BHETSA
A seismic isolation system for the test masses of the Einstein Telescope

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Abstract

The Einstein Telescope (ET) gravitational wave interferometer will be the biggest research infrastructure built in Europe in the next decade and its design and construction will bring unprecedented technological challenges.

Third-generation gravitational wave detectors, such as ET, aim at reducing their noise to the lowest possible level for an Earth bound detector, broadening their detection band down to 2 Hz. This improved sensitivity, with respect to Virgo and LIGO, gives access to the early Universe by detecting high red-shift black hole mergers, to the extreme space-time curvature of high mass black holes. It makes possible to detect neutron star inspirals well before they merge, allowing a multimessenger observation of extreme states of matter.

The sensitivity increase in the low frequency region will put however challenging constraints on the suppression of seismic noise. On the basis of the experience accumulated in construction and running the Virgo interferometer for the last two decades, we are developing a suspension system that seismically isolates the test masses of ET at frequencies above 2 Hz with the same height - of about 10 m - of current Virgo Superattenuator. With respect to the baseline design for ET, this study aims at reducing the size of the isolation system, resulting in very significant cost savings in ET civil works. The project foresees an evaluation of possible solutions performing simulation with software tools validated by the previous experience, a detailed mechanical design of the first isolation stages, that are most critical, their construction and successive tests at the Sar-Grav laboratory located in the Sos Enattos mine in Sardinia, candidate as the site to host ET, due to its unique seismic characteristics.

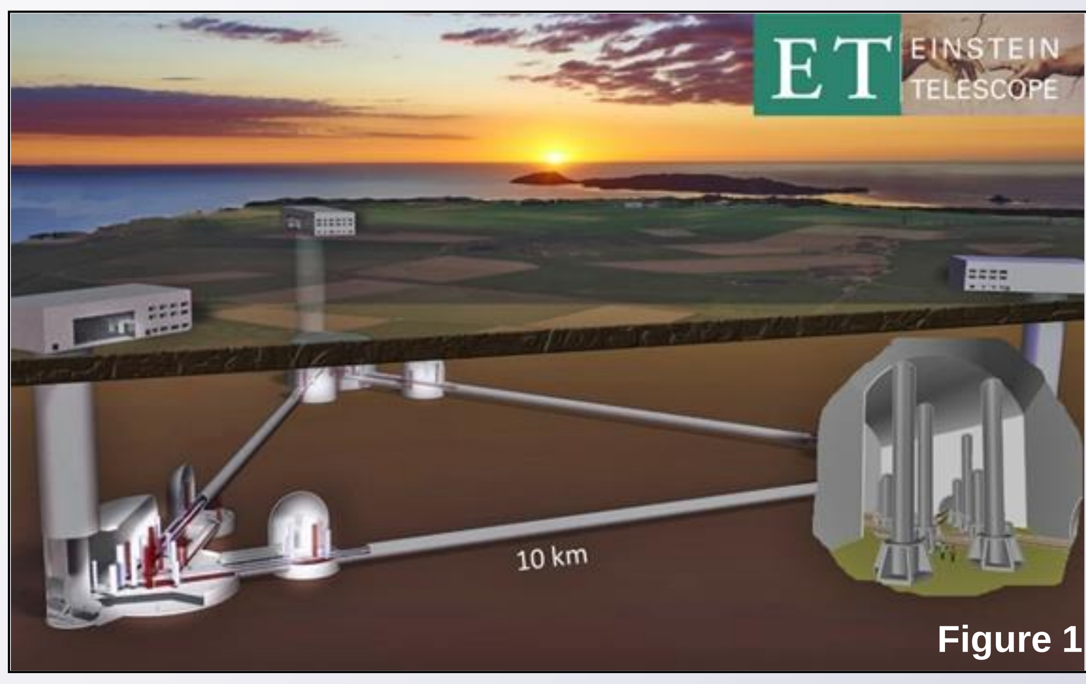

Figure 1

Introduction

The gravitational-wave interferometers of next generation, Einstein Telescope (ET [1], see figure 1) and Cosmic Explorer [2], aim at gaining a factor of 10 in noise level, respect to Virgo and LIGO, but also extending at low frequency their detection band as shown in Figure 2. This improved sensitivity, gives access to the early Universe by detecting high red-shift black hole mergers, to the extreme space-time curvature of high mass black holes.

