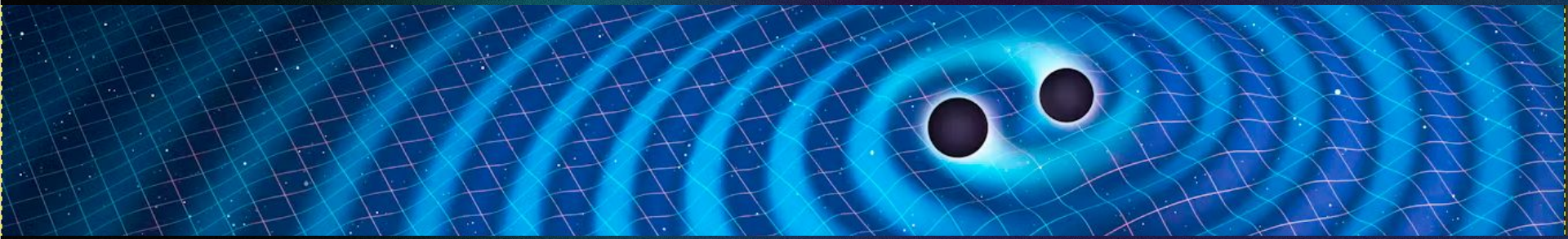
Magnetic noise mitigation for upcoming Gravitational Waves detectors



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INFN Genova

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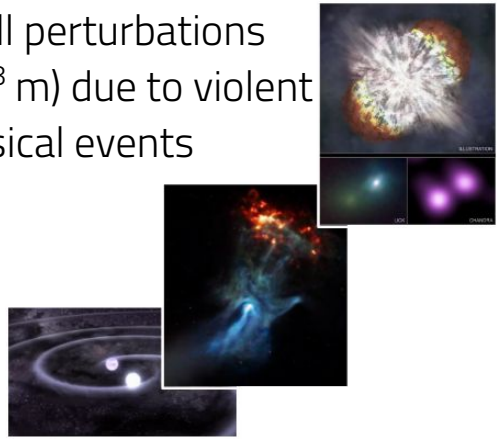
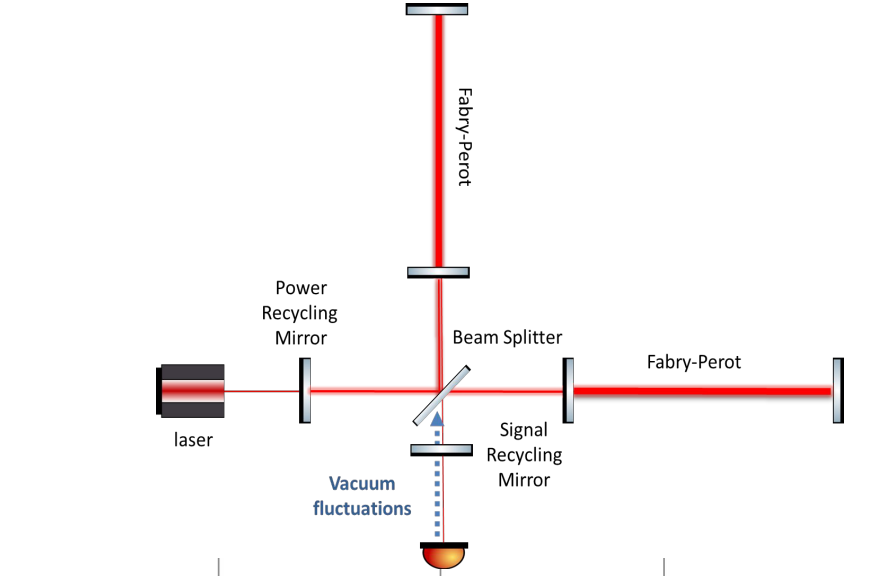
1. INTRODUCTION - Gravitational Waves

Ripples in spacetime predicted in 1916 by Albert Einstein with the theory of General Relativity

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Very small perturbations ($\Delta L \sim 10^{-18}$ m) due to violent astrophysical events

