Magnetic noise: ET mitigation POC, capitalizing on Virgo lessons

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with
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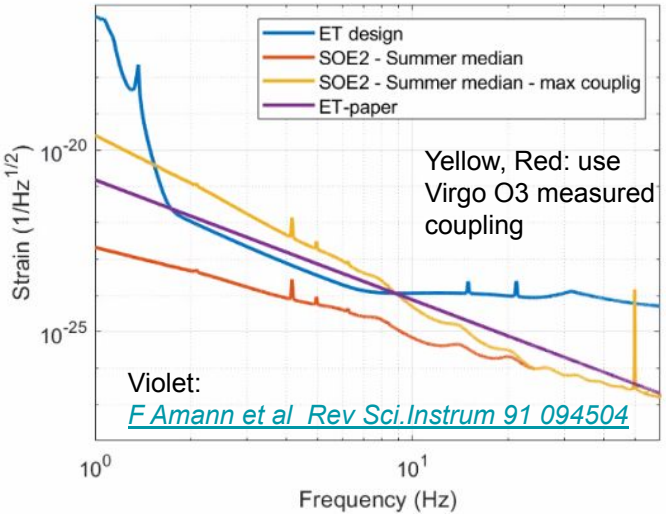
ET-0175A-23

XIII ET Symposium - Cagliari - 8-12 May 2023

The magnetic noise issue

- Magnetic noise has been studied and addressed by Virgo and LIGO, A. Cirone et al Class.Quant.Grav. 36 (2019) 22] A.Cirone et al Rev Sci Instrum 89, 114501 (2018), B P Abbott et al 2016 Class. Quantum Grav. **33** 134001, P Nguyen et al 2021 Class. Quantum Grav. **38** 145001
- Two ingredients:
  - Ambient noise level: Earth noise (= Schumann Res.) + sources close to ITF (Self-inflicted noise)
  - Strength of coupling to ITF (at sensitive locations)
- Expectation for ET is based on the extrapolation of measurements done in Virgo O3, M C Tringali et al Galaxies 2020 8(4) 82

  Warnings: measurements are only partially supported by models. No direct measurement below 10Hz.
- Noise reduction goals:
  - Ambient noise at Earth noise level
  - and reduce coupling by a factor 10^2-10^3 wrt current ITFs
  - Similar requirement from stochastic correlated noise study, K Janssens et al PhysRevD 104 (2021) 122006



ET magnetic noise projection, assuming ambient noise is just Earth noise. Rosario De Rosa's talk this conference

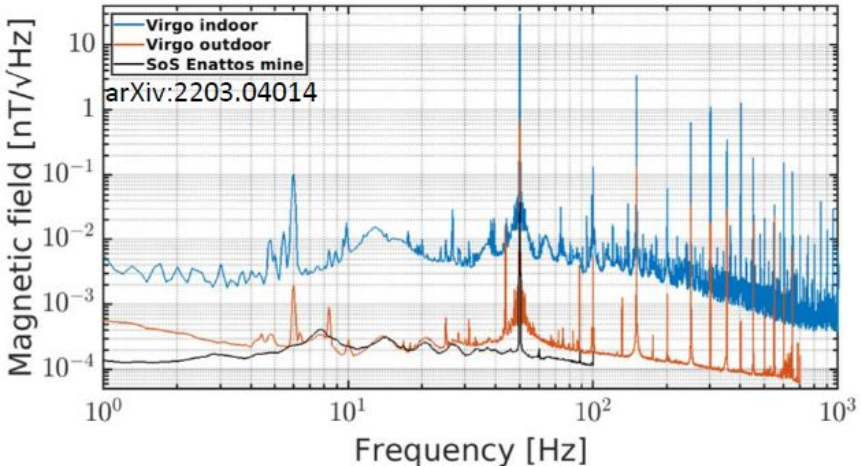
Self-inflicted magnetic noise

- Sources are part of the site and experimental infrastructure, e.g. e.m. fields radiated by power cables
- Virgo is overwhelmed by “self-inflicted” noise, which is ~10 to 50 times above local Earth noise
- KAGRA has achieved a quieter magnetic condition, close to the (local) Earth noise
- Reduce self inflicted noise is possible!

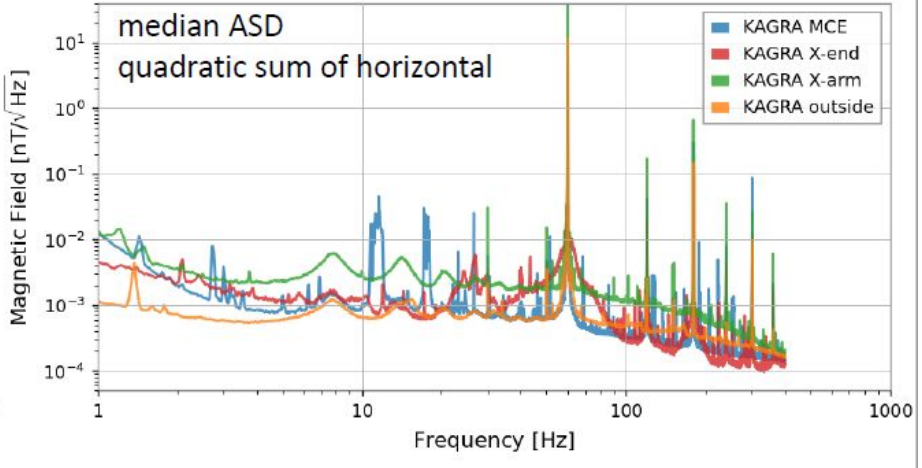
Schumann noise is observed to be larger in the arms tunnel.
In T.Washimi’s talk

