# Mechatronics for Virgo seismic isolation

**V. Boschi**

*Istitituto Nazionale di Fisica Nucleare (INFN)*

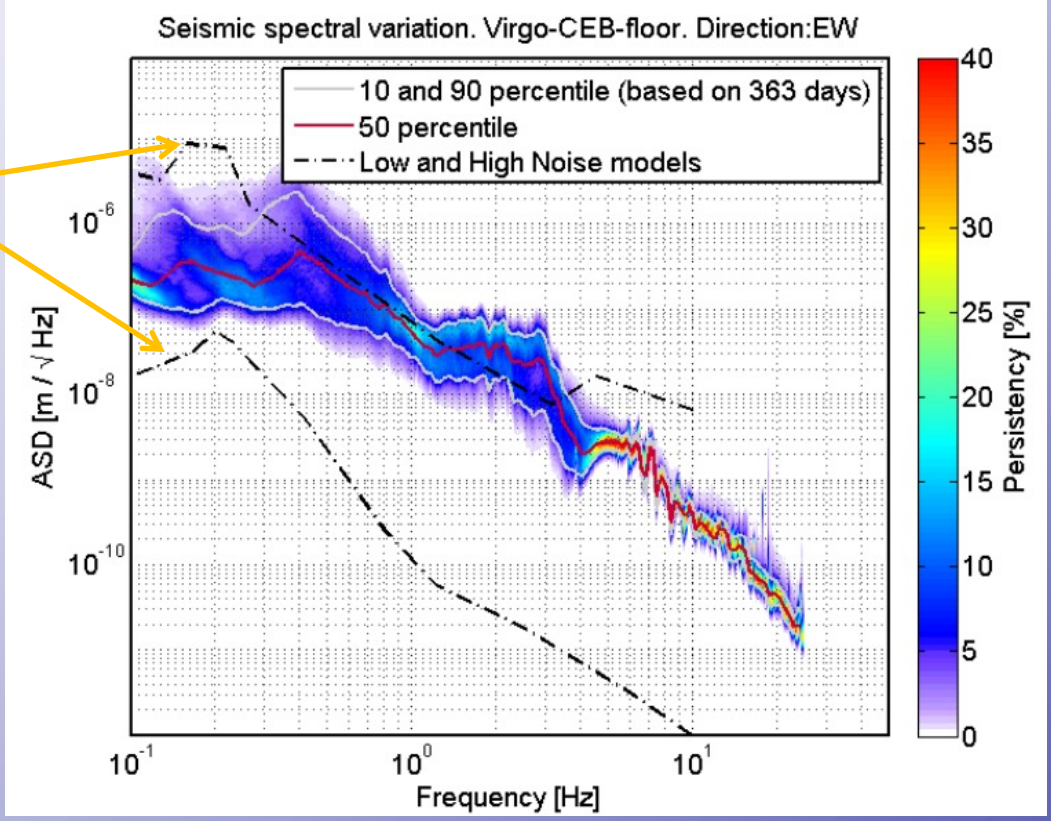
# Introduction
## Seismic Noise on Earth

- Seismic noise has both natural and human origins and can vary by few orders of magnitude from site to site.