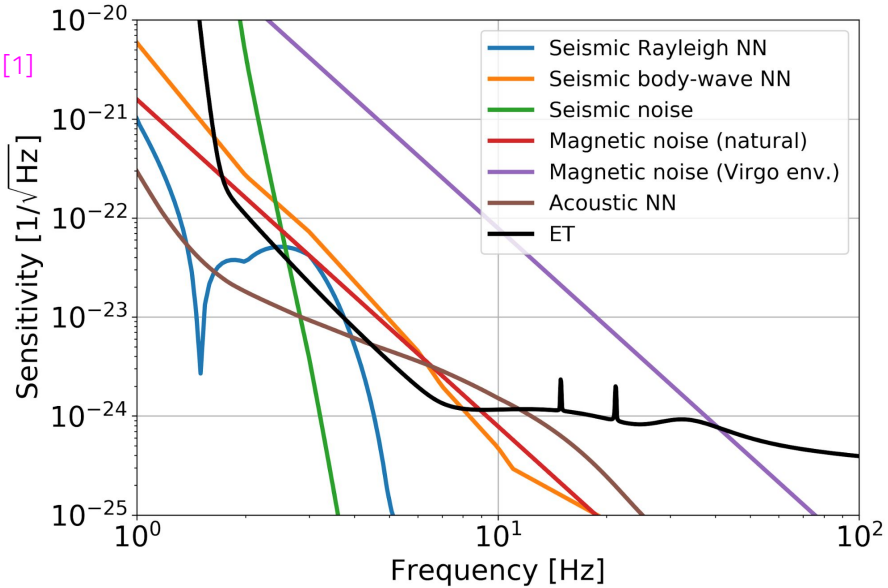


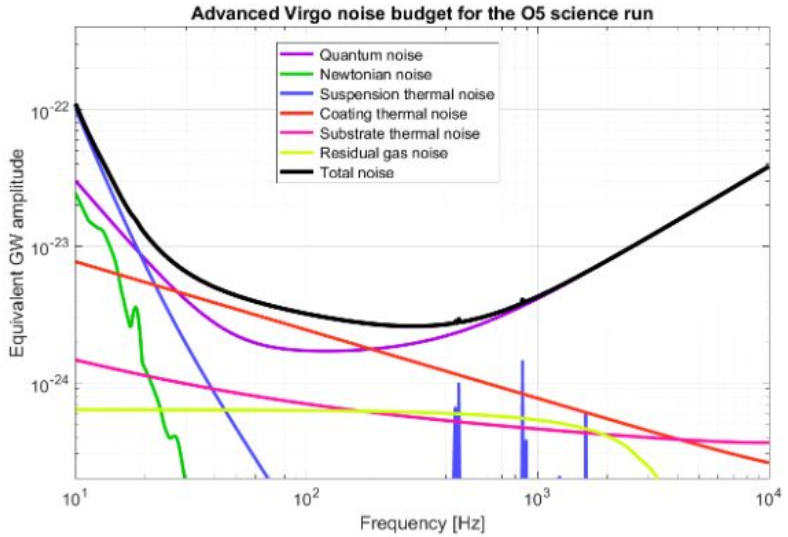


Geo600 Virgo KAGRA LIGO

Future GW detectors:
Einstein Telescope sensitivity curve compared to AdV

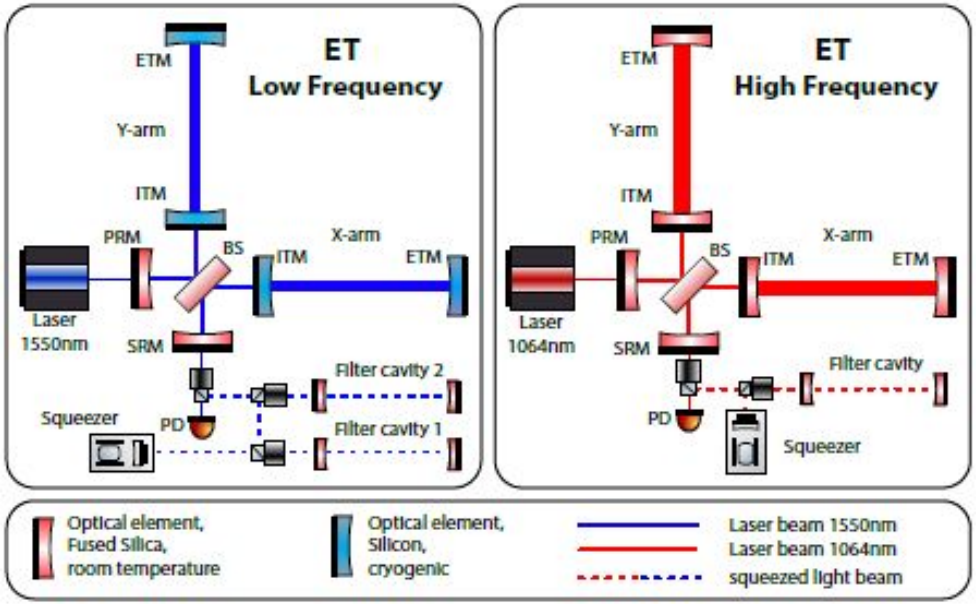
[1]



