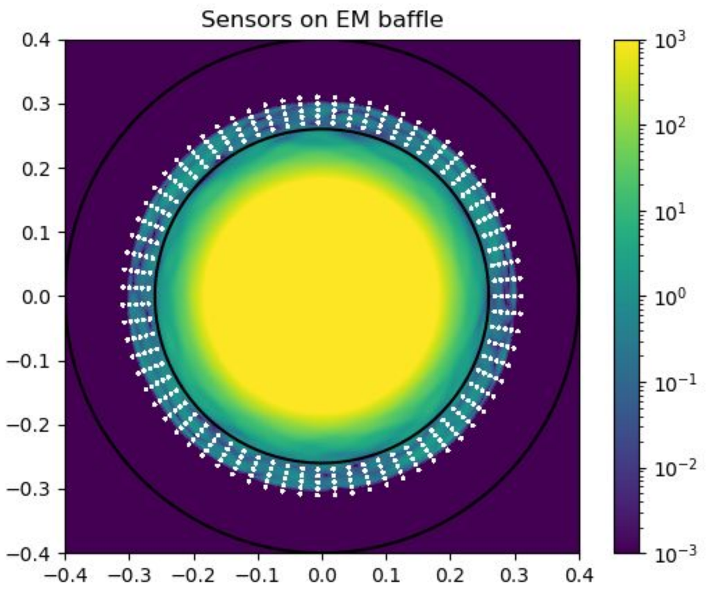
Stationary Interferometer Simulation (SIS)

- FFT-based code
  - Simulate field propagation in a resonant cavity
  - Spatial distribution of field with given resolution
- Use realistic optical components
  - Mirror surface maps, cryobaffle…
  - Thermal deformation, coating absorption
- Introduce defects in the cavity
  - Misalignment, beam displacement
  - Defects on mirror surface



Principle of the simulations

- Simulate different configurations
    - Aligned cavity - perfect mirrors
    - Aligned cavity - realistic mirror maps
    - Misaligned cavity
    - Point absorbers on mirrors
- Get spatial distribution of power on mirrors
- Compute power in each sensor

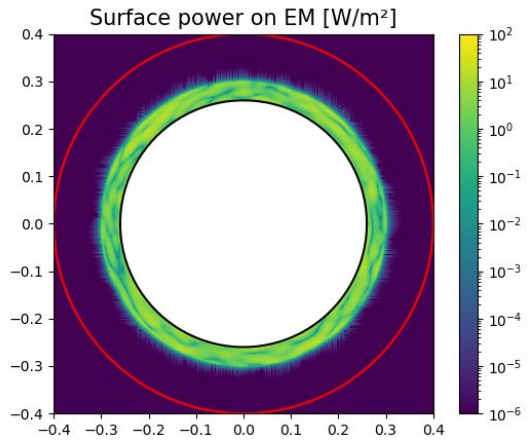


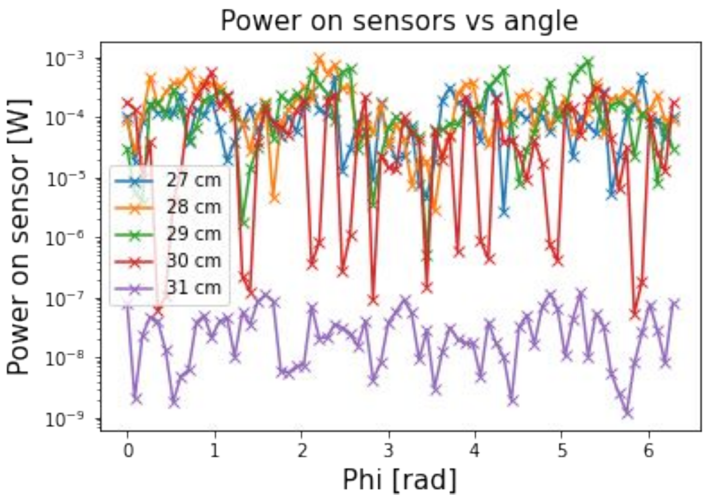
Expected power on EM in nominal configuration (sensors in white)

Nominal configuration

Perfectly aligned cavity, realistic mirror maps, thermal deformation and coating absorption

