Future Gravitational Wave Detectors: Phase Noise Investigation and Magnetic Noise Mitigation Strategies

Barbara Garaventa[1] with the collaboration of
Quantum Noise Team: V. Sequino[4], F. Sorrentino[1], J. P. Zendri[7], W. Ali[1,2]
Magnetic Noise Team: A. Chincarini[1], I. Fiori[3], F. Armato[1,2], F. Paoletti[5], G. Quéméner[6], M. C. Tringali[3], M. Graziaplena[3], R. De Rosa[4]
[1] INFN Genova, [2] University of Genova, [3] European Gravitational Observatory (Cascina), [4] University of Naples and INFN Naples, [5] INFN Pisa, [6] LPC Caen, [7] INFN Padova

Abstract The sensitivity of future gravitational wave (GW) detectors, such as the Einstein Telescope (ET), is constrained by quantum noise across the entire frequency range (10 Hz - 10 kHz) and by magnetic noise at low frequencies (a few Hz to around 100 Hz). Squeezed light states are injected into the dark port of the interferometer to reduce quantum noise. Magnetic noise results from the interaction of environmental fields, like the natural background from Schumann Resonances and "self-inflicted" noise, with magnetized components. This poster examines the mechanisms of squeezing degradation, particularly phase noise analyses, and also highlights strategies to mitigate magnetic noise, including reducing emissions from critical sources and shielding sensitive coupling locations.

Phase Noise Investigation

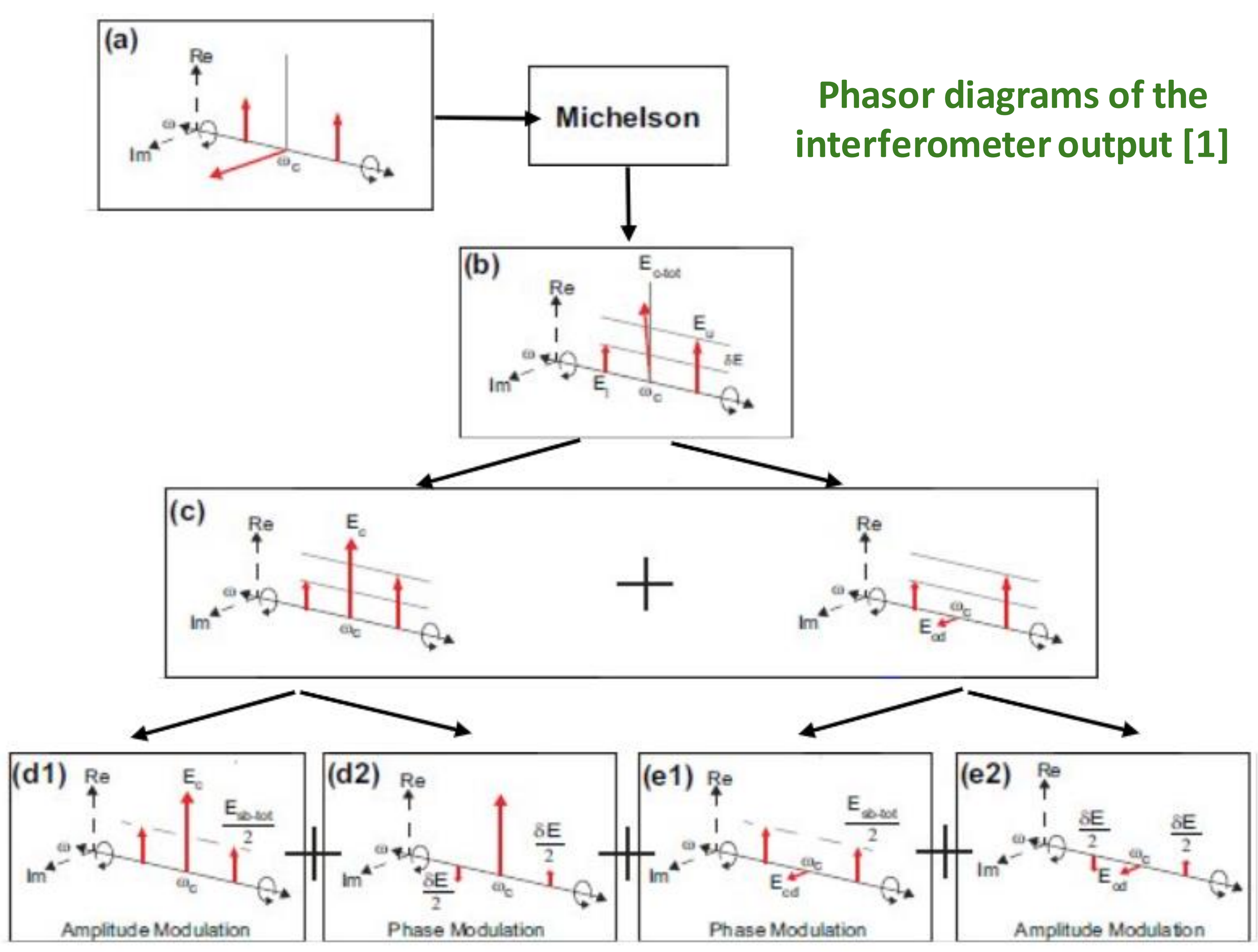
Quantum noise manifests in fluctuations in phase (shot-noise) and in amplitude (radiation-pressure noise).
Two mechanisms degrade squeezing level:
- optical losses;
- phase noise, that mixes the fluctuations in the two quadratures.