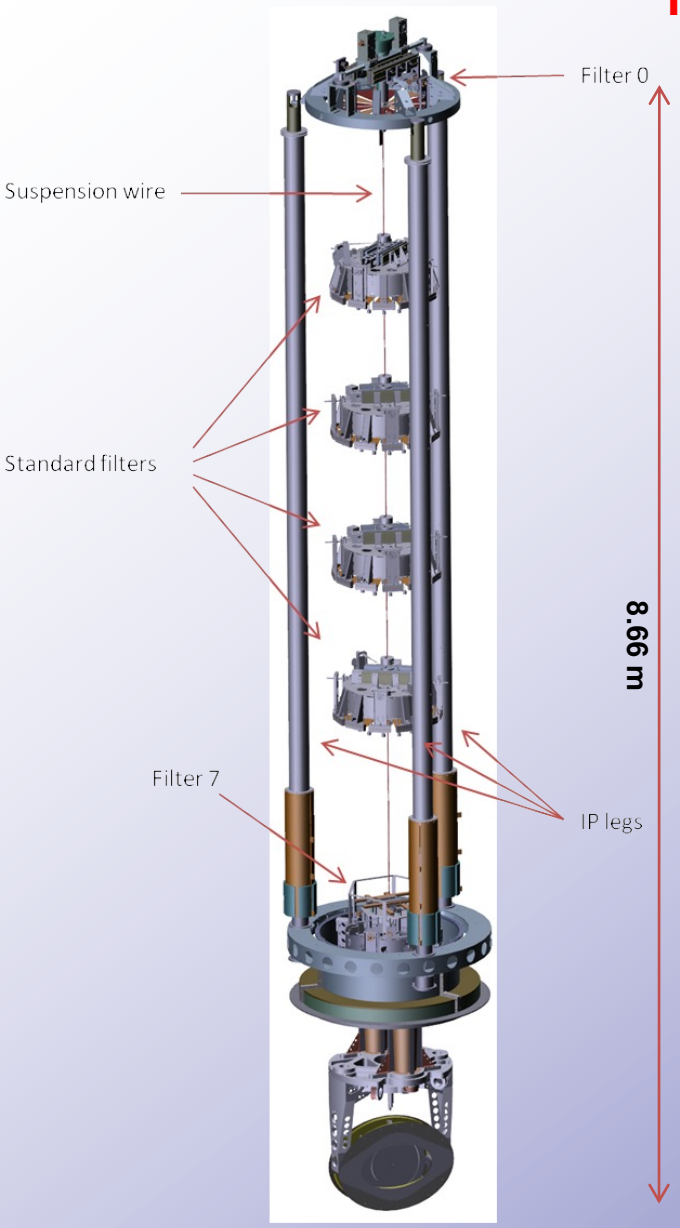
- Al ground motion displacement spectra observed worldwide share some common characteristics: they have essentially the same amplitude in all three orthogonal space directions and they exhibit a low pass behavior that follows the empirical law for f > 0.1 Hz

$$x(f) \sim A\ (1\ \mathrm{Hz}/\mathrm{f})^2\ \text{m/sqrt(Hz)}$$

Peterson's High and Low Noise Models



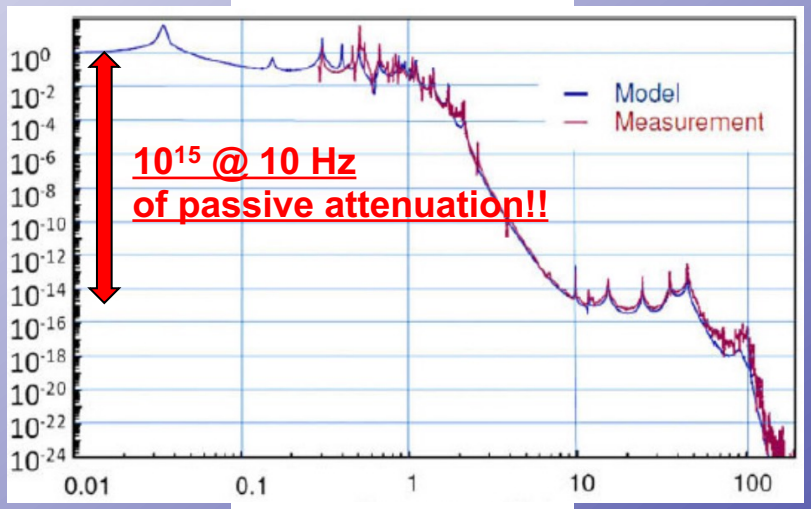
# Mechatronics in Virgo
## The superattenuator (SA)




The AdVirgo superattenuator (SA) is a complex mechanical device capable of providing more than 10 orders of magnitude of passive seismic isolation in all six degrees of freedom above a few Hz

- The SA is a passive mechanical system constituted by a 5 stage pendulum supported by a 3-leg elastic pre-isolator called inverted pendulum (IP).
- All the normal mode resonance frequencies of the SA are kept below 2 Hz.
- The SA mechanical structure, consists of three fundamental parts: the inverted pendulum, the chain of standard filters, the payload.
- Mechanical design for AdVirgo is essentially the same of Virgo except for the payload.