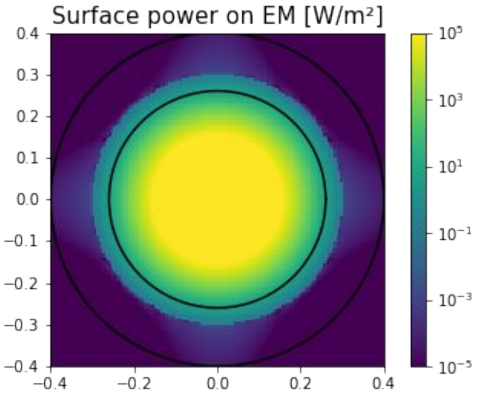
- Measured O3 map for IM
- Simulated O5 map for EM
- ~ 390 kW circulating in the cavity
- Average power in sensors:
  - 10^{-4} W from 27 to 30 cm
  - 10^{-8} W at 31 cm (field clipped by cryobaffle)
- Non-isotropic distribution and large variance
  - Scattering from imperfect mirrors



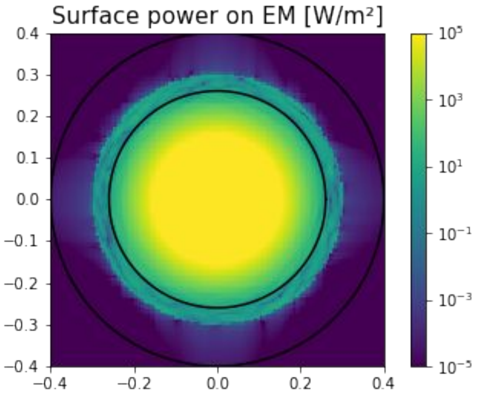


Estimated power seen by each sensor (effective area 0.49 cm²)

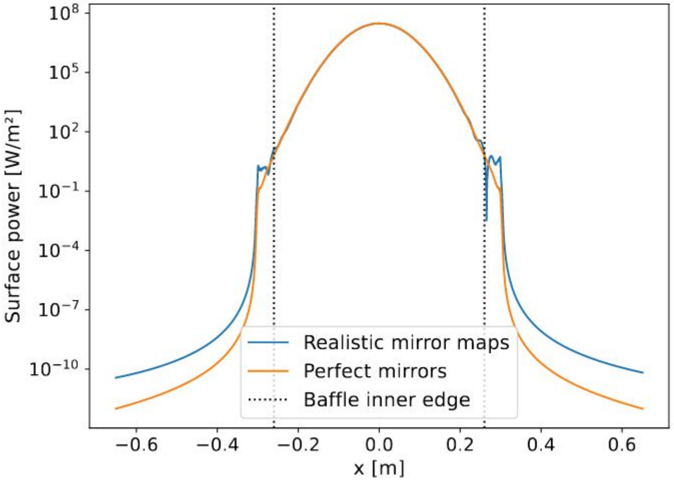
Effect of mirror maps



Perfect mirrors



Realistic mirrors



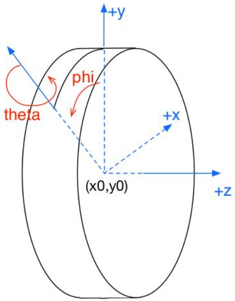
Beam shape with and without mirror maps

- ➔ Spatial structure appears with realistic mirror maps in the inner layers
- ➔ Scattering from mirrors -> ~ 10 times more power in sensors area

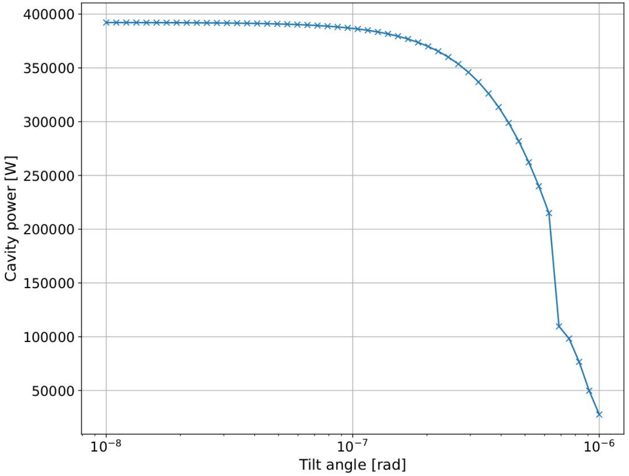
Misaligned cavity

Simulate misaligned cavity by introducing a tilt in the end mirror

- Decrease power in cavity
- Development of higher order modes in the beam
  - ➢ Decrease overall sensitivity
- Critical range: 0.1 - 1 µrad -> power drops from 95% to 10%