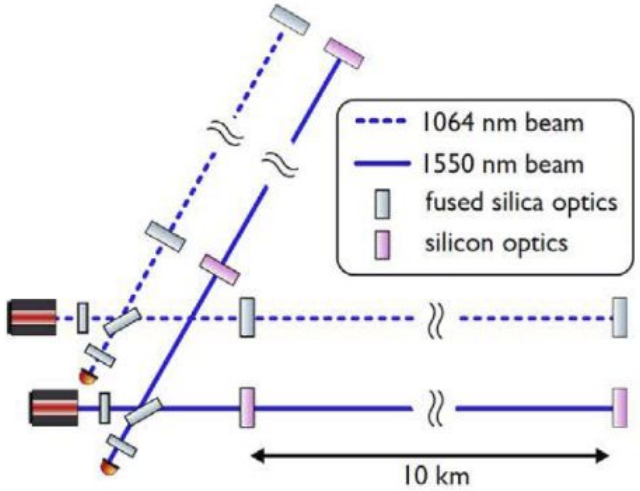


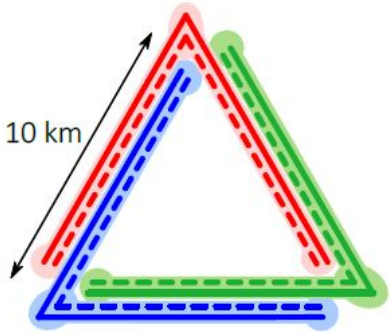
- Wider frequency bandwidth
- Improve low-frequency sensitivity compared to the current GW detectors → Infrastructure approximately 200m underground → specific noise sources reduced (fluctuations of EM field, vibrations and deformations..)

ET Infrastructure



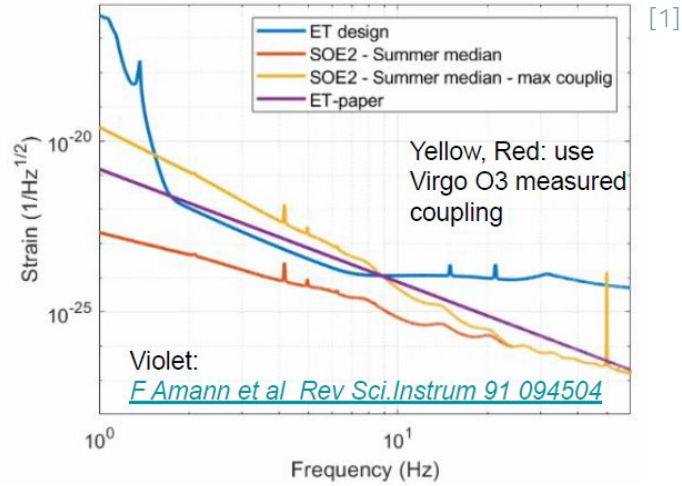
ET Low Frequency (~1 Hz - 30 Hz)
ET High Frequency (~30 Hz -10 kHz)



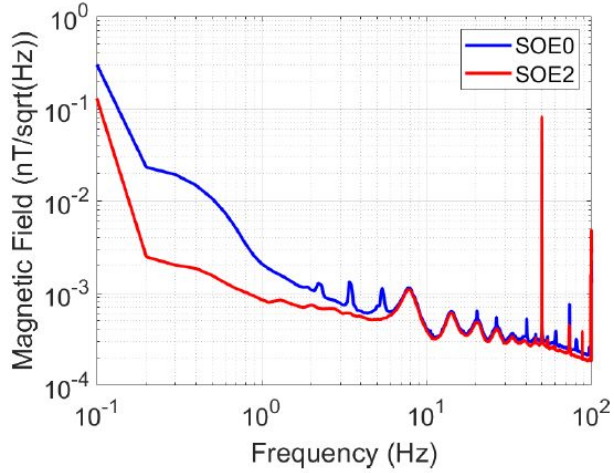


2. MAGNETIC NOISE

- Limited noise from few Hz up to 100 Hz in the next GW detectors
- MN sources: Natural Terrestrial component (Schumann Resonances, on the order of pT/√Hz) and Environmental noise component of the interferometer ("self-inflicted noise")
- MN presence: Coupling of environmental magnetic fields with magnetized components of the interferometer



