Low-frequency magnetic noise in terrestrial GW detectors: the case study of AdV+ Faraday isolators

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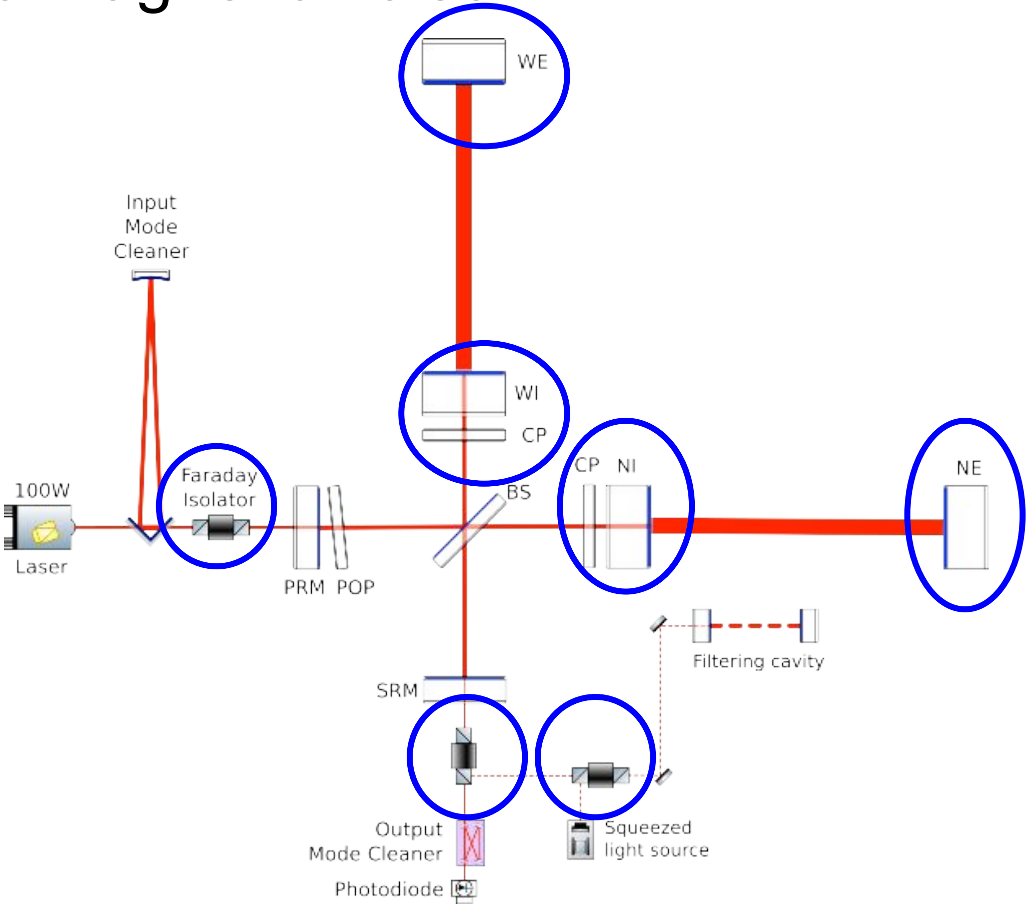
Virgo places sensitive to magnetic noise

- Present interferometers, like Virgo, are sensitive to environmental magnetic fields
- Several sources are part of the interferometer infrastructure
- Coupling occurs at magnetized components (e.g. magnetic actuators of mirrors and suspension chains, Faraday isolators, …) or conductive materials (because of Eddy currents)



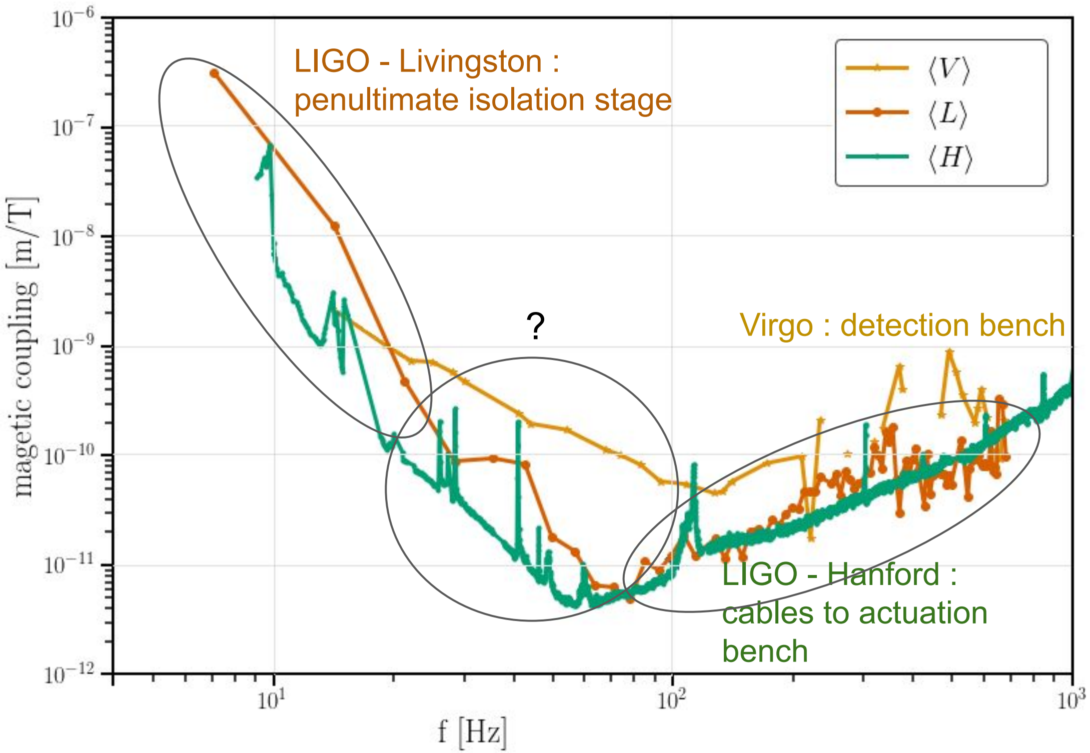
Current & future magnetic noise projection on sensitivity