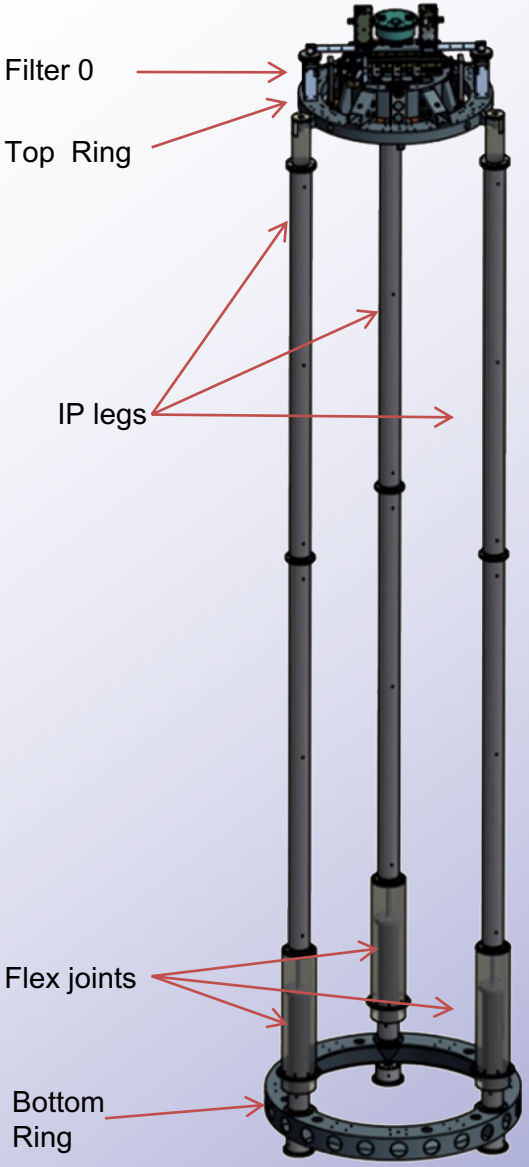
**Transfer function**



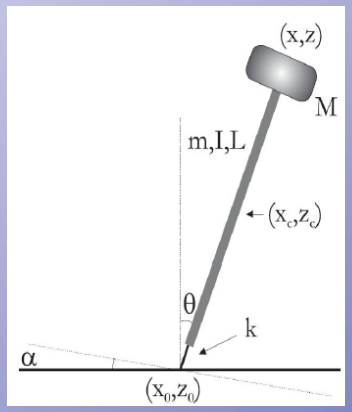

**Frequency [Hz]**

# Mechatronics in Virgo

## The inverted pendulum




- A low frequency pre-isolator constituted of three 6 m-long hollow legs, each one connected to the ground through a flexible joint and supporting an interconnecting structure (the top ring) on its top.
- The structure horizontal normal modes are tuned at about 30-40 mHz.
- A simple mechanical model such as this