Tatsuki Washimi - ET-0165A-22

Virgo



KAGRA



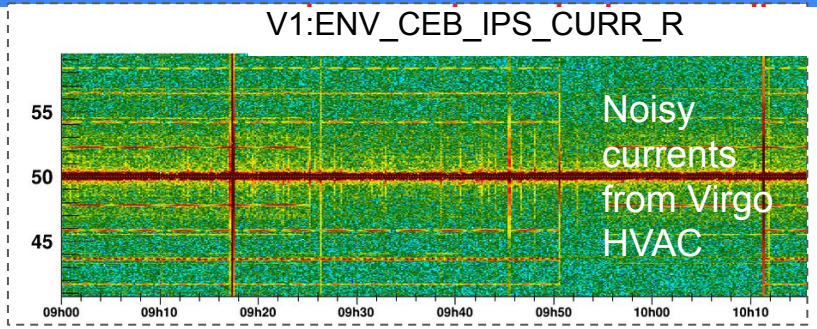
Power distribution system

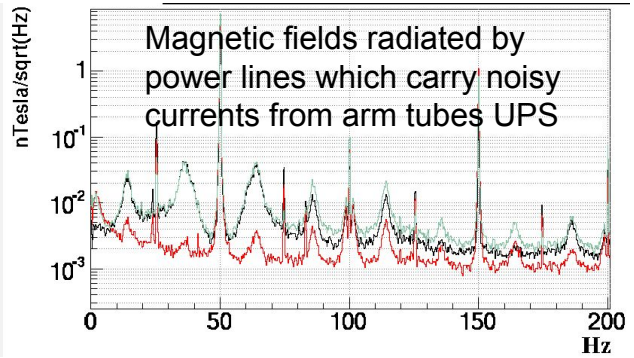
EM fields radiated by cables/wires is the major source of magnetic pollution at Virgo, e.g. HVAC, UPS

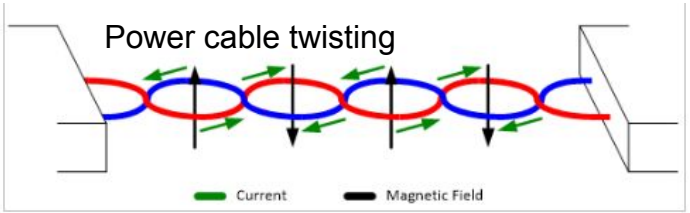
Guidelines:

Visit M.C.Tringali's poster

- Power cables
  - Route cables at distance from interferometer
  - Twist phase wires, shielding. Several mitigation techniques exist for HV power distribution lines, *JC Bravo-Rodríguez Energies **2019**, 12(7), 1332*, *A.Canova, L.Giaccone CIRED 2009 IEEEXplore*
- Power supply grids: separate power grid of site facilities (heavy machinery) and low noise electronics to avoid noise from "dirty" loads
- Beware of noisy UPS
- Grounding: separate ground of VAC chambers / low-noise electronics from ground of heavy machinery, stray currents
- Remote DC generation and distribution, *F Nocera F.Paoletti VIR-0737B-09*, *VIR-0545B-10*







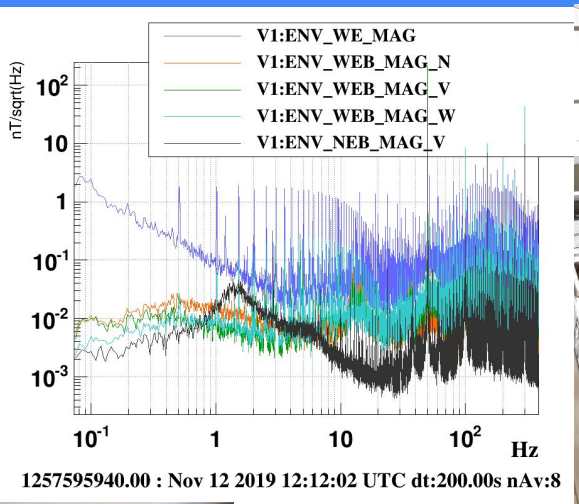
Devices

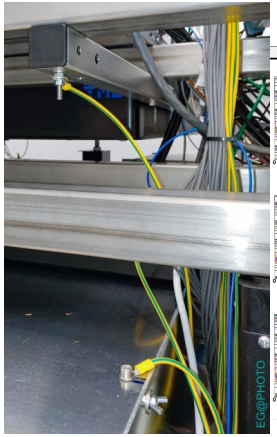
Magnetic fields from Electric and Electronic devices

