First Tests on Pendulum Inverted Pendulum

University of Pisa

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"Who am I?"

Postdoctoral research in *BHETSA* (Black Holes for ET in Sardinia).
PI: Francesco Fidecaro (INFN Pisa, Università di Pisa), financed by the MUR about the PRIN project.
BHETSA activities in Pisa: development of software, simulation of transfer function, study of a new prototypes for seismic isolation, called **Pendulum Inverted Pendulum** (PIP).

Ministero dell'Università e della Ricerca

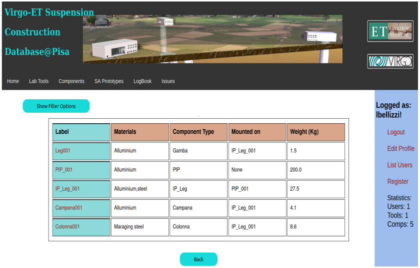
PRIN
Portale dei bandi PRIN della Direzione Generale della Ricerca del MUR

My project:

- experimental activity aimed at the development and test of PIP;
- creating a database for ET and Virgo laboratory (see Michele's talk);
- contribute to simulations.

My coworker:

- M. Baratti and S.Ardito (master students);
- Michele Vacatello (PHD).

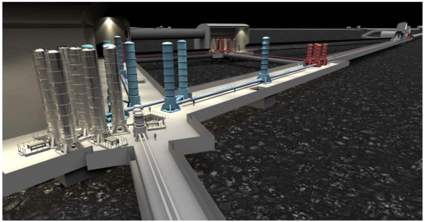


Label	Materials	Component Type	Mounted on	Weight (Kg)
Leg001	Alluminium	Gamba	IP_Leg_001	1.5
PIP_001	Alluminium	PIP	None	200.0
IP_Leg_001	Alluminium,steel	IP_Leg	PIP_001	27.5
Campana001	Alluminium	Campana	IP_Leg_001	4.1
Colonna001	Maraging steel	Colonna	IP_Leg_001	8.6

A little screenshot of the Pisa construction DB

The main goals:

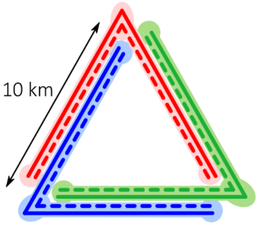
- improve the sensitivity ten time better than 2G detector;
- extend the range of frequencies from $\sim 3-$ to several kHz;
- increase the distance of the Universe observable.



Horizont for ET (et-gw.eu).

Peculiarities of ET:

- three nested detectors in a triangular pattern;
- the length of each arm is 10 Km;
- located at 100-300 m underground;
- xylophone design.



Design Report Update 2020 for the Einstein Telescope

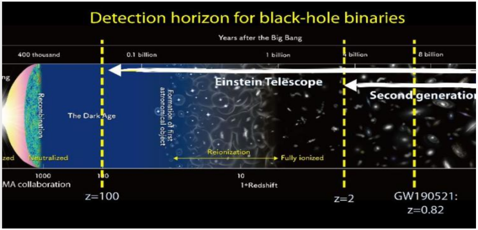
Low frequencies

Improve the sensitivity at LF:

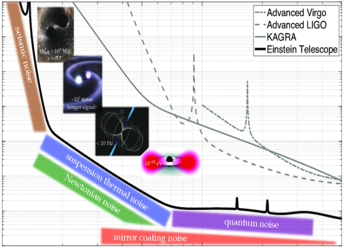
- early-warning localization;
- signals from early Universe;
- increase the bulk of Universe;
- improve S/N on continuous signal;

ET-Low Frequency Noise:

- microseism motion;
- newtonian noise;
- thermal noise;
- control noise.

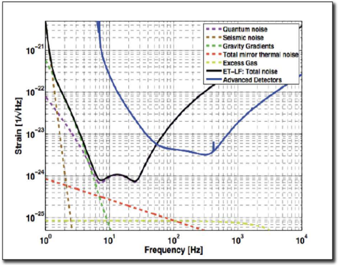


Horizont for ET (et-gw.eu).



Contribution noise at ET-LF (Stefan Hild, g2net WG3).

ET Attenuation



Contribution noise at ET-LF (Stefan Hild, g2net WG3).

Seismic noise:

- f from 0.1 to 10 Hz;
- $\widetilde{x} \sim \frac{\alpha}{f^2}$, where $\alpha = 10^{-7} mHz^{\frac{1}{2}}$;
- noise decreases underground:

$$\frac{x(f,d)}{x_{depth(f,d=0)}} = e^{-4\frac{d}{\lambda}} \tag{1}$$

Some strategies:

- it will be located in a place with low seismic motion;
- ET will be installed at $\sim$ 200 m underground;
- Super attenuator (SA) baseline design will be high $\sim$ 17 m;
- large cryogenic (10 -20 K) silicon test masses.

Planimetry of the SOS Enatos and where the ET will be located.

BHETSA project

Inside the project *"Black Holes for ET in Sardinia"* (BHETSA) a new concept of filter has been developed: the **Pendulum Inverted Pendulum** (PIP). The main goal is to short the super attenuator untill 10 m (see the Fidecaro's presentation).