Even in a site with very low seismicity, the required seismic attenuation from the ground to the mirrors of the interferometers is of more than eight orders of magnitude. In Virgo this has been achieved at a frequency of 4 Hz with the Virgo Superattenuator [3]. However extending the present scheme at lower frequency leads to an increase of dimensions that might be incompatible, technically and financially, with locating the interferometer underground, as required to minimize local gravity fluctuation.

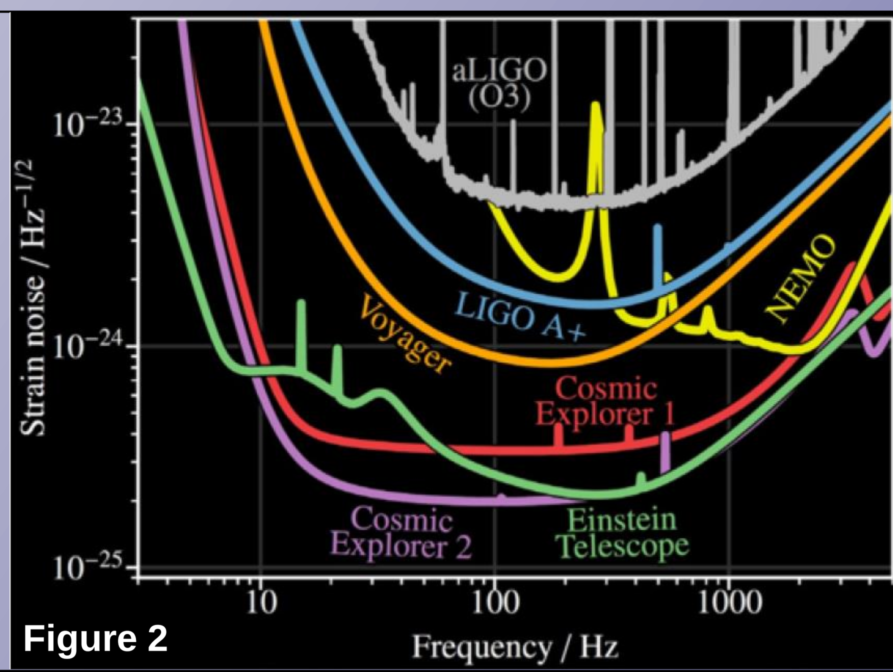

Figure 2

New Mechanical Design

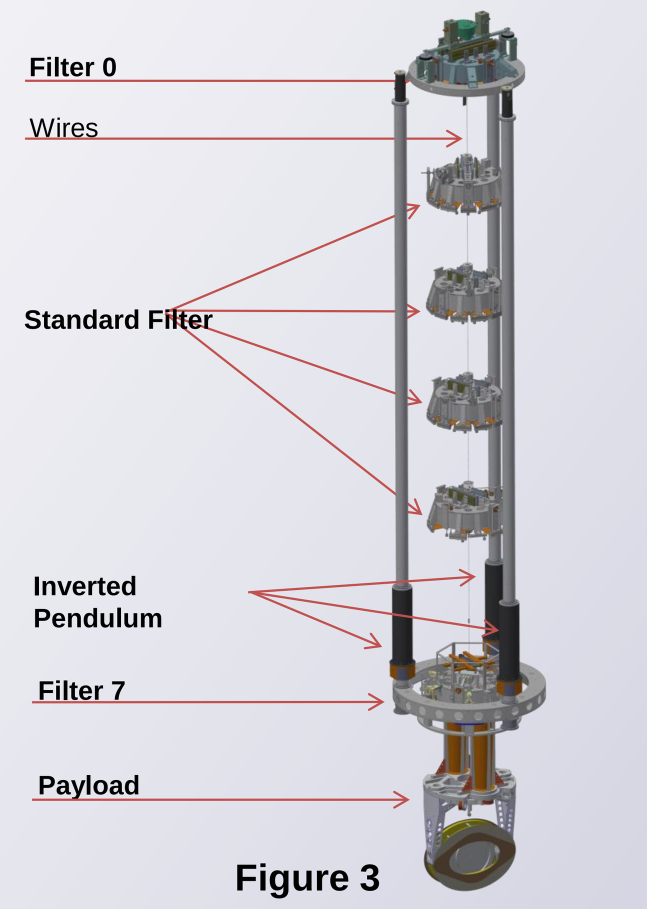

Figure 3

Black Holes for ET SArdinia (**BHETSA**) [*] is a 3-year project funded by the PRIN2020 MIUR call. Its goal is the design of a suspension system that isolates seismically the test masses of ET at frequencies above 2 Hz with a height of about 10 m, similar to the one of the Virgo Superattenuator (SA), shown in figure 3. To test the new design a prototype will constructed, tested and validated.