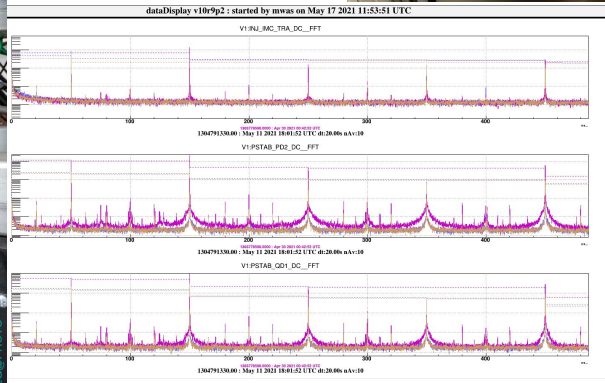
- radiated by devices
- radiated by powering cables << most relevant
- radiated by digital communication wires << most relevant

Guidelines:

- Select devices with low magnetic emission
- Deprecated devices: e.g. PWM based, switching power supplies, open core transformers, *I Fiori et al Handbook of GW astronomy*
- Distancing sources and cables/wires from coupling locations
- If distancing is not possible, study and test ad hoc shielding solutions
- Grounding of electronics, M Was ET-0423A-21
- Digital devices: optical fiber communication
- Standardization of electronics (racks, boards, connectors ….) *F Nocera F Paoletti VIR-0737B-09*, *VIR-0545B-10*







Anthropogenic

Magnetic noise from sources within a few km from the site:

- Trains (sitewide magnetic glitches from 2-3km far railways) F.Paoletti's talk
- Galvanic currents from methane pipes

Produce stray current in the vacuum pipes (by induction or conduction)

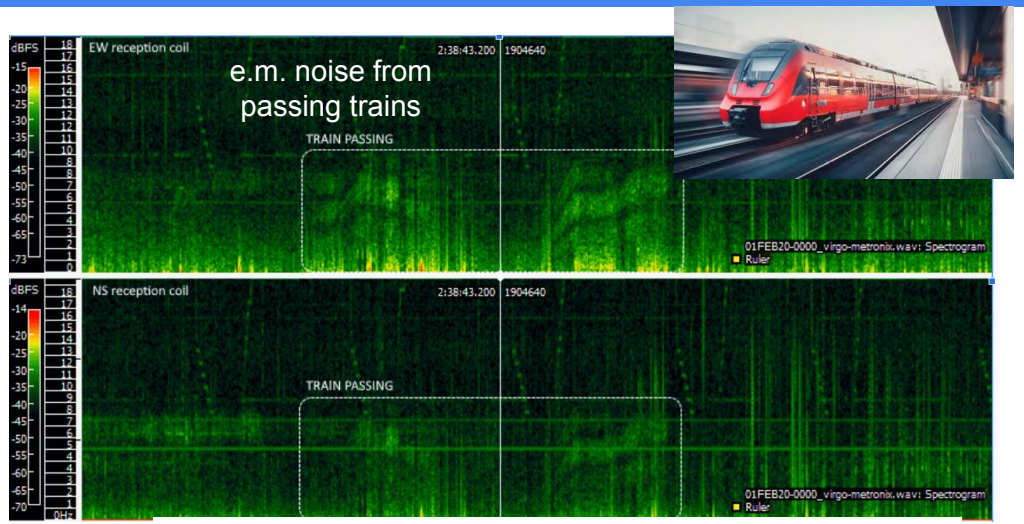
Measured amplified magnetic field close to vacuum pipes

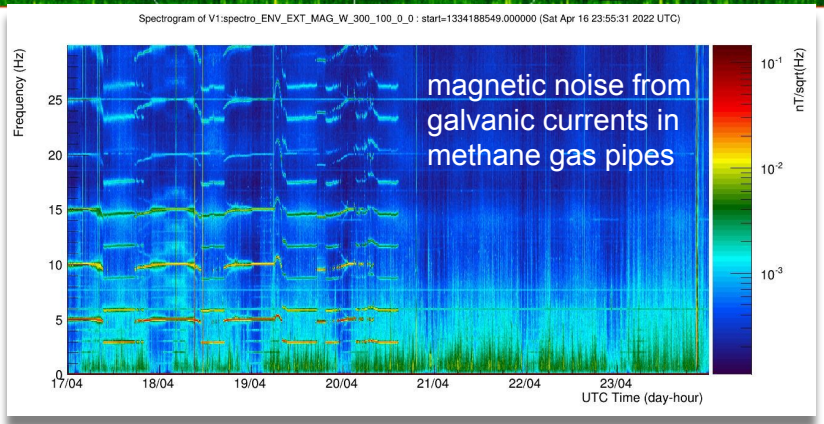
Similar amplification effect is measured at Virgo pipes for Shumann resonances (T.Washimi's talk)

Can be an issue close to TM/Suspended optics chambers

Mitigation:

Electrically insulate chambers from pipes





Couplings to ITF

Coupling of ambient fields is not uniform throughout the ITF

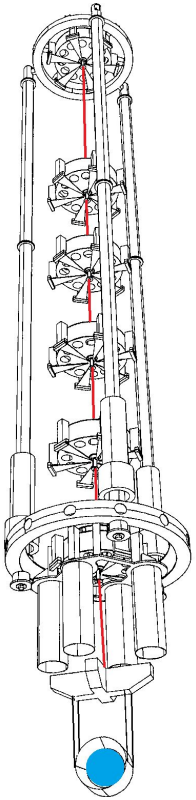
Most critical coupling sites are the suspended elements carrying permanent magnets: test masses, optical benches and their suspension systems