- Measurements at LIGO and Virgo during O3 show that coupling with external magnetic fields is large especially at low frequencies

- Mitigation requires to :

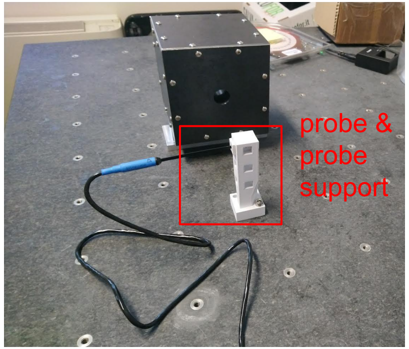
  - reduce environmental fields close to sensitive parts by mitigating sources

  - identify and properly shield coupling locations

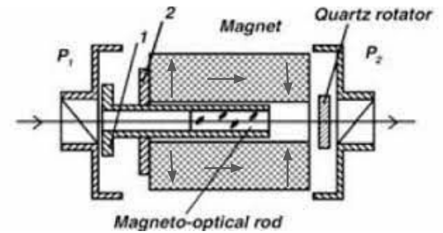


Faraday isolators

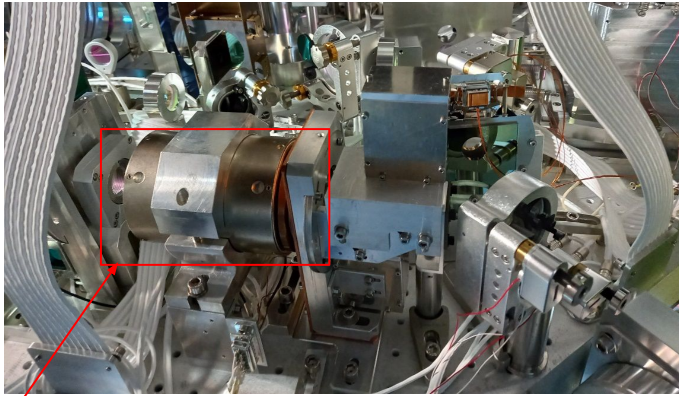
- Focus on coupling from Faraday isolators
- Faraday isolators are optical diodes made of a magneto-optic crystal immersed in a intense static magnetic field (~1-1.5T).
- At Virgo one F.I. is placed on input and output port suspended benches, named SIB1 (Suspended Injection Bench) and SDB1 (Suspended Detection Bench) respectively
- Industrial component :
  - Exact composition & magnetization unknown
  - Different rings of magnets magnetized in radial or axial direction (Halbach configuration)



Measurement setup



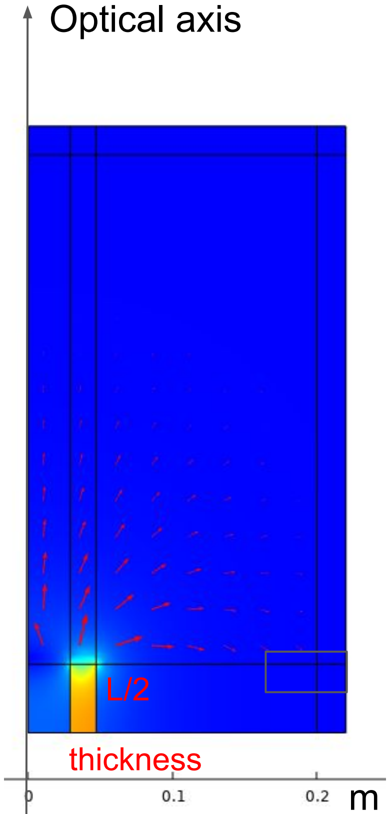
L = 9.5 cm
R = 3.8 cm



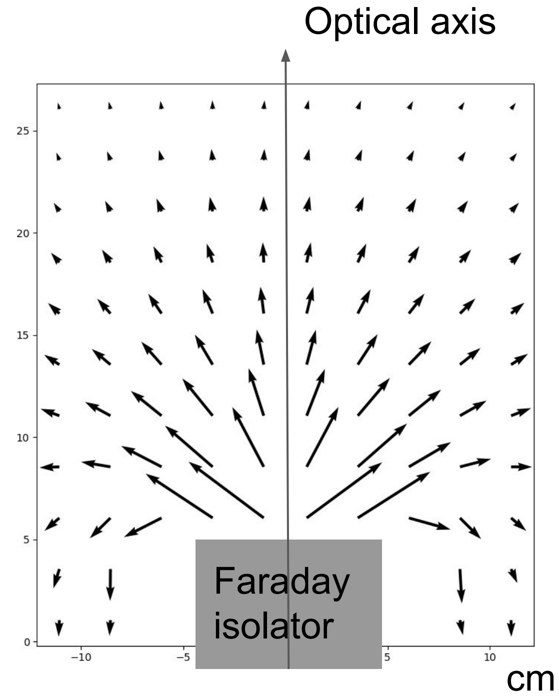
SDB1 Faraday Isolator (1T)