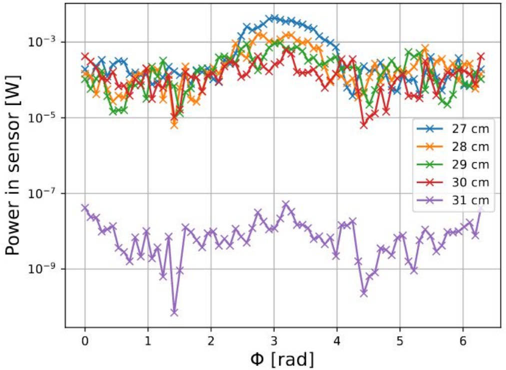


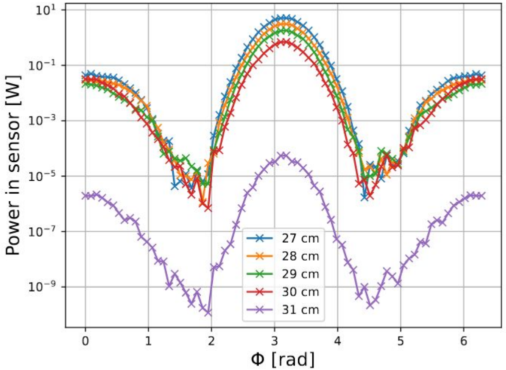
EM is rotated along the y axis, introducing a yaw angle (credit: H. Yamamoto)



Power circulating in cavity vs tilt angle

Misaligned cavity (2)





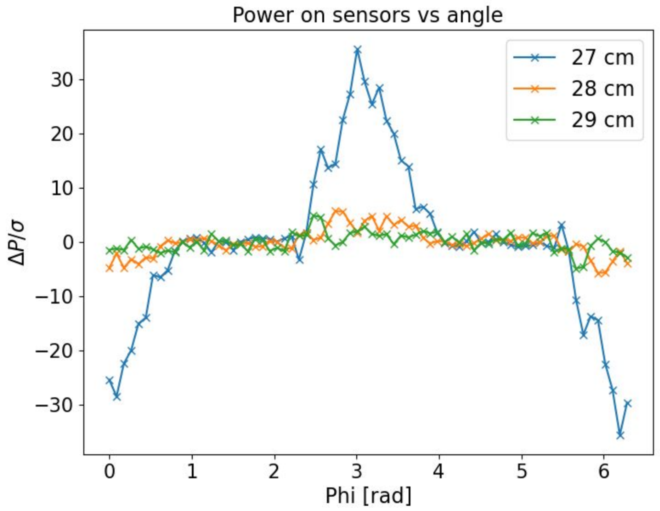
Power seen by each sensor with a tilt angle of 0.3 μrad (left) and 0.8 μrad (right)

Beam is off-centered w.r.t the center of the mirror: excess power in the direction of misalignment

Monitoring misalignment

Differential power along opposite sensors: $\Delta P(\phi, r) = P(\phi + \pi, r) - P(\phi, r)$

- Nominal configuration: 0 mean, variance $\sigma \sim 10^{-4}$ W
- Compute $\mathbf{\Delta P(phi, r) / \sigma}$
  - ➢ SNR that quantifies misalignment



SNR of the differential power for a tilt angle of 0.3 μrad

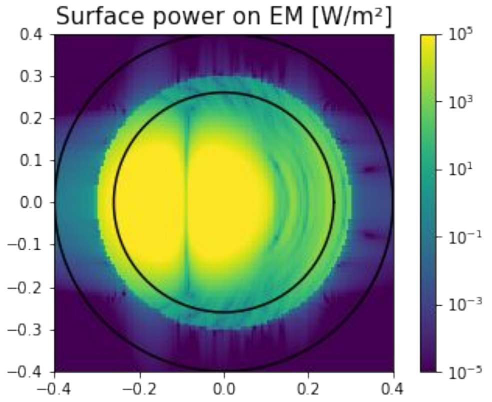
Conclusion:

- Sensors are able to monitor misalignment in the critical range 0.3 - 0.8 μrad
- Sensors closer to the mirror are most useful

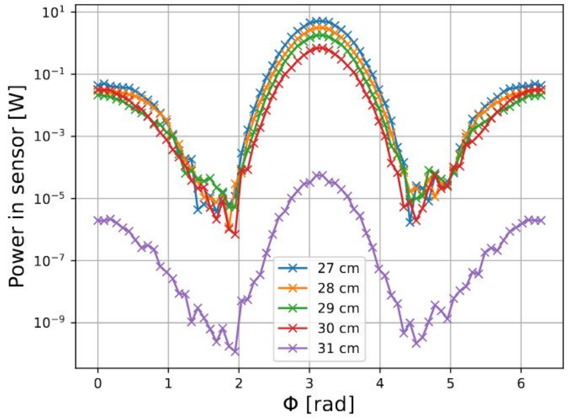
Large misalignment

When misalignment becomes too large (>~ 1 μrad), cavity lock is lost

- Cavity power drops
- Beam dominated by higher order modes
- Power in sensors in the inner rings can go up to ~1 W
    - ➢ Sensors will saturate
- Sensors in outer ring (31 cm) prove useful in this particular case