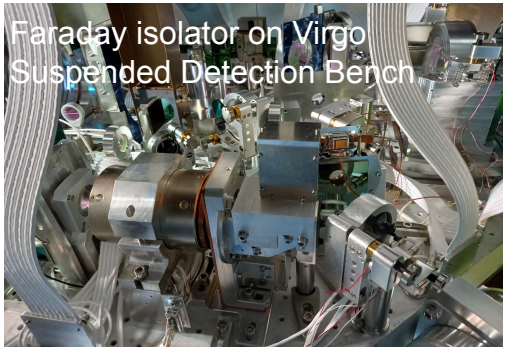
Critical components:

- Coil magnet actuators, Faraday isolators, pico-motors
- Cables (e.g. coil drivers), electronics, connectors (induced currents)
- Conductive parts close to actuation magnets, because of eddy currents, e.g. Virgo payload cage, *A.Cirone et al Rev Sci Instrum 89, 114501 (2018)*

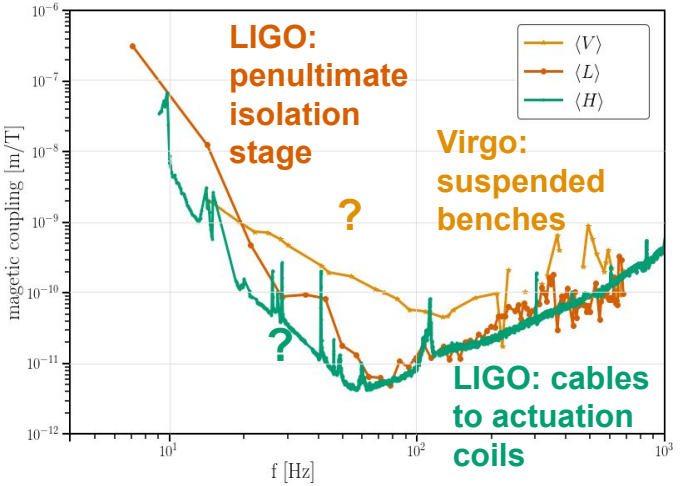
Some rough indications from Advanced Virgo and LIGO

Currently under study in AdV+





Magnetic coupling functions measured in O3



Mitigation strategy

Challenging mitigation goals:

- ★ Preserve environmental noise at Schumann noise level (~0.3 pT/sqrtHz,10-50 times less than Virgo)
- ★ Reduce couplings by factor 100-1000 with respect to present ITFs.
- ★ Focus on coupling sites

Actions (pursue both):

1. Global shields (also multiple shields) to protect critical coupling sites (TMs, optical benches …)
2. Ad-hoc strategies for sources close to critical coupling sites (e.g. cables, vacuum devices, cryogenic devices …)

Main lessons learned from Virgo:

- ★ Reduce noise by design - build a low-magnetic-noise infrastructure. Attention to site facilities (HVAC, UPS) and experimental equipments
- ★ Use robust and maintenance-free technologies

Overview of mitigation strategies

$$\text{Shielding factor} \quad S(x,y,z) = \frac{|\text{ Magnetic field in absence of shield }|}{|\text{ Magnetic field with shield }|}$$

	passive shielding			active shielding
	magnetostatic	eddy currents	source canceling	exotic solutions	active cancelling
Freq.	better @ low f	better @ high f	independent	solution specific	solution specific
How	high permeability ferromagnetic materials	highly conductive materials	set of permanent magnets in suitable configuration	metamaterials superconductors composites	feedback circuit consisting of sensors, dsp, amplifiers and conductors in various configurations

Prefer passive solutions

PRO: simplicity, operational stability, safer (no generated extra fields), no need of maintenance … and cheaper.

CONS: less effective (smaller shielding factor) >> use multiple shields (“shield the shield”).

Exotic and active solutions: only for ad hoc implementations and if no need of extra structure (e.g superconducting screens)

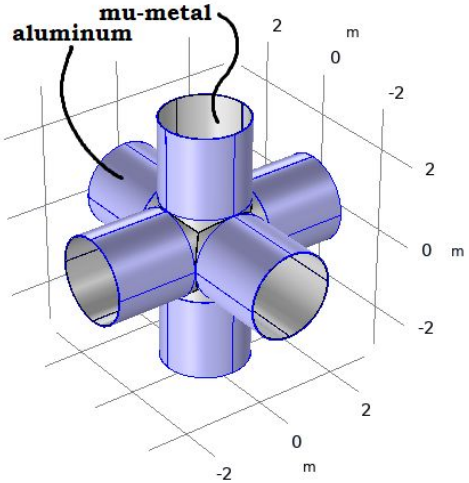
Simulation works

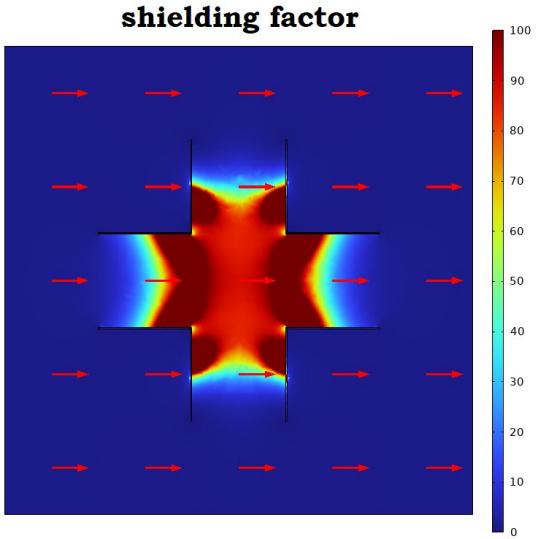
Objective: shield the sensitive volume of suspended elements from external fields (payloads, detection benches, …)