Magnet modelling

- Measured a 2D map of the static magnetic Field of the spare F.I.
- Design a model of the F.I. magnet that best fits the measured data : adopt a magnetized cylinder model
- Optimal dimensions found using chi squared method with the grid of measurements
- Parameters for the cylinder : length, thickness, internal radius
- Equivalent magnetic moment : μ = 74 N*m/T

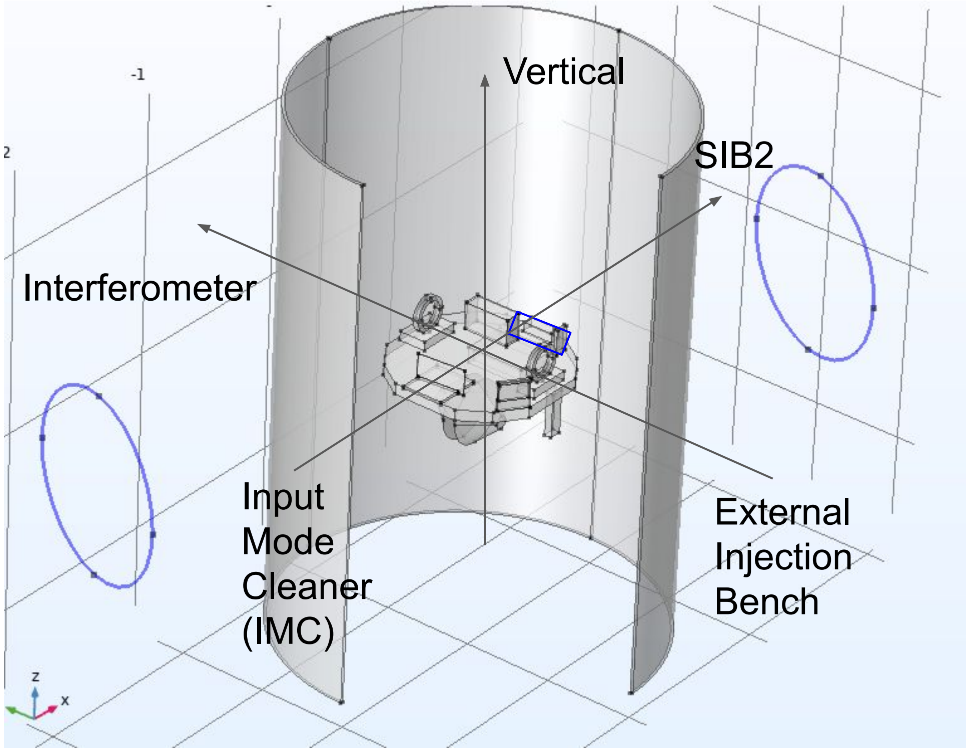


Axisymmetric model of magnetized cylinder



Map of measured magnetic field (logarithmic arrow size)

SIB1 Bench simulation



- Simulated vacuum chamber & largest metallic (conductive) structures on the bench
- Simulated two 1m diameter coils in anti-phase configuration at opposite sides of the vacuum chamber, injecting unitary current for various frequencies (range 1-1000Hz)
- Output of the simulation : Magnetic field at the position of the Faraday isolator (1.5T, in blue)

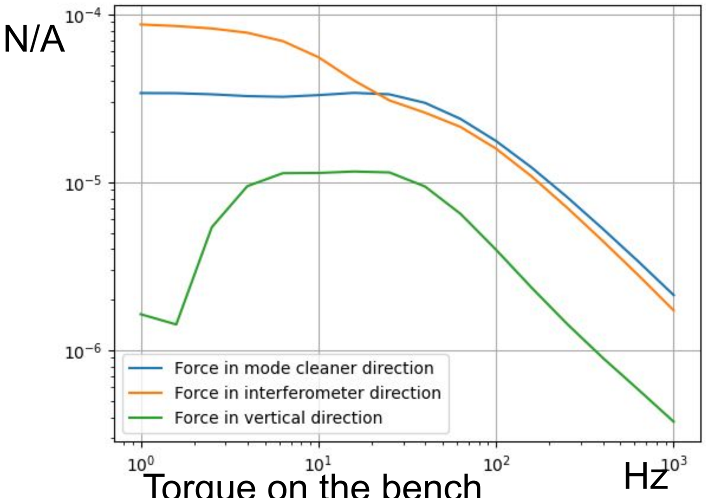
Force & Torque calculations

- Far field hypothesis : FI is supposed uniformly magnetized on its volume such that it is possible to use the equivalent dipole