**Gravitational Anti-spring**

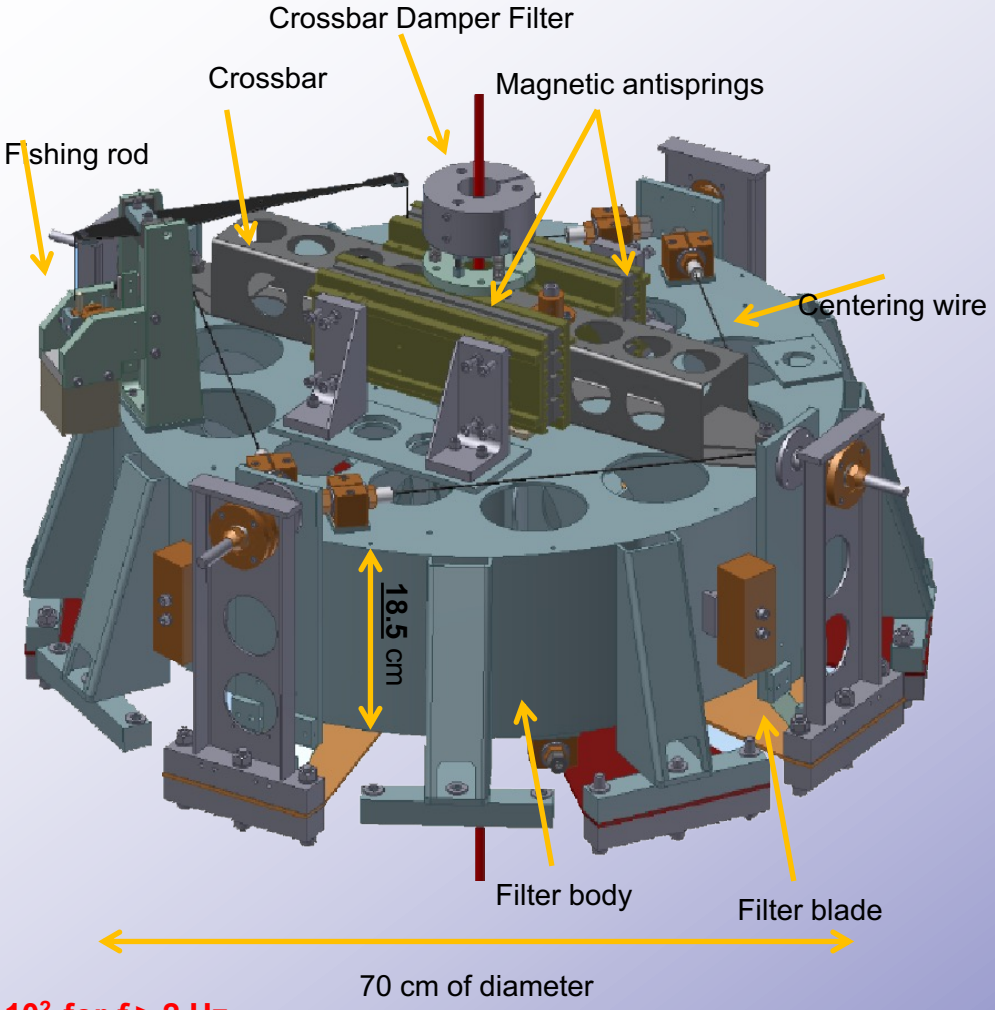
gives $$\omega_0 = \frac{k - (M + m/2)g/L}{M + m/4 + I/L^2}$$

- Since the system is very soft, it requires very low forces to be moved:

for f<<f0 $F \simeq M\omega_0{}^2 x$

- The top ring is a mechanical support for an additional seismic filter, called filter 0, similar to those used in the chain.
- The filter 0 is equipped with a set of sensors and actuators, placed in a pinwheel configuration, that are used to actively damp the IP resonance modes.

# Mechatronics in Virgo
## Vertical Attenuation: Standard filters

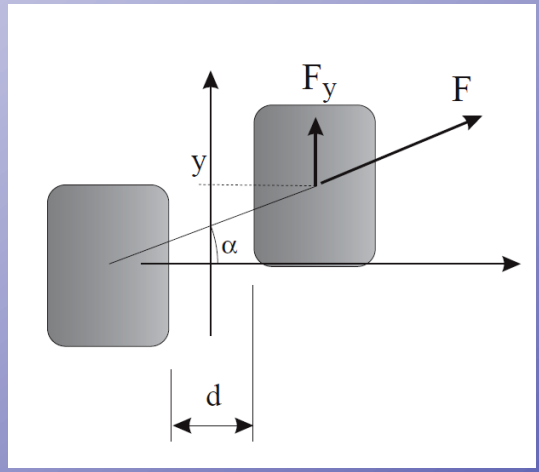



**$10^2$ for $f > 2$ Hz of passive attenuation in both horizontal and vertical direction !!**

The first four pendulum stages of the SA are denominated Standard Filters (SFs).