Double shielding:

1. Magnetostatic shielding: mu-metal layer added to steel vacuum chamber
2. Eddy current shielding: aluminum hollow cylinders

Federico Armato's talk & poster

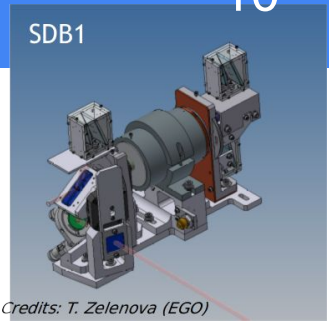




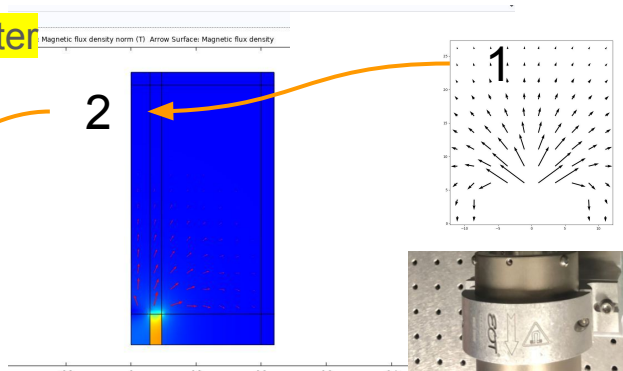
Magnetostatic shield for Faraday isolators

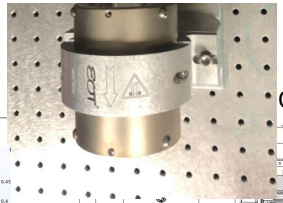
Visit Jean-Loup Raymond's poster

1. Source study - simplified model based on measures
2. simulated equivalent source - FEA implementation & optimization
3. Simple Fe screen design- FEA model
4. Model validation - experiment
5. Realistic screen - FEA model
6. Screen prototype - design
7. Final prototype - realized
8. Annealing thermal cycle
9. Test & acceptance

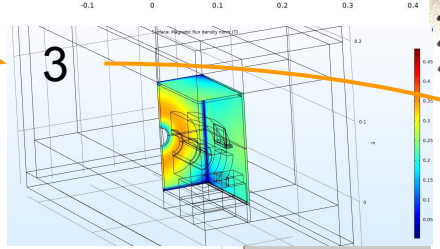


Credits: T. Zelenova (EGO)

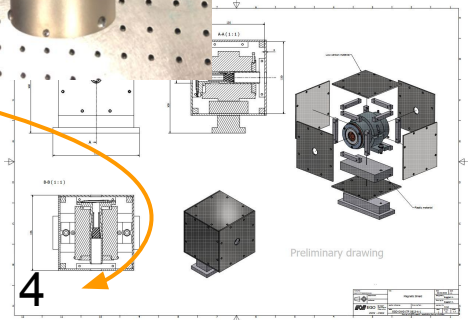


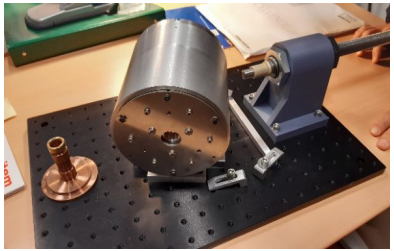


Credits: A.Buggiani (EGO)



Achieved shielding factor 165 (simulation)





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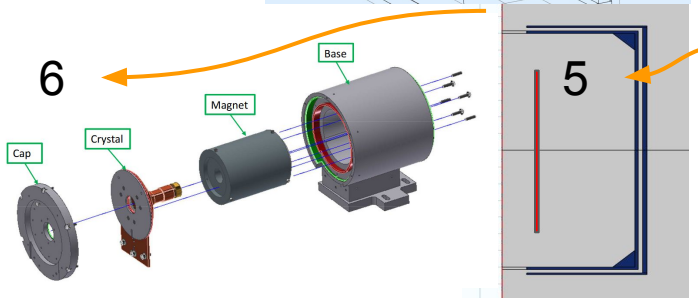
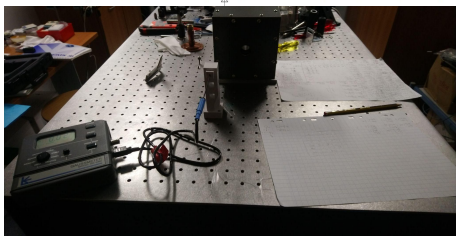