The current ET baseline solution has a height of 17 m, requiring suitable underground halls, where the test masses must be located to minimize local gravity fluctuations; lowering the experimental hall height would lead to a reduction of the volume of excavated rock and consequently a simplification of civil engineering works, with an estimated cost reduction of the order of 10 million euro.

The mechanical solutions proposed envisaged both an upgrade of the standard filters (see figure 4) and of the inverted pendulum pre-isolator (IP). A two-nested IP design is proposed (figure 5), taking out one attenuation filter from the chain and reducing its length. This improved pre-isolation stage relaxes requirements on the passive filtering chain and might allow going well beyond the stated ET requirements, in the perspective of a planned lifetime of 50 years with further improvements in the ET detector.

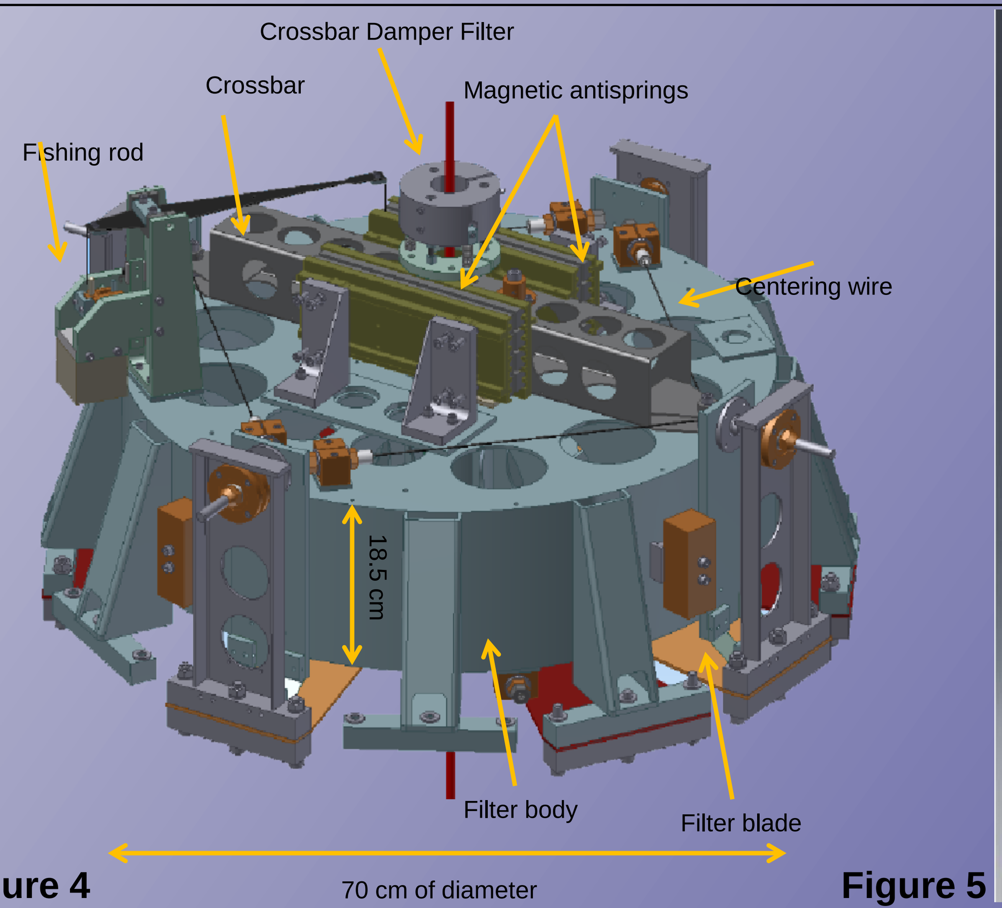

Figure 4

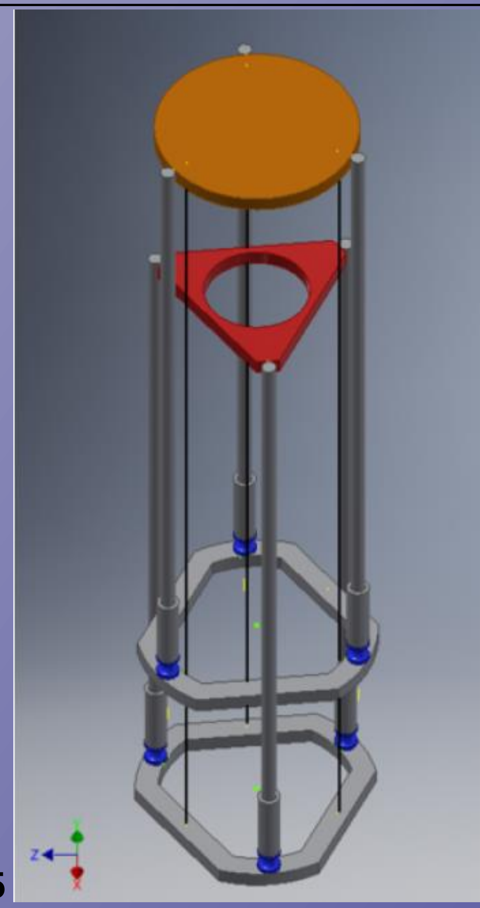

Figure 5

New Control System

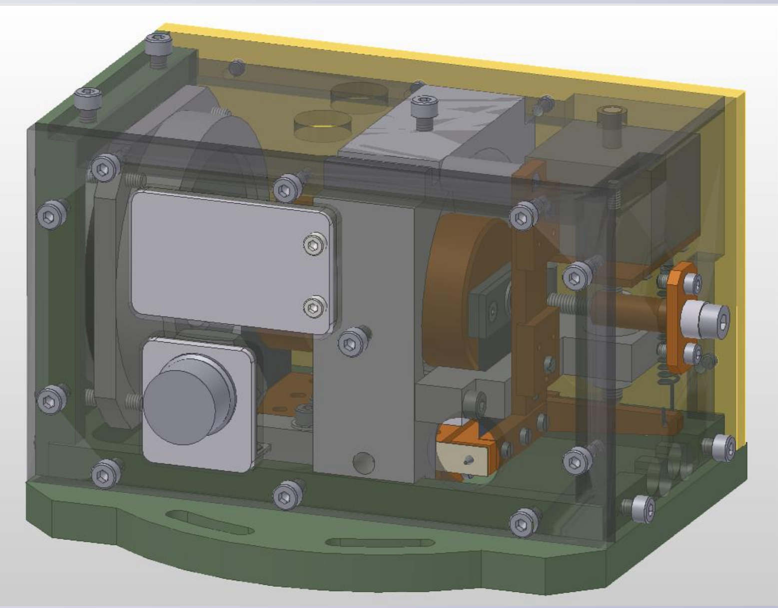

Figure 6

- **Accelerometers**: VIRGO accelerometers [4] (figure 6 and 7) have shown high reliability and very good noise performances but need to be redesigned comparing the seismic noise level at VIRGO [5] with the one in ET candidate sites such as Sos Enattos (see figure 9). The lower expected displacement of the suspended mass allows using an optical readout, while a lower maximum force needs to be applied, reducing the actuation noise.
- **Displacement Sensors**: sensors used to monitor and control seismic isolation system displacement have constraints similar to those of inertial sensors. Several displacement sensors will require the need of an extended dynamic range. The arms of ET are 10 km long and the tidal strain of the Earth crust is 3 times higher as in Virgo. This strain needs compensation of hundreds of microns to keep the interferometer locked around the clock. On the other hand, the noise introduced must be below the seismic noise activity, possibly measured at the top of the first IP, giving for a noise level of 1 pm/sqrt(Hz) a dynamic range of more than 10^8 sqrt(Hz).
- **Control:** We propose to develop a prototype of control system based on machine learning that can initially be trained on a simulated version of the system, and later refined on the real suspension platform. A first result will be a set of definitions that describe the data format used to store the data coming from the hardware, and development of libraries capable of reading and writing data to this format. The second result will be an integrated system made of GPU-based hardware and software package capable of training deep learning algorithms for controlling the suspensions, using reinforcement learning approach.