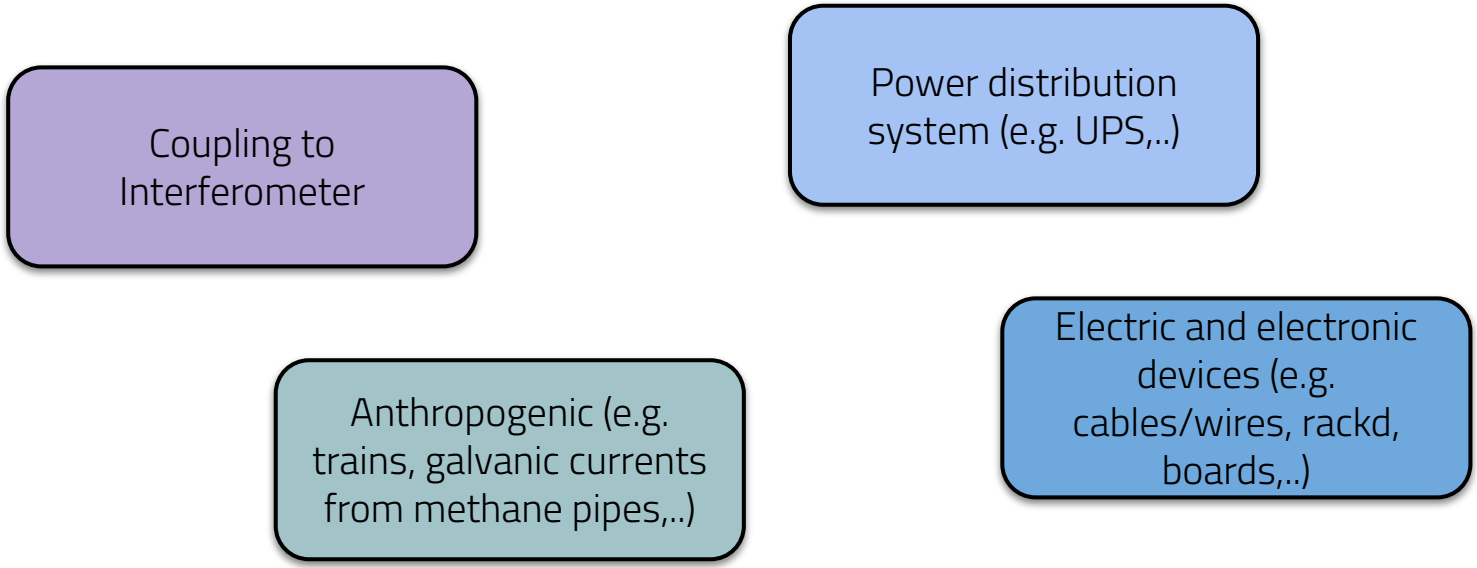
[1]



How to do?

- ➢ Environmental noise at Schumann Noise level (~0.3 pT/√Hz)
- ➢ Investigation strategies: Experience with the Virgo (Italy) and KAGRA (Japan) interferometers
- ➢ Mitigation strategies

MAGNETIC NOISE ISSUE – "self-inflicted noise"



ET target: reduce magnetic couplings by a factor of 10^2–10^3 compared to current GW detectors (**Virgo** is overwhelmed by "self inflicted noise", **KAGRA** has a quieter magnetic condition)

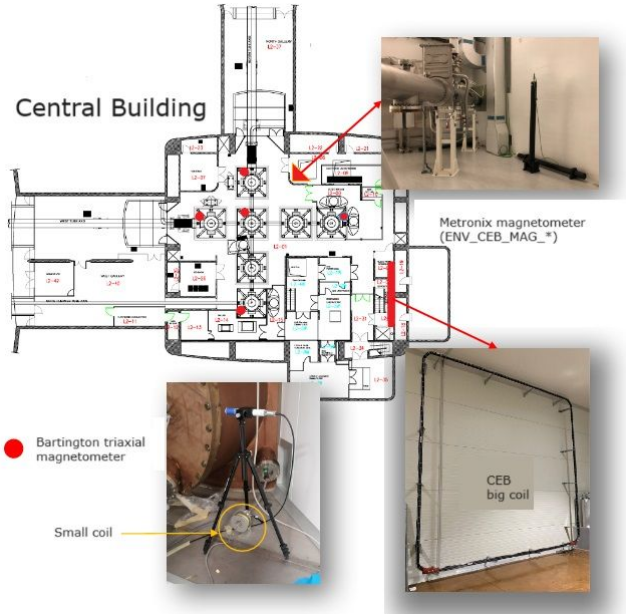
Coupling Functions (CFs) → magnetic noise injections at various coupling points (N towers)

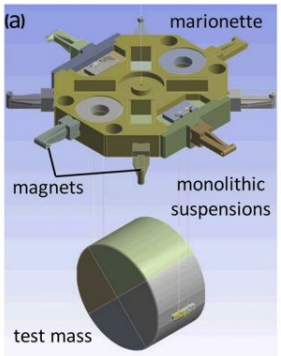
$$CF_{BC}(f) = \sum_{i}^{N} \alpha_i CF_{i,SC}(f)$$

far-field injection (big coil)

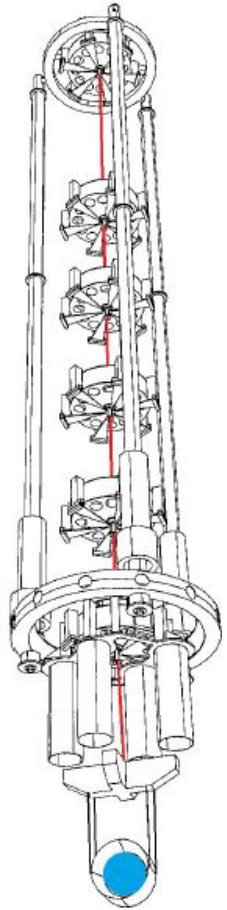
Coefficients estimated by the fitting

near-field injection (small coil)