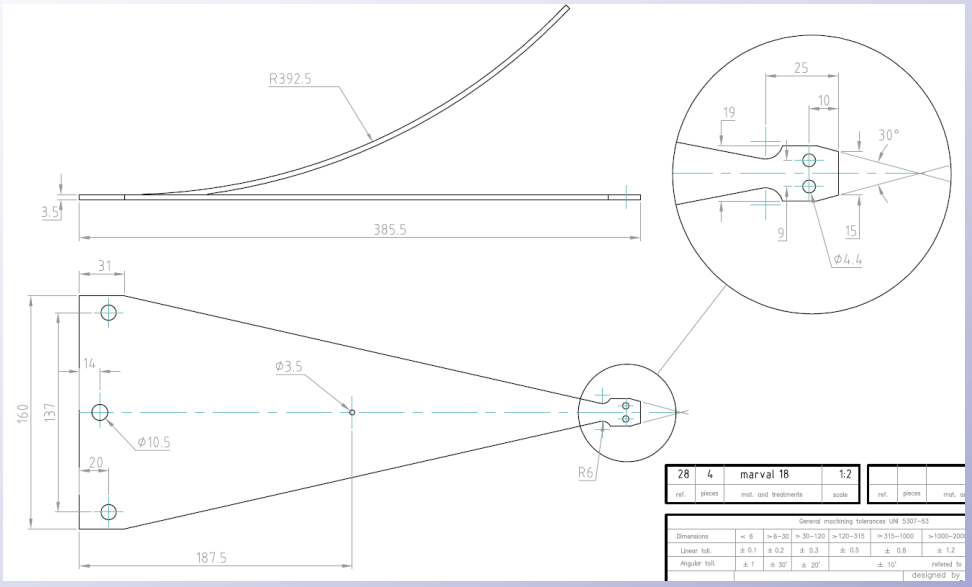
The SF is essentially a rigid steel cylinder supporting a set of maraging steel cantilevered triangular blades clamped along the outer surface of the filter body.

A magnetic anti-spring system, assembled on each filter, is designed to reduce its fundamental vertical frequency from about 1.5 Hz down below 0.5 Hz.