Monitoring

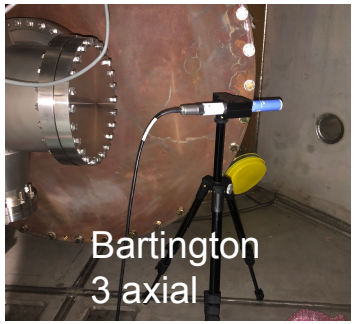
Active monitoring of couplings

- Large and small coils like at LIGO and Virgo
- Better and more distributed system to be studied

Passive monitoring

Distributed array of sensors

- Outside and inside vacuum
- At coupling sites, at potential sources (electronics racks, devices …)
- Instrumented robots (mapping)



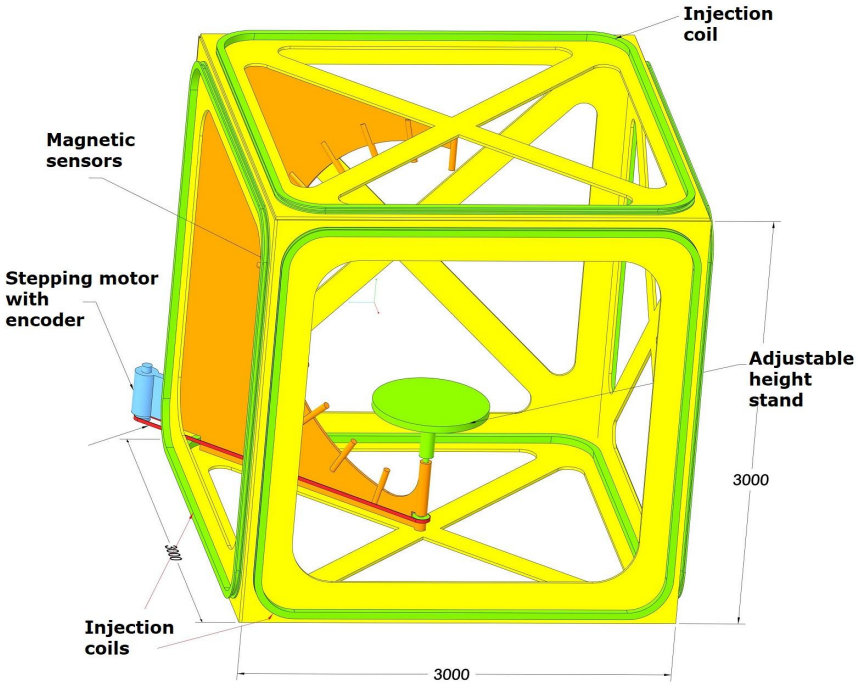
Magnetic facilities

Magnetic facilities are need for ET:

- Laboratory to characterize noise emission of devices (selection), test mitigation solutions
- Workshop to treat and machine magnetic components (e.g. mu-metal cutting, annealing treatment, degauss, etc.)

MANET - MAgnetic Noise test facility for ET

- Small scale laboratory to be realized at EGO
- Part of ETIC project
- Design is in progress
- Procurement of parts in progress



Conclusions

Challenging goals:

- Preserve Earth noise condition AND reduce coupling by 100-1000 times wrt current detectors.

Mitigation strategies:

- Focus on sensitive locations (suspended optics). Global shields of the critical in-vacuum volumes (e.g. magnetostatic and eddy current shields) AND address local (closeby) sources with ad-hoc solutions (e.g. power cables and wires)
- Whenever possible use passive shielding (magnetostatic and eddy current shielding). Active techniques are also considered for ad hoc solutions.

Magnetic mitigation is a transversal task which is linked to many ET SYSs and Sub-SYSs:

- INFRA_DEV (electricity); VACUUM (chambers shielding and material compatibility for in-vac mitigation solutions); PAY and SUSP (actuator design, marionetta-cage design). ANM-Environmental_sensors for extensive monitoring of the environmental noise also in-vacuum, and the magnetic injection system for measure and monitor the magnetic coupling. OTHERS (low noise electronics, wiring & communication, standardization of devices).

A lot of simulation work, prototyping and testing

- Need of magnetic noise measuring facility. The MANET small scale laboratory will be realized at EGO.