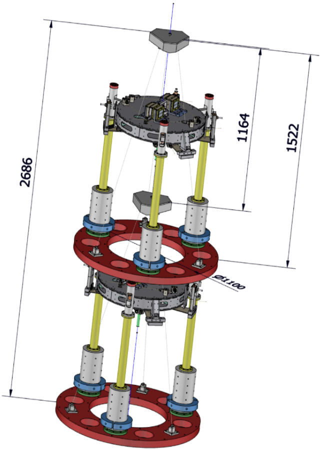
The attenuation is given by:

$$A(\omega) = \left(\frac{f_0^2}{f_0^2 - f^2}\right)^2 \qquad (2)$$

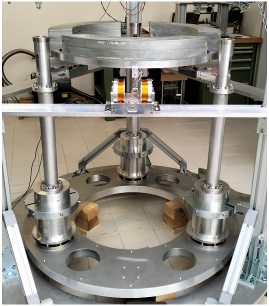
ET seismic filter required:

$$5.2 \cdot 10^{-5} \text{ at } 2 \text{ Hz}$$

A single PIP can attenuate $\sim 2.7 \cdot 10^{-2}$.
Three PIP connected can attenuate $\sim 1.9 \cdot 10^{-5}$ and occupy only 4 m.



Concept of two PIP linked each other.

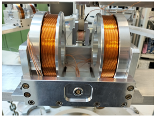


The PIP prototype in our laboratory in Pisa. The horizontal bar in the middle-height supports the LVDT for displacement measurements.

Measuring PIP prototype performance

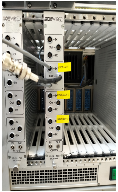
We are using:

- **linear variable differential transformer** (LVDT) as position sensors and attuator, controlled by Virgo electronic boards;
- a **Moku:Pro** is to able to generate electric signal and read the data from LVDT.

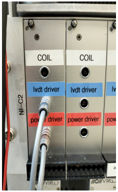


LVDT MP configuration

Moku:Pro

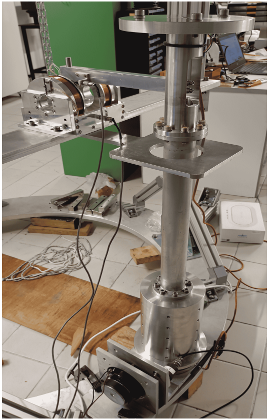


LVDT board

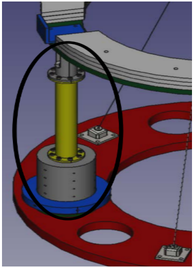


Attenuators board

Characterization of the leg



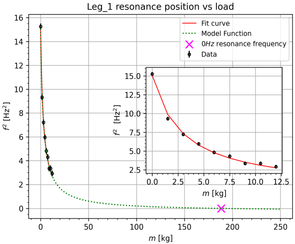
A picture of the Inverted Pendulum took during the characterization.



Using the LVDTs we can read the position of the top and at the base of the leg. From figure below it is possible to know the equation 1 and then compute the value of k of the flexible joint:

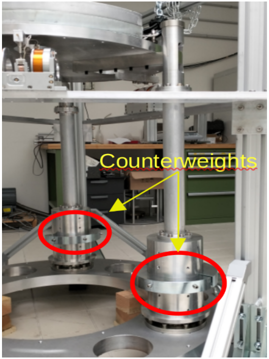
$$f_0^2 = \frac{1}{4\pi^2}\frac{k - (M_{load} - M_{leg}/2)\frac{g}{l}}{M_{load} - M_{leg}/3} \tag{3}$$

Stiffness is: $k_1 = (1775 \pm 61)\frac{N}{m}$



From the data it is possible to compute the fit, finding the stiffness of the flexible joint.

Percussion Point



Counterweight are supported on the leg of IP.

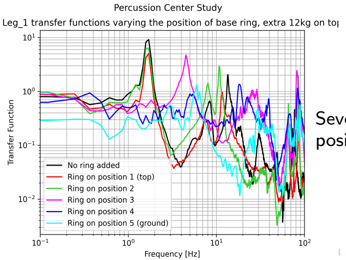
Transfer function

Using counterweight on each leg of inverted pendulum it is possible to modify the position of the percussion point reducing the motion at the top of the leg.

$$\frac{X(\omega)}{X_0(\omega)} = \frac{\omega_0^2 + \beta\omega^2}{\omega_0^2 + \omega^2} \qquad (4)$$

where:

$$\beta = \frac{m/4 - I/L^2}{M + m/4 + I/L^2} \qquad (5)$$

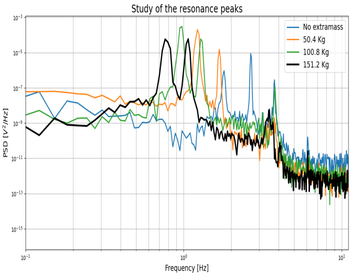


Several transfer function at different position of the counterweights

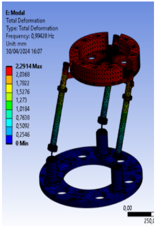
Study of the peak of resonance

We have compared the measurements with simulations of the PIP under stress. The simulation is made with Ansys and indicates that the two lower frequencies modes are superimposed. The values are reported in the table:

	Simulation		Data	
	mode 1 (Hz)	mode 2 (Hz)	peak 1 (Hz)	peak 2 (Hz)
No masses	2.24	2.24	1.80	2.65
50 kg	1.52	1.52	1.22	1.69
100 kg	1.12	1.12	0.97	1.28
150 kg	0.99	0.99	0.763	1.07



Spectrum at the top legs varying the mass. As expected, the resonance peaks shift towards lower frequencies.



Ansys provides to compute the values of the first 6^{th} *armonics*.