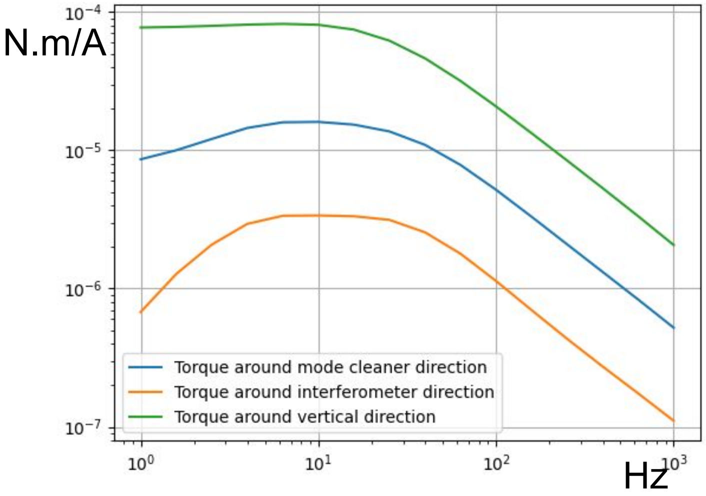
$$\vec{\tau} = \vec{\mu} \times \vec{B} \qquad \vec{F} = (\vec{\mu} \cdot \vec{\nabla})\vec{B}$$

- Force (N) and Torque (N*m) for unitary current and number of turns of the coils, along the axes of the IMC reference system

Force on the bench



Torque on the bench



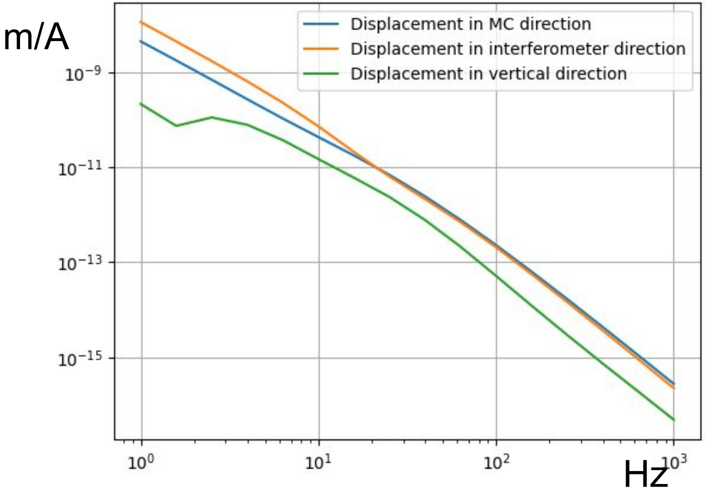
Displacement transfer function

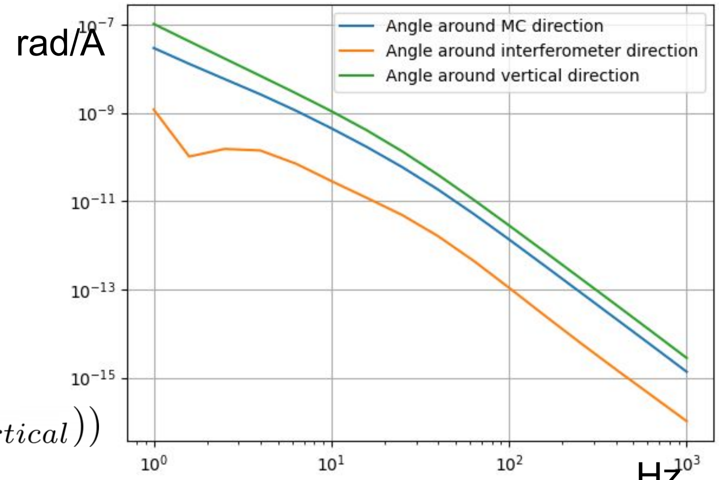
- Free mass mechanical model

$$\ddot{X} = \frac{F}{m} \qquad \ddot{\Theta} = I^{-1}T$$

- Displacement (m) and Angle (rad) transfer function for unitary current and turns
- Final displacement prediction is obtained by correcting displacement by adding a component due to rotation

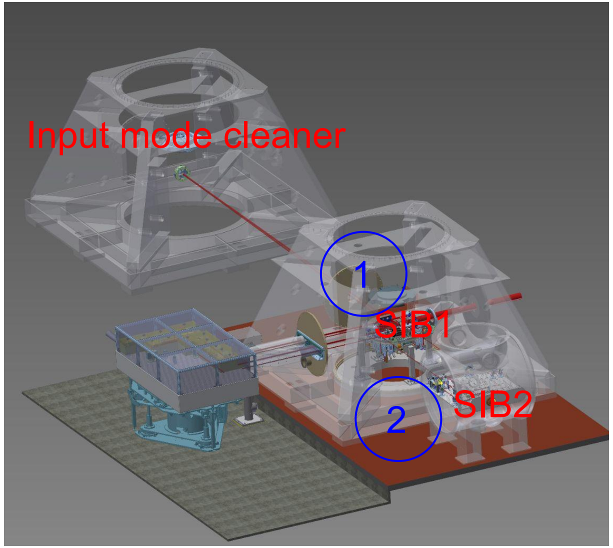
$$D_{corr} = D + d_{dihedron} * (\cos(\theta_{IF_0}) - \cos(\theta_{IF}) * \cos(\theta_{vertical}))$$