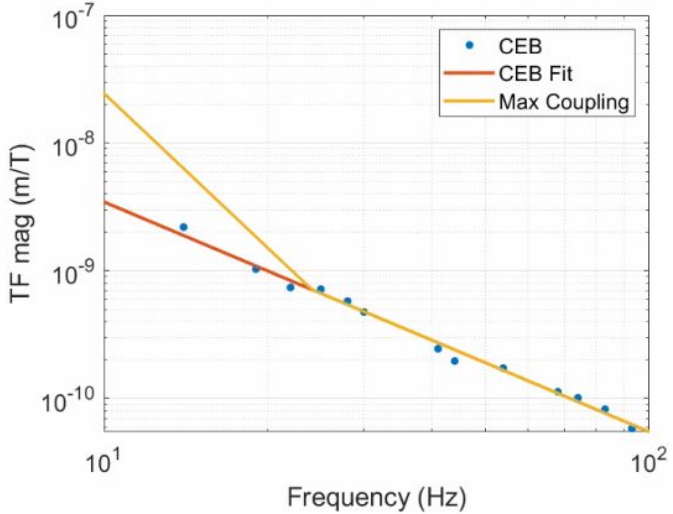
Backup slides

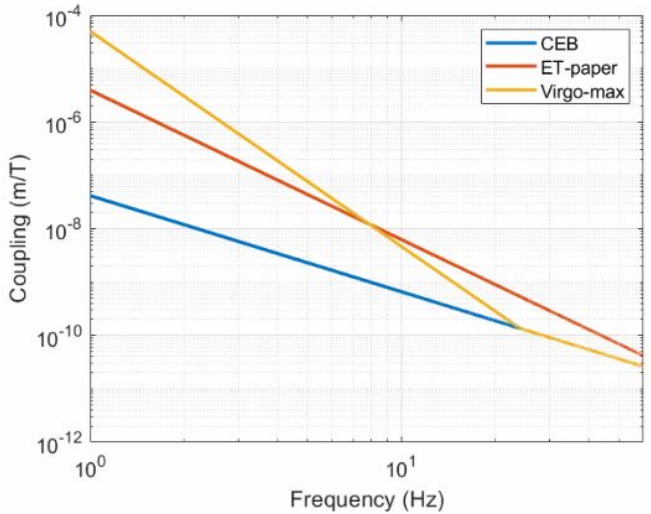
Rosario De Rosa - talk SPB session Monday

Noise Coupling

Results from Virgo and Sos Enattos

- The noise coupling as measured at Virgo, including only the contribution measured at CEB, or the full contribution (CEB+NEB+WEB) is compared with the coupling used in the ET paper. The noise model is compared with the measurements performed in Sos Enattos





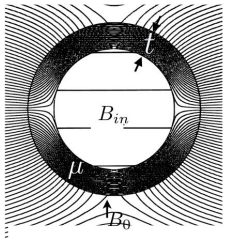
Magnetostatic shielding

Ferromagnetic materials warp and capture magnetic field lines

Several effects:

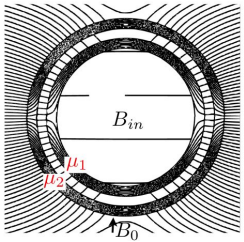
- Saturation: use multi-layers
- Nonlinearities in the B-H curve
- Careful handling and material working
  - μ degrades with cutting and bending
  - Need annealing treatment to recover
- Shield position, geometry and external field, uniformity
- Beware of discontinuities and air gaps

Single layer

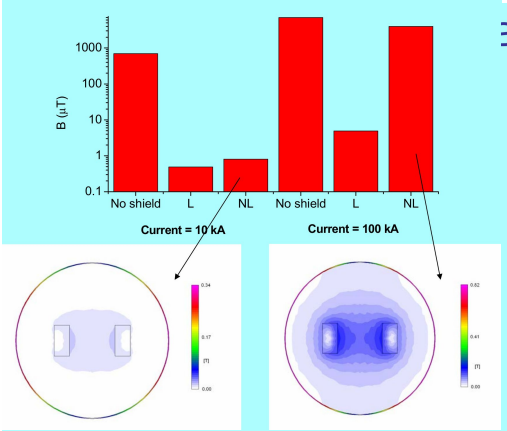


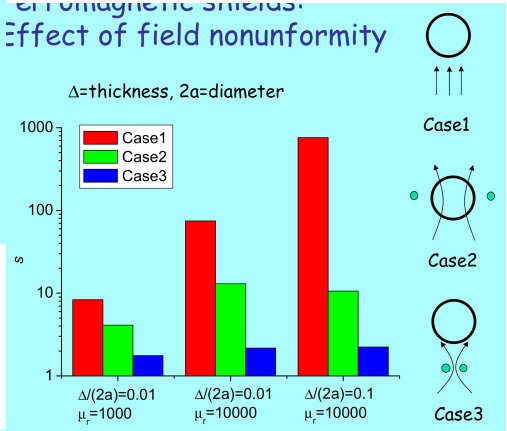
$$S = \frac{B_0}{B_{in}} \propto \mu t$$