Sources of Phase noise

- From the **squeezer**: OPO (Optical Parametric Oscillator) cavity length control and crystal temperature fluctuations;
- From the **interferometer**: residual sidebands from OMC (Output Mode Cleaner), higher order modes (Gouy phase), alignment issues and contrast defect at the output port.

Phase noise due to Contrast Defect

Contrast defect is due to the asymmetry of the Michelson arm reflectivities and to the reflection beam spatial overlap.



Phasor diagrams of the interferometer output [1]

The total rms phase fluctuation [1,2]:

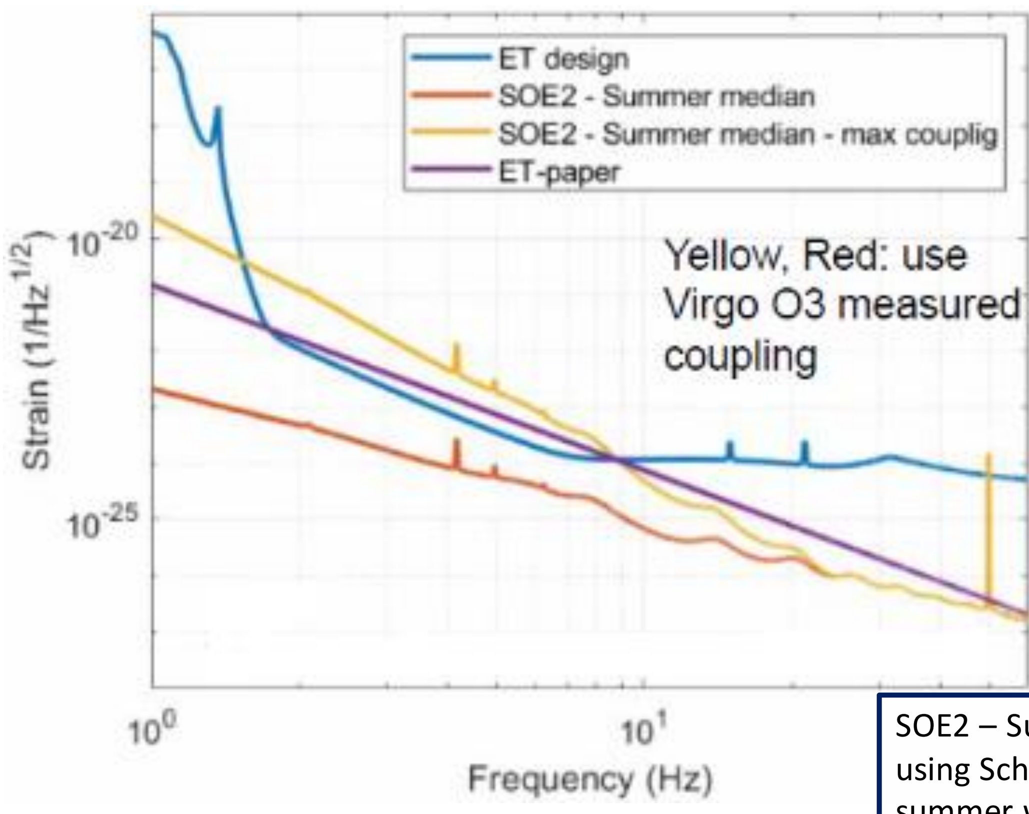
$$\tilde{\theta}_{cd} = \sqrt{(\tilde{\theta}_{c-AM})^2 + (\tilde{\theta}_{cd-PM})^2} = \sqrt{\frac{T_{sb} 2\bar{P}_{sb} P_{cd}}{P_c P_{c-tot}}}$$