Surface power on EM for a tilt angle of 0.8 μrad



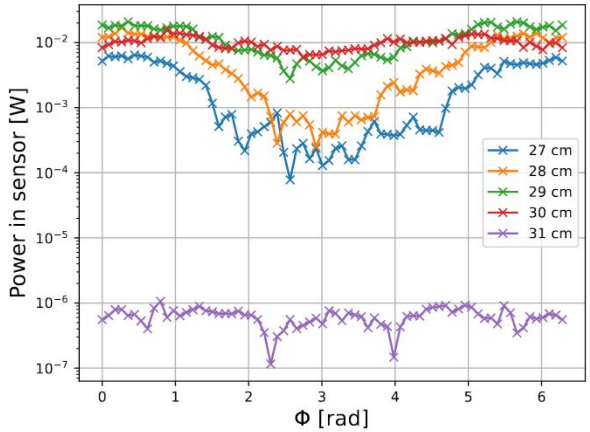
Point absorbers

Point absorber (PA): point-like defect in the mirror that generates scattered light

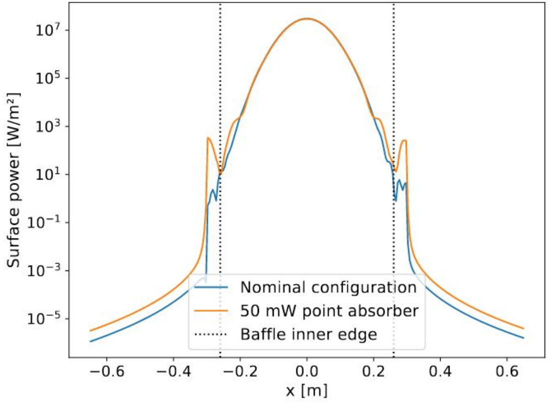
- Typical absorption: ~ 0.1 ppm
  - For 390 kW -> 50 mW (large value)

  Sensors see an excess of power (>10 mW)

- Larger effect in outer rings



Power in sensors for a 50 mW PA located 1 cm to the right of the EM center

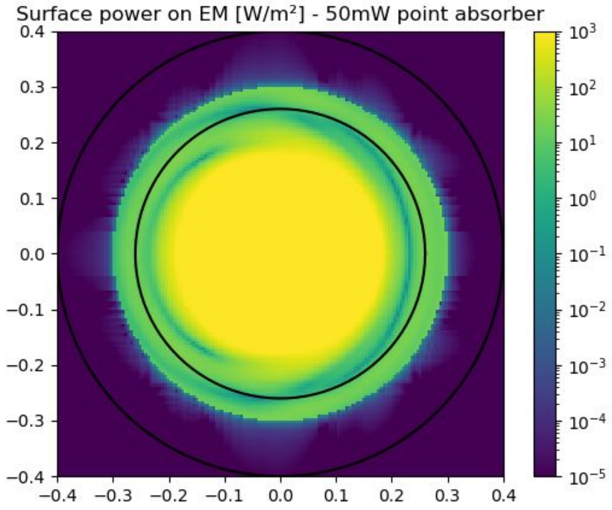


Beam shape with and without PA

Point absorbers (2)

PAs generate effects with high spatial resolution

- Sensors cannot map the precise distribution of surface power
- Difficult to interpret the output of sensors
    - Excess of power can indicate the presence of one or more PA’s
    - Inferring position of PA is not possible



Surface power on EM with a 50 mW PA at 1 cm to the right of the center

Conclusion

- ➔ Photosensors should see a power of ~ 10^{-4} W in nominal configuration from 27 to 30 cm
    - Large variance due to imperfect mirror surface maps
- ➔ Misalignment can be monitored from ~ 0.3 µrad
    - Beam off-centered by ~ 0.1 mm
    - 5% decrease in cavity power
    - Need sensors as close as possible to the mirror (r = 27 cm)
    - Sensors on outermost ring could help for very large misalignment
- ➔ Point-like defects generate an excess of power in sensors
    - Not enough precision to infer the position of point absorbers

Complementary work:

- Estimate potential effect of instrumented baffle on Virgo's sensitivity curve (reflexion and backscattering from sensors)
- Consider layouts with less sensors (focus on alignment?)