[2]



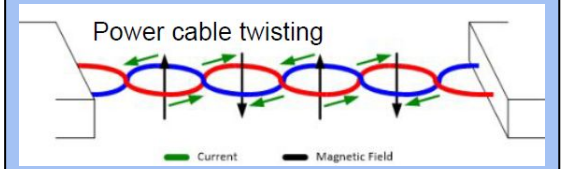
Virgo as reference

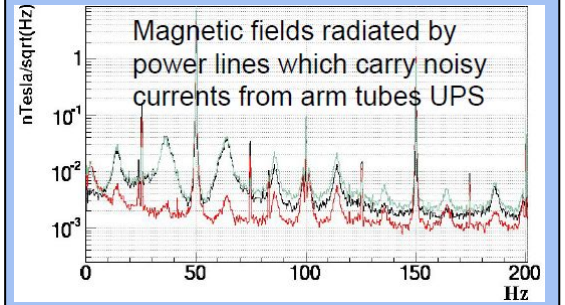
Virgo as reference

ET-0175A-23

Power Distribution System

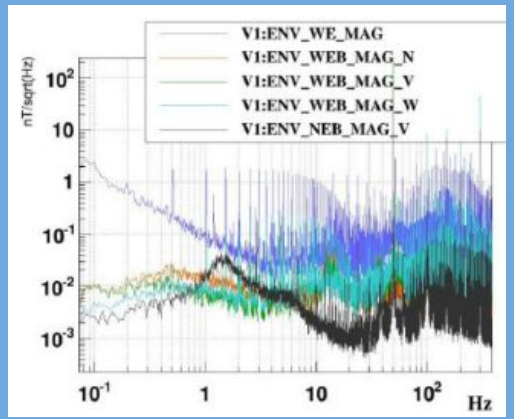
EM fields radiated by cables/wires (e.g. HVAC, UPS,..)





Devices

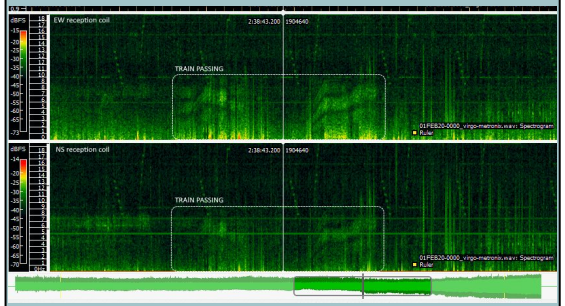
Magnetic fields from electric and electronic devices



ET-0163-A-23

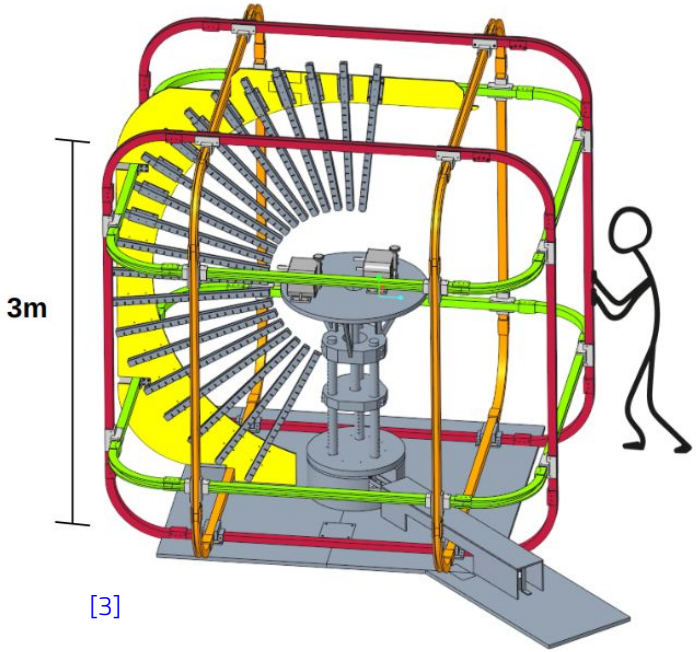
Anthropogenic

- Trains (sitewide magnetic glitches from 2-3 km far railways)
- Galvanic currents from methane gas pipes