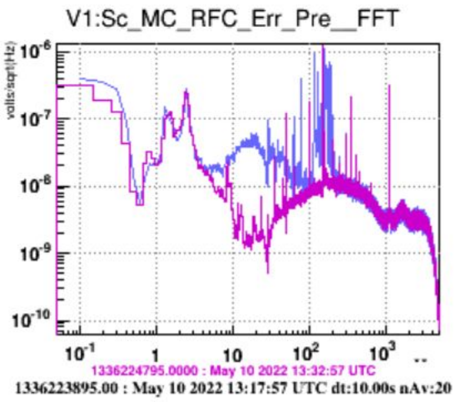


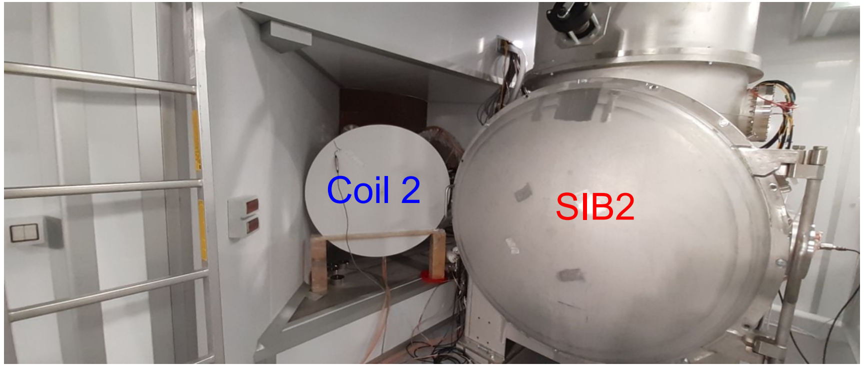


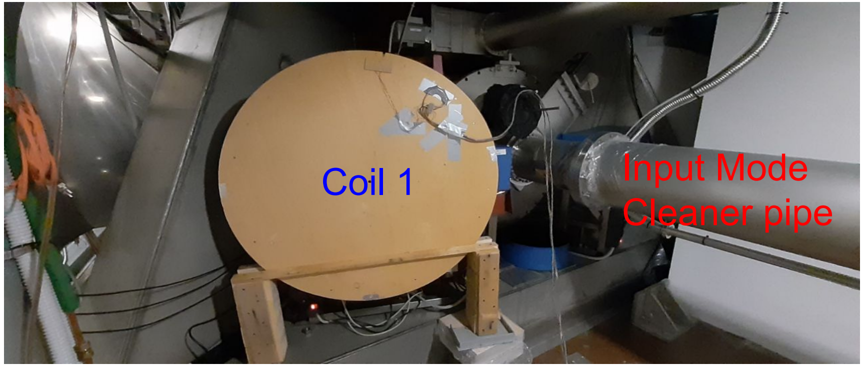
Experimental validation

- The displacement of SIB1 along the Mode Cleaner axis can be measured using the reference cavity (RFC) sensor with good accuracy (10^{-14} m/√Hz)
- Coils put in anti-phase setup at a 18° angle with Input mode cleaner axis
- Injecting a current white noise (0.025 A/√Hz in spectral density) and measuring bench displacement using the reference cavity signal