Measurements of Contrast Defect

O4 Virgo detector data sending to zero the dark fringe offset: contrast defect measurements for each control sidebands < 1 mrad.
The filtering of sidebands by the OMC is crucial. A possible solution for future detectors may be a higher finesse for OMC.

Magnetic Noise Mitigation Strategies

The next GW detectors target, as for ET, is to improve low-frequency sensitivity by two-orders of magnitude [3]:



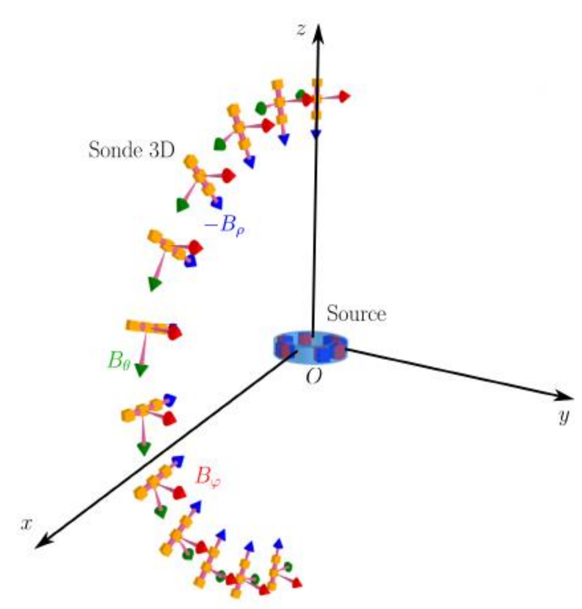
SOE2 – Summer median [4]: Magnetic noise projections using Schumann Earth noise measured at SOS Enattos in summer when Schumann Resonances are most intense.

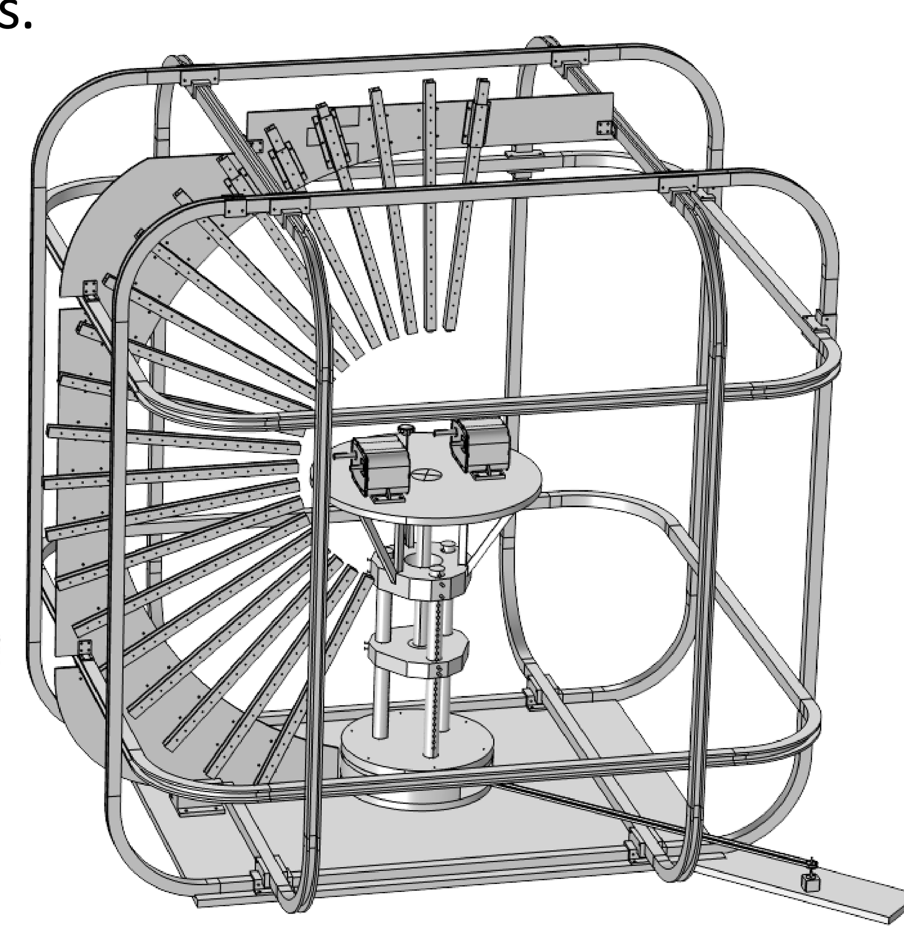
→ lowering the environmental noises at Earth Noise level;