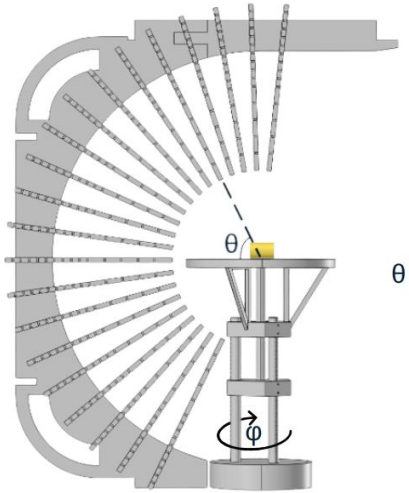


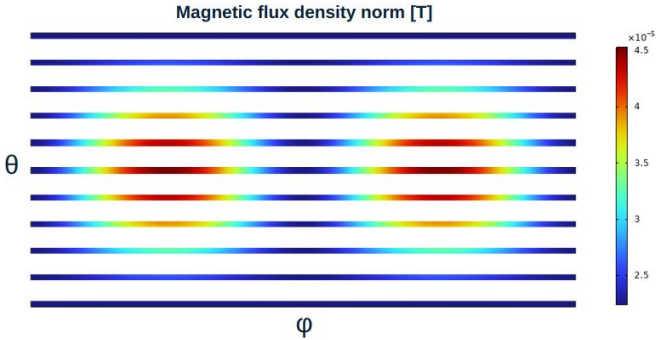
2.1 Investigation strategy: **MANET**

MAgnetic **N**oise facility for **ET**: characterization of the magnetic noise emissions of various devices, analyzing their response to external magnetic fields, and evaluating magnetic mitigation strategies

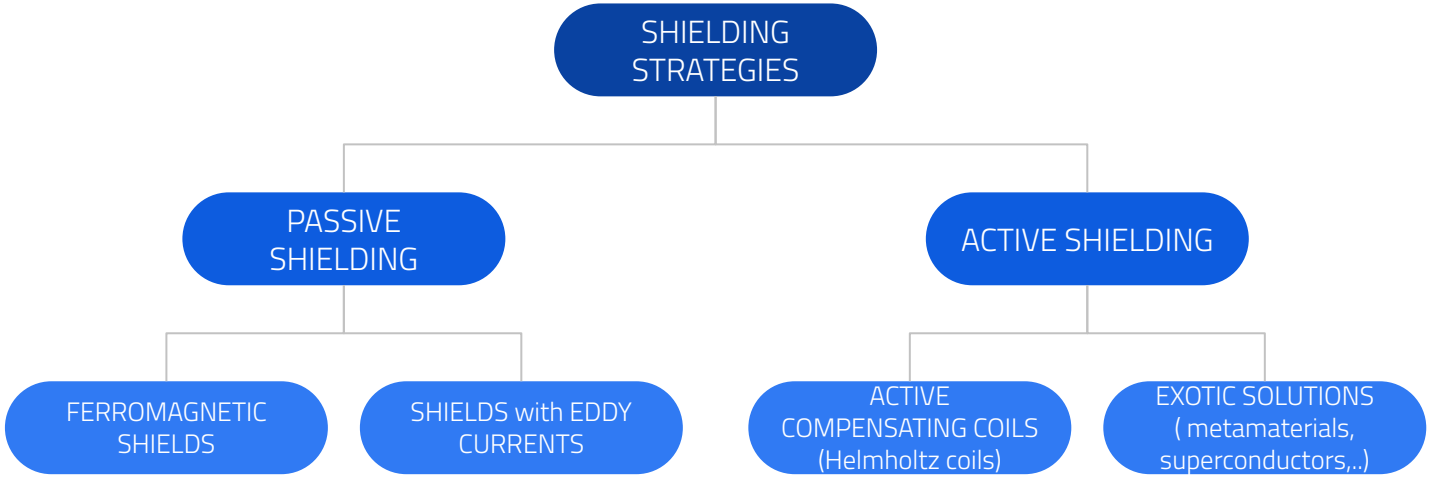


[3]