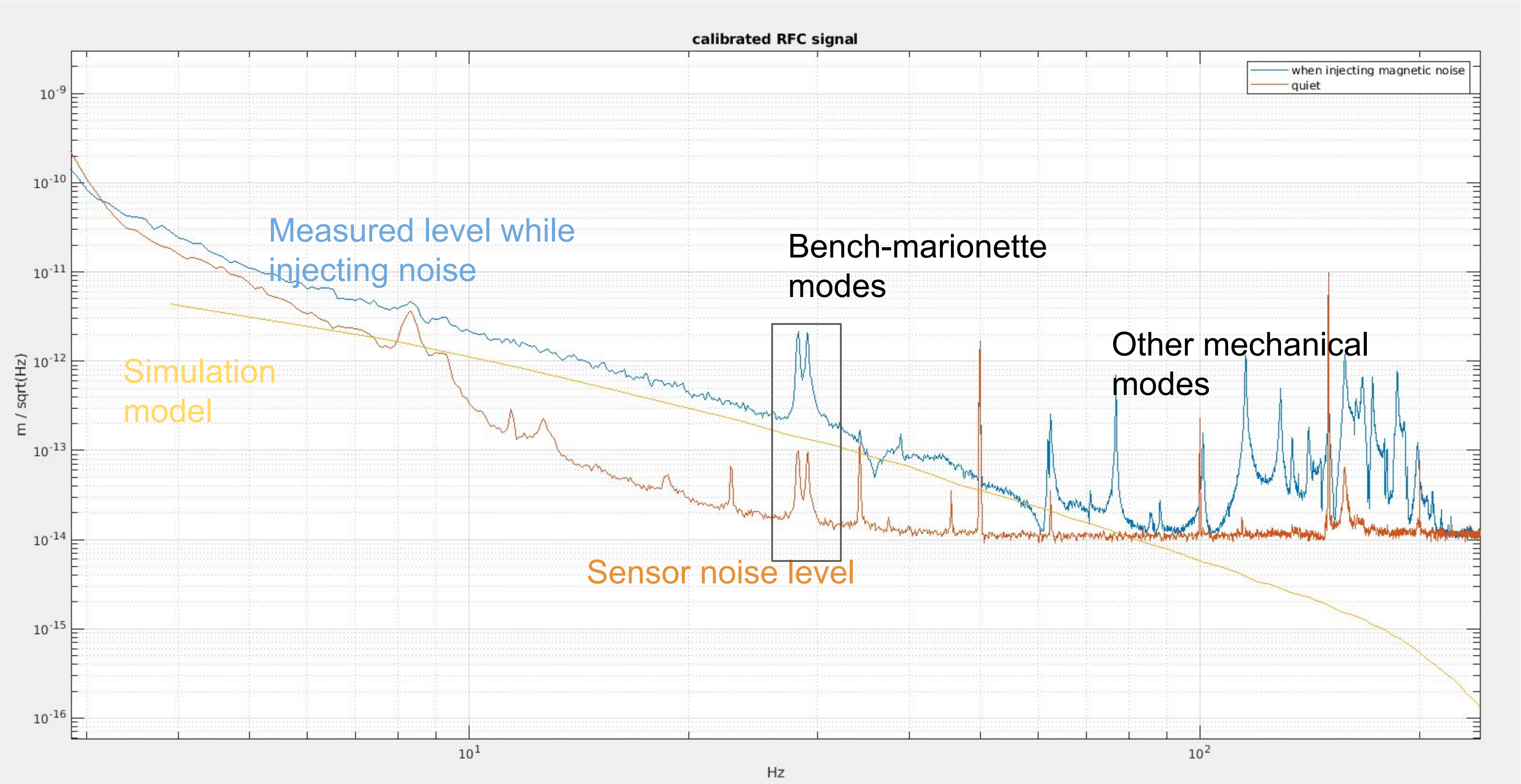








Experimental results



Possible error sources

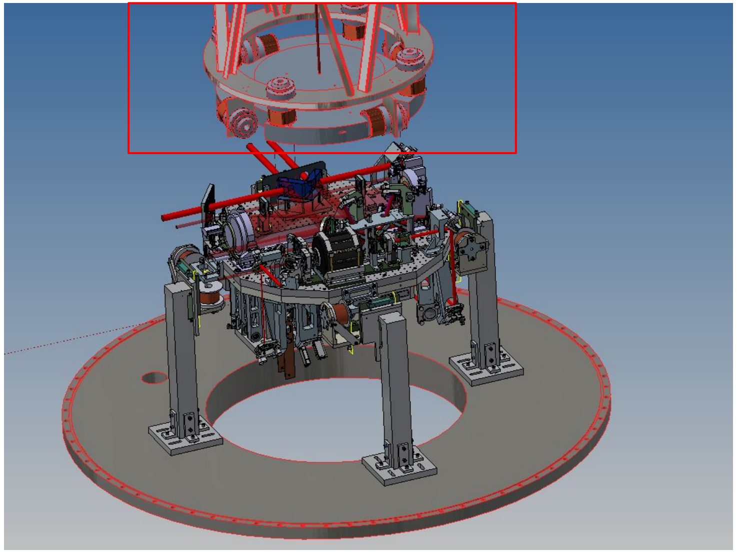
Simulation

- Mechanic model : pendulum resonance at lower (~0.6Hz) frequencies, dihedron resonances at higher frequencies
- Uncertainties on material conductivities and magnetic properties
- Meshing (~11% error at the center of the coils)
- F.I. magnetic model

Measurement

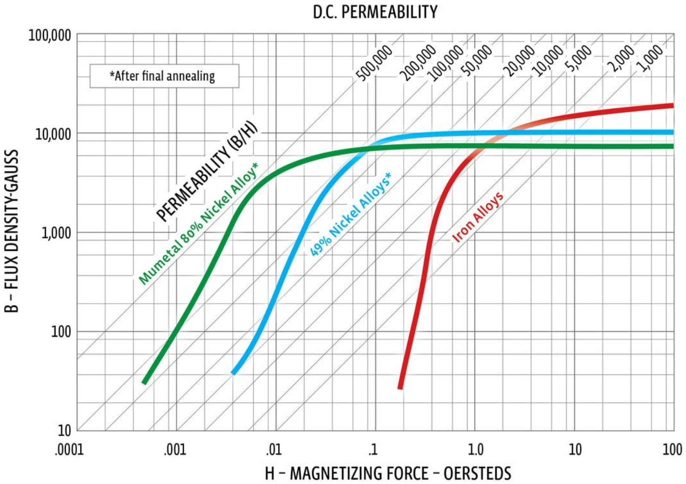
- Statistical uncertainties : average on 30 samples
- Calibration of experimental setup
- Influence of magnets actuators of the upper stage (marionette)