Magnetic antispring working principle

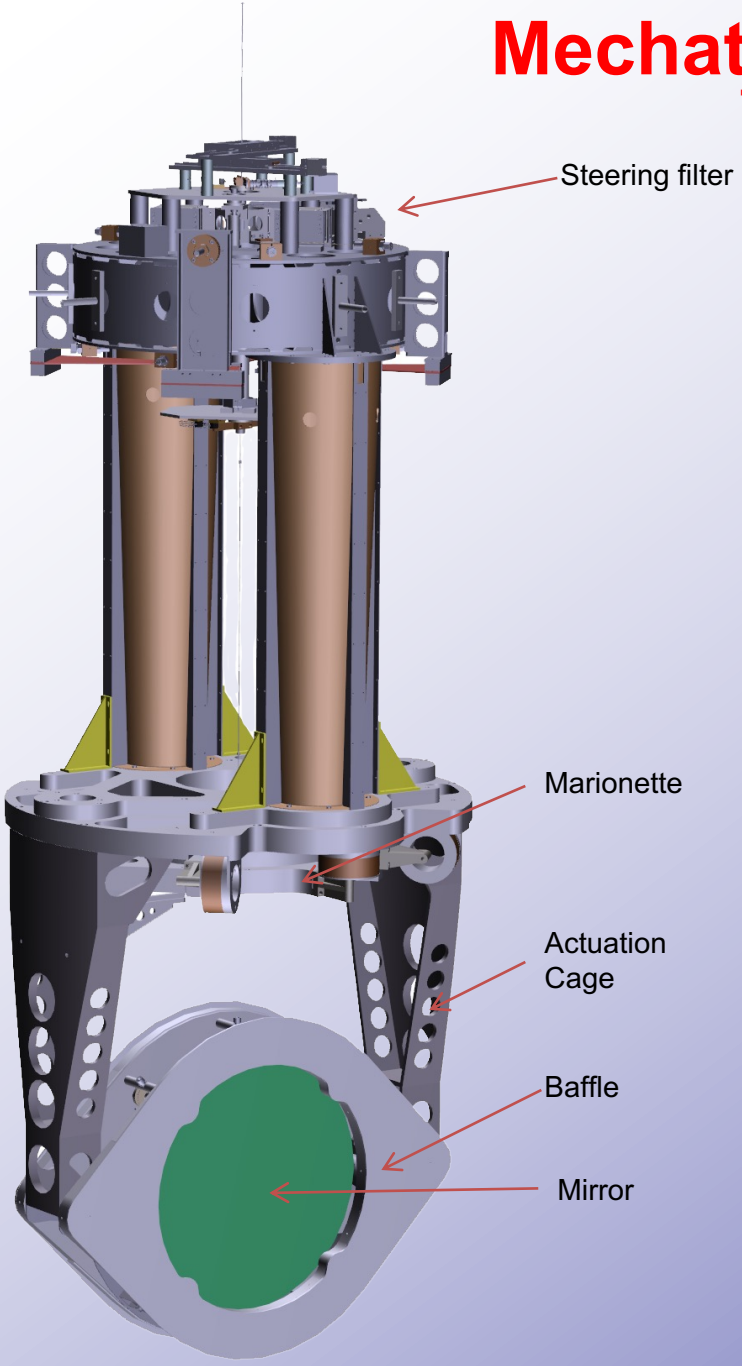
# Mechatronics in Virgo
## Vertical attenuation: Blades