3. MITIGATION STRATEGIES

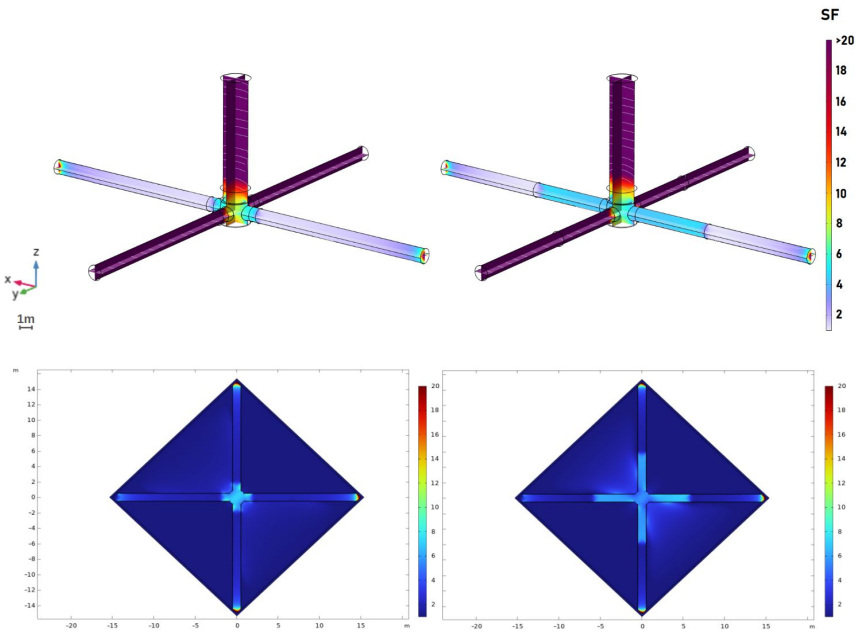


- Passive shields: simplicity, safer, operational stability, cheaper, less effective (or use multilayers shields)
- Active shields: more effective, only for ad hoc implementations

Shielding factor

$$S(x,y,z)=\frac{|\text{Magnetic Field without shield}|}{|\text{Magnetic Field with shield}|}$$

3.1 Passive Shielding - TM TOWERS- Ferromagnetic Shields



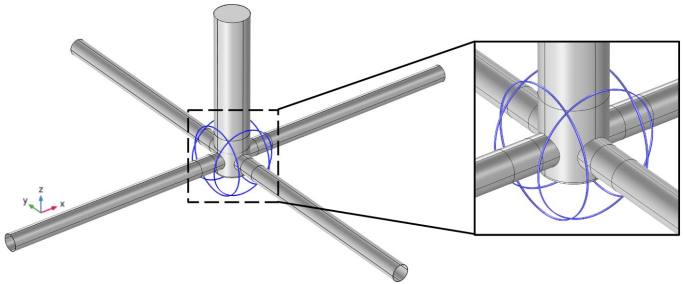
[3]

- Test Mass Tower: one of the most sensitive component (Virgo as reference)
- Strategy: Attract and move magnetic field lines away from the area
- High magnetic permeability layer covering the tower and the intersection area over lengths of 1-5 m

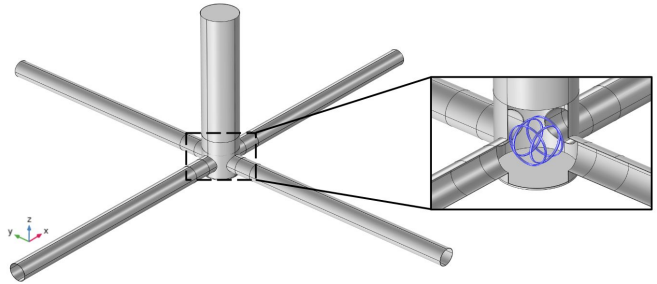
μr	Thickness (mm)	SF (B_ext along one arm)	SF (B_ext at 45°)
100,000	0.4	3.9	3.6
100,000	1.2	5.7	5.2
100,000	2.0	7.3	6.7
50,000	2.0	5.2	4.8
10,000	2.0	3.5	3.2
1,000	2.0	3.0	2.8

3.2 Passive Shielding - TM TOWERS - Shields with Eddy Currents

Outside the tower



Inside the tower



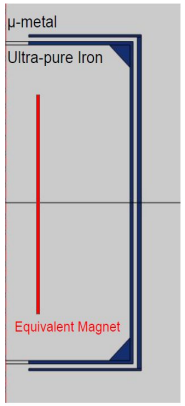
[3]

- Test Mass Tower: one of the most sensitive component (Virgo as reference)
- Strategy: as described by Faraday's law, generate an induced magnetic field to partially cancel the one coming from the source
- By enclosing the arms at their intersection with hollow cylinder (conductive material) in an Helmholtz configuration

Frequency (Hz)	Thickness (cm)	Height (cm)	SF (B_ext along one arm)	SF (B_ext at 45°)
1000	2.0	5.0	1.8	1.8

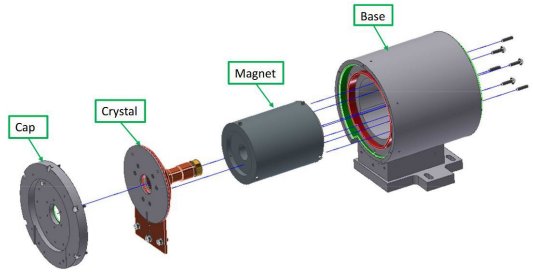
Frequency (Hz)	Thickness (cm)	Height (cm)	SF (B_ext along one arm)	SF (B_ext at 45°)
500	2.0	5.0	2.4	2.5