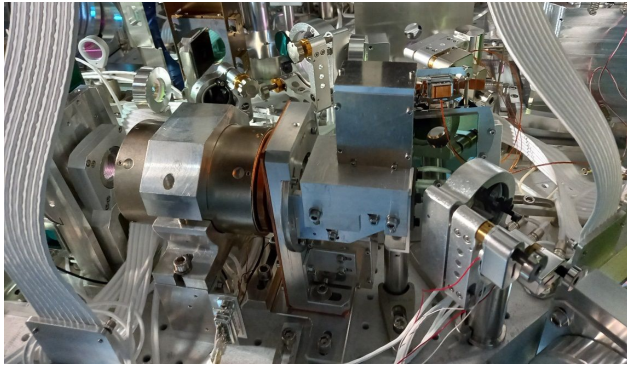
Magnets of the marionette

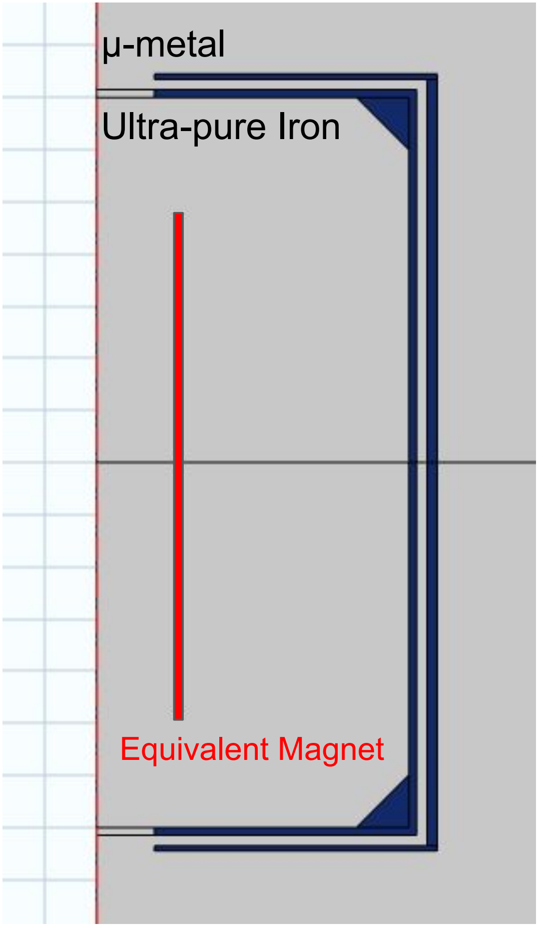


Shielding

- Sensitive optical components on the updated version of the SDB1 bench set target attenuation factor : ~100 (defined as the ratio of magnetic field norm at a specified position on the bench with and without screen)
- Double layer to avoid saturation : inner layer of ultra-pure iron, outer layer of mu-metal
- Space constraints - optimization of the layers
- Iterative process : measurements and simulation (1st experimental validation was a success)





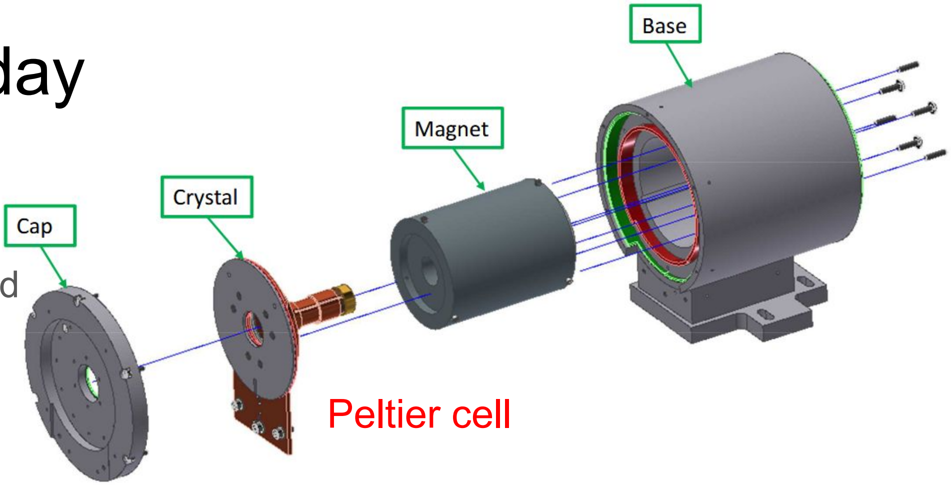


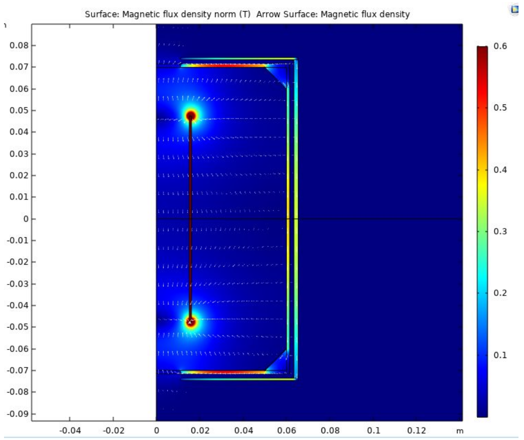
Axisymmetric screen model

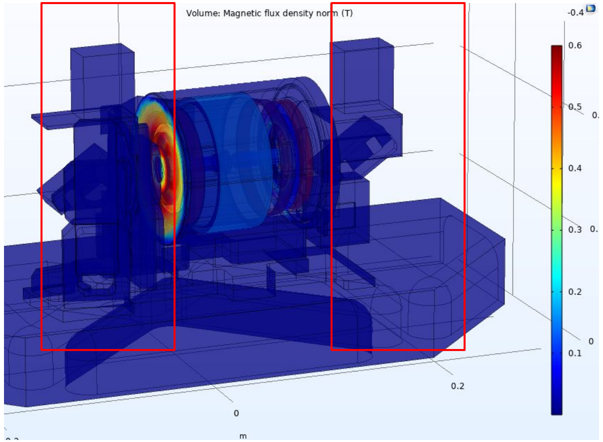
Final screen for SDB1 Faraday

Realistic screen prototype :

- Geometrical constraints in front of and behind the Faraday Isolator
- Tight mechanical and thermal requirements (Peltier cell)
- Assembly problematics