Figure 7

Tests at SAR-GRAV facility

Figure 8

- **SAR-GRAV:** the Sos-Enattos area (close to Lula in Sardinia, Italy, as shown in fig. 8) is one of the two candidate sites to host the Einstein Telescope. This location is among the seismically quietest sites in the world. Sardinia is a stable region from the geodynamical point of view and, moreover, the area around the Sos-Enattos dismissed mine is sparsely populated. In these years, a seismological study was performed, and the expected quietness was verified [6]. Figure 9 shows, the night, median and minimum probabilistic power spectral density (PPSD) of two underground stations SOE1 (-84 m) and SOE2 (-111 m). Below 0.5 Hz and between 2 Hz and 5 Hz, the noise power is close to the Peterson's New Low Noise Model (NLNM) [7, 8]. Between 5 Hz and 10 Hz, it is close to the self noise floor of the digitizer.
- **Tests:** The prototype will be installed in the SAR-GRAV central hall. The first tests will concern the measurement of the resonance frequencies and their tunability. The goal of these first experimental tests will be to confine the two resonance frequencies of the coupled IPs within 40 mHz. The second series of test will be about the control of the pre-isolator, with particular care of the couplings of the tilt-to-translation degrees of freedom. The final tests foreseen in the present project will be the measurement of the horizontal and vertical transfer functions.

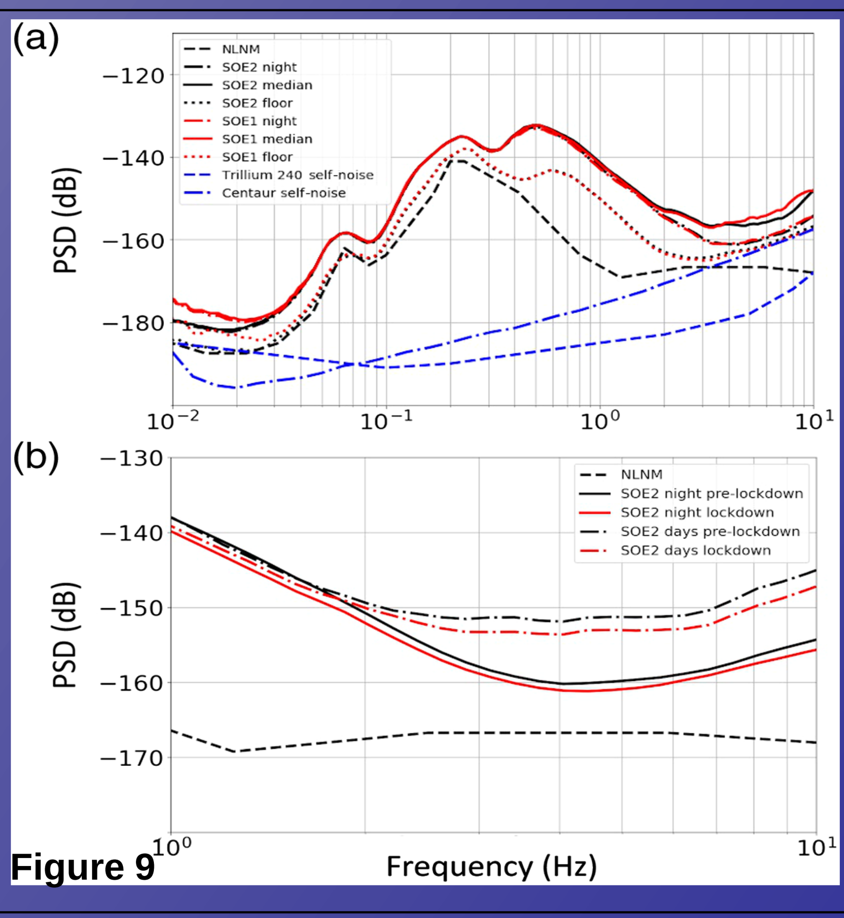

Figure 9

[*]: Project Website: http://bhetsa.df.unipi.it/