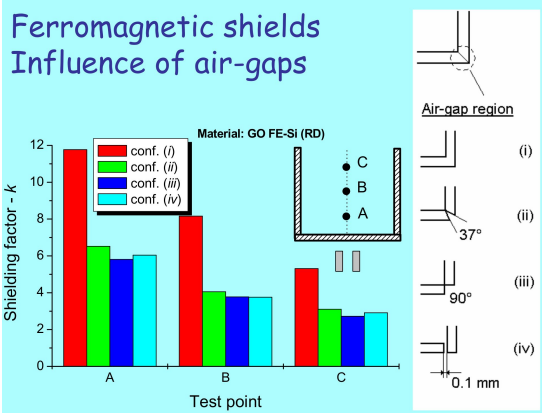
Multi-layer

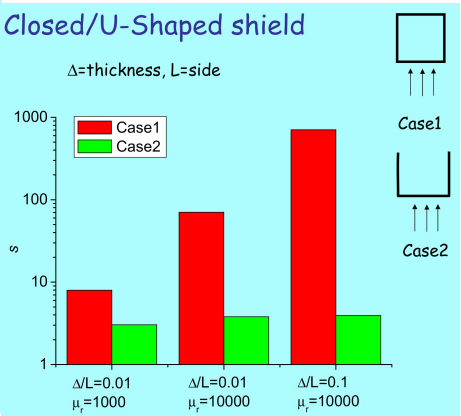


$$S = S_1 \times S_2 \propto \mu_1 t_1 \times \mu_2 t_2$$







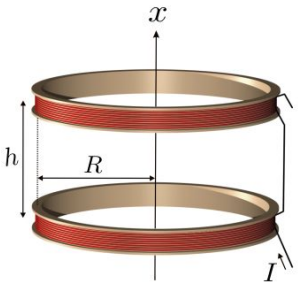


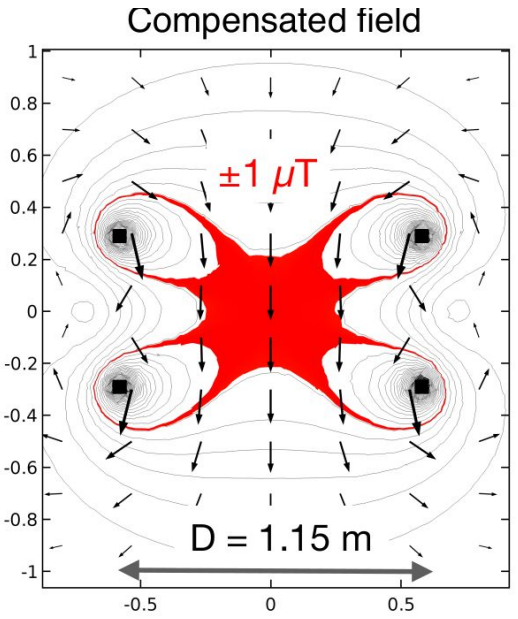
Eddy current shielding

Induced currents create counter-acting compensating magnetic fields

- Can be both passive and active
  - active HeCo are the standard in industry
- Mono-directional component
  - superimpose fields of different Helmholtz pairs
- Most homogenous region → ~R/2
  - Large region → large coils (2R)
- In passive configuration can be coupled to a resonant circuit to screen particularly nasty frequencies (i.e. 50Hz)
  - Nested solutions, combined approaches can be devised, high design freedom
- Spherical shells → best shielding and homogeneity

Helmholtz coil





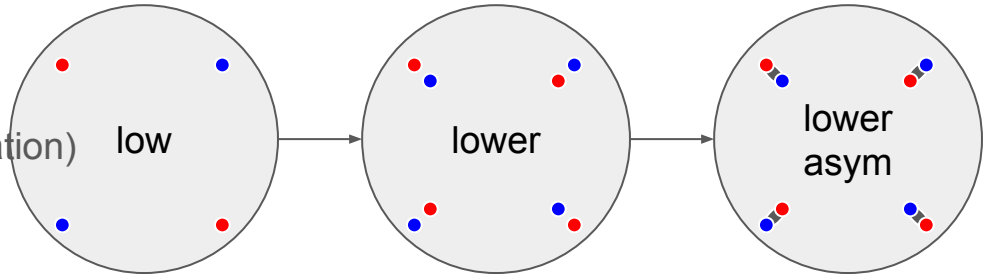
Takeaway for Helmholtz coil:
good homogeneity for its simplicity, versatile design, insufficient screening if used alone (passively)

Actuation magnets design

Objective: reduce effective dipole moment of magnets

Techniques:

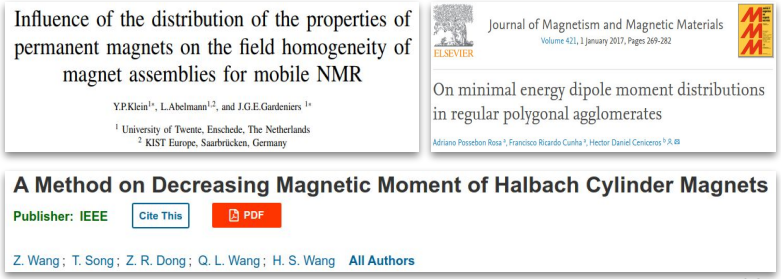
- counter aligned magnets (Halbach configuration)
- mu-metal shields around permanent magnets of the marionette, the test masses and first suspension filter



Several papers on perm. magnet shape & topology optimization.

- Mainly refer to specific applications but conceptually one could imagine a suitable set of magnets to shape a local field with given characteristics (within limits)
  - minimize dipole moment
- Main target: test mass / big optics alignment

Shaped field permanent magnets, arrangement and optimization examples:


Influence of the distribution of the properties of permanent magnets on the field homogeneity of magnet assemblies for mobile NMR

Y.P.Klein[1*], L.Abelmann[1,2], and J.G.E.Gardeniers [1*]

[1] University of Twente, Enschede, The Netherlands
[2] KIST Europe, Saarbrücken, Germany

Journal of Magnetism and Magnetic Materials
Volume 421, 1 January 2017, Pages 269-282

On minimal energy dipole moment distributions in regular polygonal agglomerates

A Method on Decreasing Magnetic Moment of Halbach Cylinder Magnets

Publisher: IEEE Cite This PDF

Z. Wang ; T. Song ; Z. R. Dong ; Q. L. Wang ; H. S. Wang All Authors