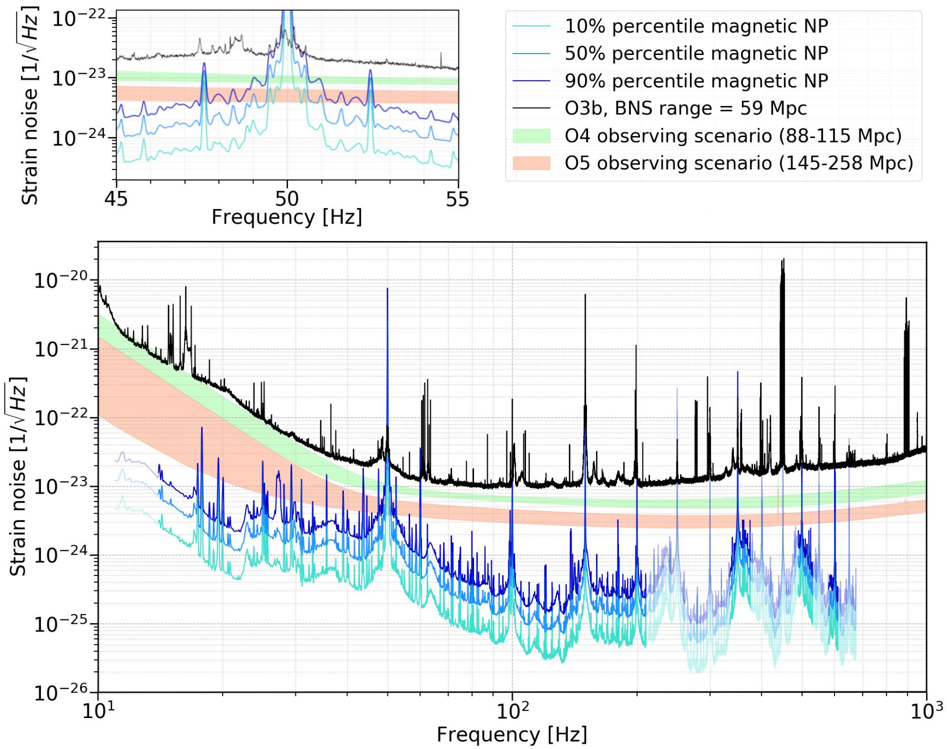




Prototype simulated attenuation factor is higher than target : ~165

Conclusions

- Low frequency magnetic noise is one important limiting factor of future detectors sensitivity
- We have illustrated a paradigm for the measurement of the coupling to critical components and the mitigation of the coupling
- A Faraday shield prototype is being produced to test mechanical details and assembly



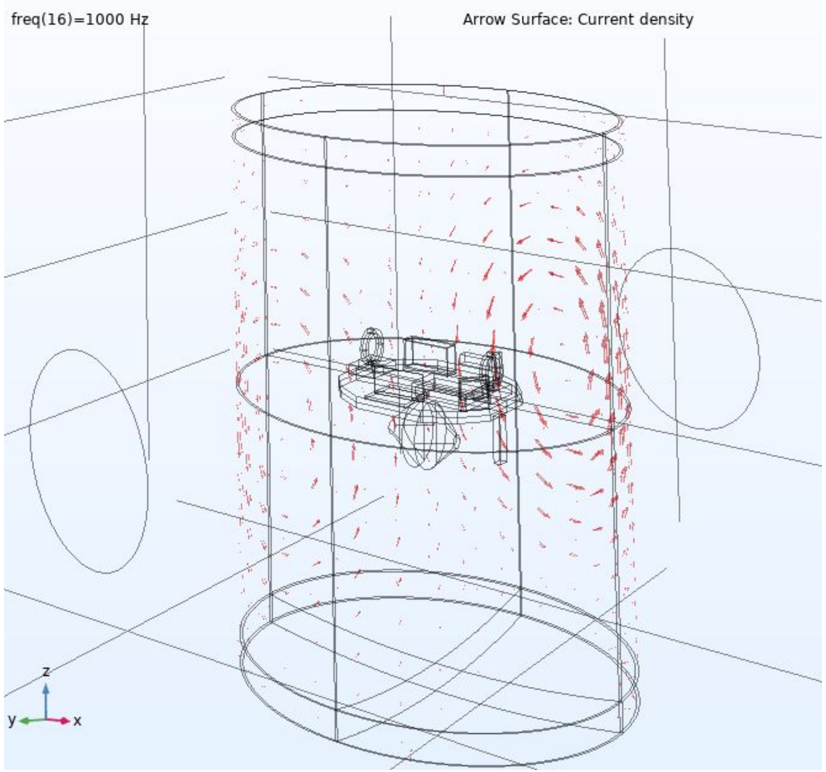
Next steps

- During the advanced Virgo commissioning, the coupling measurement will be repeated in the same and other interesting locations, to eventually produce a budget of magnetic noise on the Virgo sensitivity
- For E.T. : extrapolated projection indicates that a reduction factor of up to ~10^4 is needed below ~30Hz (https://arxiv.org/abs/2110.14730 K. Janssens et al, Phys. Rev. D 104, 122006)

Concerning the F.I. shield :

- The final shield will be realized and subject to annealing procedure (to recover shields magnetic properties)
- The final F.I. shield installation is currently foreseen for AdV+ phase II

Backup - Eddy currents corrections



- Magnetic field generated by the Eddy currents counters the one generated by the coils

$$\mathcal{E} = -\frac{\mathrm{d}\Phi_B}{\mathrm{d}t}$$

- Effects of the Eddy currents are more important at high frequency
- Eddy currents locally distort the magnetic field
- Generates a force on the bench

=> High frequencies movements are less critical