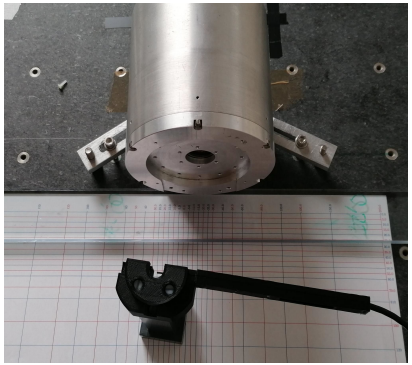
3.3 Passive Shielding - Faraday Isolator Shielding

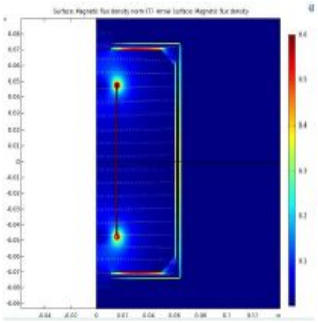


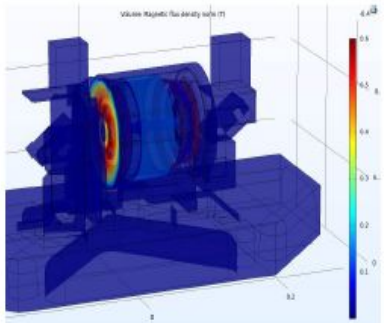
Axisymmetric screen model

ET-026A-23
ET-0016A-25





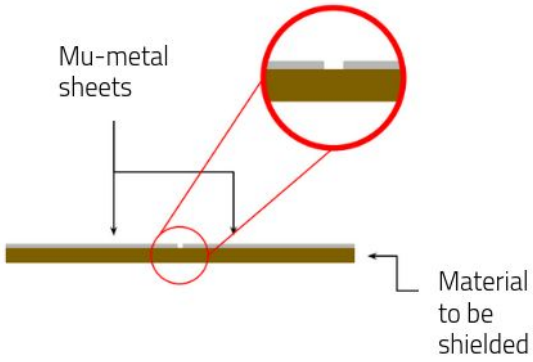




- 1 layer of mu-metal and 1 layer of soft iron
- Shielding factor in simulation ~ 100
- Shielding factor with prototype ~20

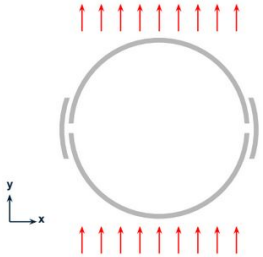
From simulations to reality

- In simulations: mu-metal separation areas are neglected



Separation distance (mm)	SF (B_ext=B_x)	SF (B_ext=B_y)
No hole	125	125
0.5	125	9
1	125	7

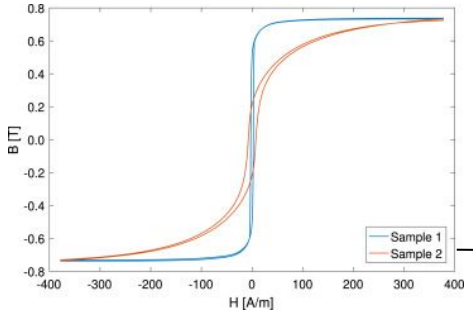
Mu-metal relative permeability: 100,000
Mu-metal thickness: 2mm



Patch length (cm)	SF (B_ext=B_y)
No patch	6
1	10
10	38

Hole size fixed: 2mm

- In simulations: mu-metal relative permeability is considered constant → Mu-metal has an hysteresis loop



Sample 1: annealed sample
Sample 2: not annealed sample

4. CONCLUSION

Future GW detectors → 3G GW detector→ Einstein Telescope

- ➢ Astrophysical challenges: Focus on massive BH and intermediate mass
- ➢ Cryogenic Underground Infrastructure (~ 200-300 m) → Optimized sensitivity at low frequencies: need to mitigate **Magnetic Noise**!

Magnetic noise strategies:

- ➢ Ambient noise at Earth noise level (~0.3 pT/√Hz)
- ➢ Reduce magnetic couplings (~10^2) compared to current GW detectors

MANET

SHIELDING STRATEGIES

THANK YOU

References

[1] Amann, F.; et al. Site-selection criteria for the Einstein Telescope. Rev. Sci. Instrum. 2020, 91, 094504
[2] Cirone, A.; et al. Magnetic coupling to the advanced Virgo payloads and its impact on the low frequency sensitivity. Rev. Sci. Instrum. 2018, 89, 114501. https://doi.org/10.1063/1.5045397
[3] Garaventa, B.; Armato, F.; Chincarini, A.; Fiori, I. Magnetic Noise Mitigation Strategies for the Einstein Telescope Infrastructure. *Galaxies* 2025, *13*, 9. https://doi.org/10.3390/galaxies13010009

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