→ Identify and shield main coupling locations.

MANET (MAgnetic Noise test facility for ET)

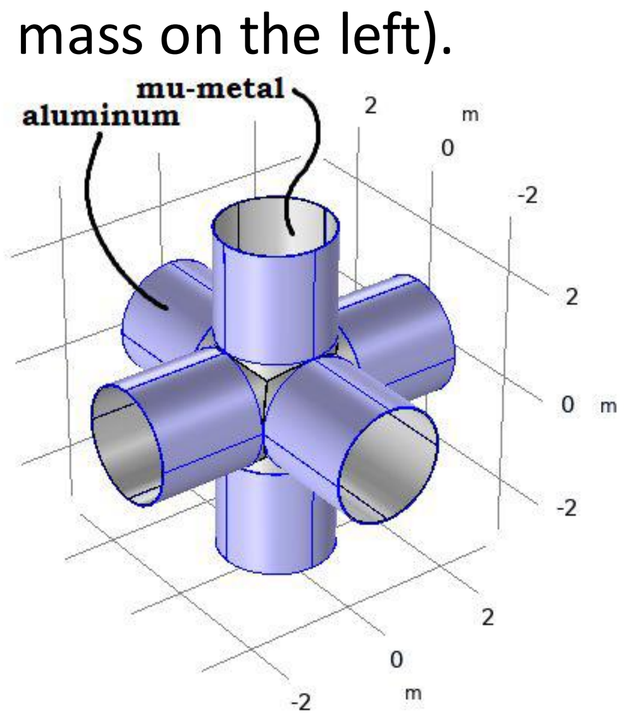
- Characterization of small and big devices noise emission and test of mitigation solutions.
- Simulation of 3D magnetic field mapper.



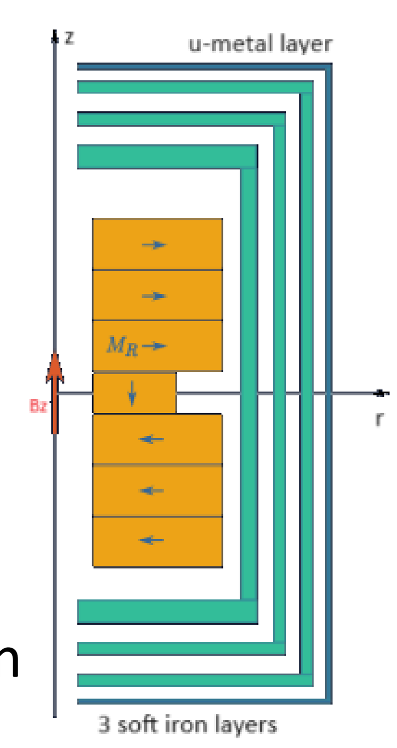


Shielding of Test-mass Tower and Faraday Isolator

The goal is to shield the most sensitive part of the interferometer (vacuum chamber surrounding one mirror test mass on the left).



For the same reason, it is necessary to shield critical component, like Faraday Isolator (order of 2T magnet) on suspended optical benches (on the right). Shielding factors achieved in simulations on the order of 100.



Conclusions

This poster shows two different aspects to take into account for future GW detectors: a mechanism that must be optimized in order to have an efficient level of squeezing to reduce quantum noise; the need to mitigate magnetic noise and some strategies in progress.

References

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