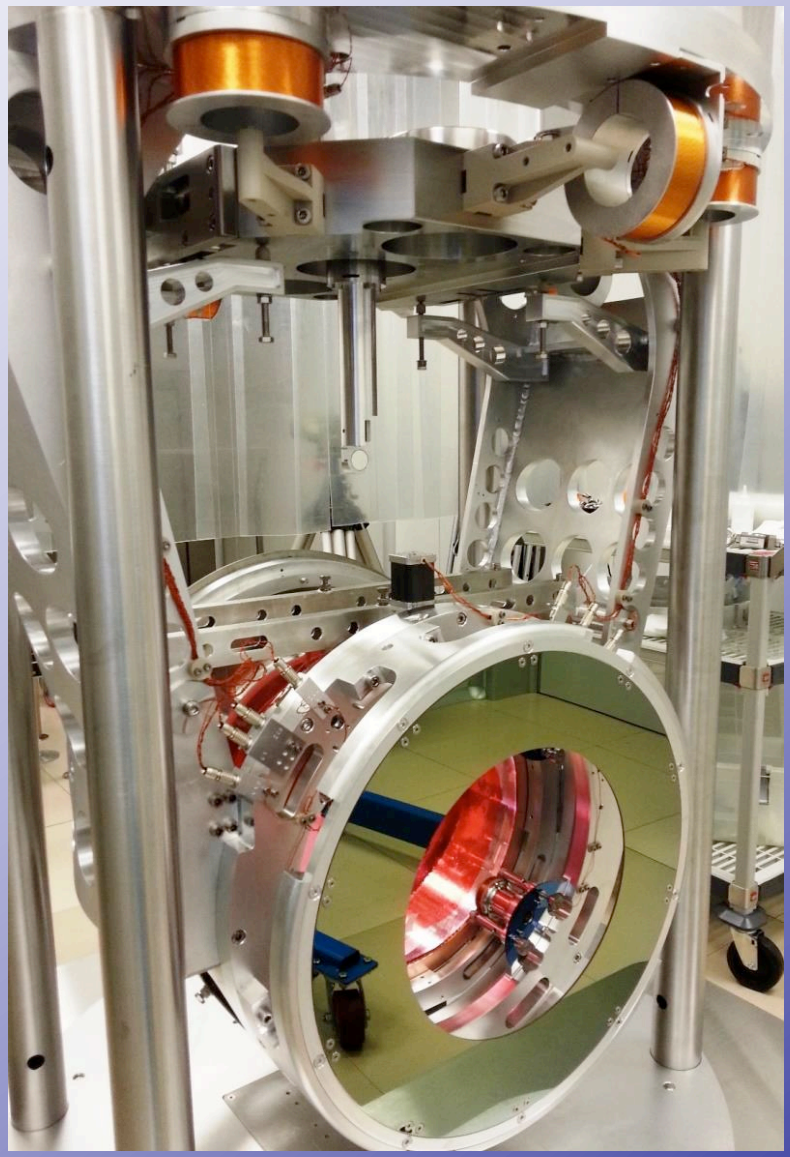



- All the maraging steel blades have a thickness of 3.5 mm, a length of 385.5 mm, while the width of the triangular base changes according with the load to be supported.
- The number of blades ranges from 12 (in the first filter of the chain) to 4 (in the filter 7) according to the suspended load. A total of 52 blades is needed for a long tower.
- The load M depends by the base width b, by the thickness t and length l with this law

$$M = \frac{Ebt^3}{12R_c gl}$$

# Mechatronics in Virgo
## The payload

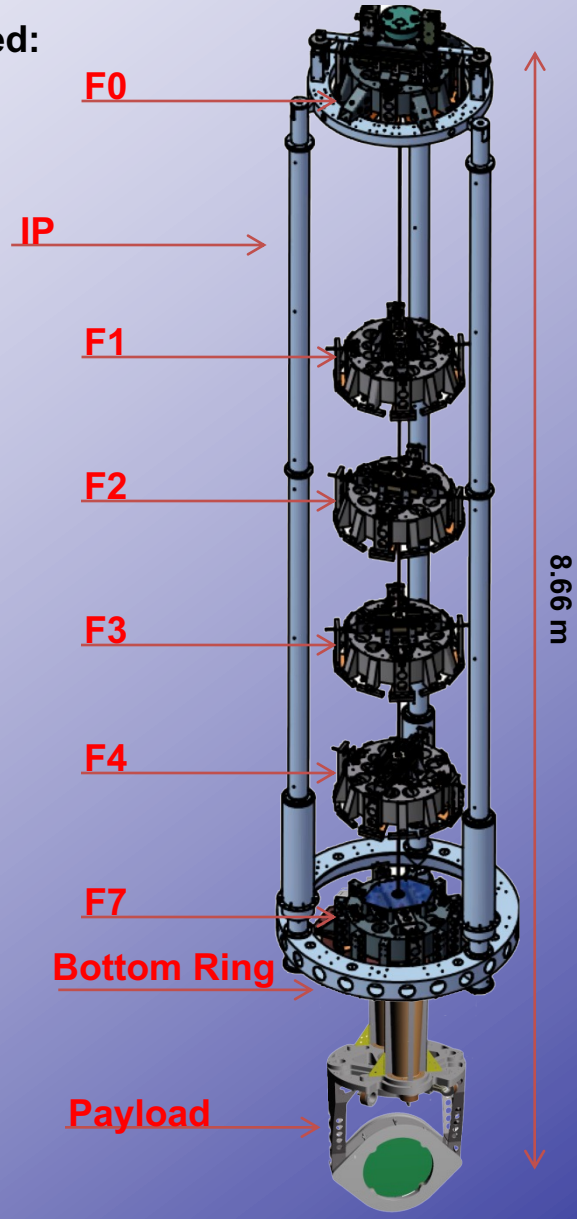


# Mechatronics in Virgo
## SA control system setup

**On long superattenuators (BS, NI, NE, WI, WE, PR, SR) are installed:**

- **18 LVDTs** of 3 different types
  - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
  - 6 F7 LVDTs
- **5 Accelerometers** of 2 different types installed on F0:
  - 3 Horizontal Accs
  - 2 Vertical Accs
- **23 Coils** of 4 different types
  - 5 F0 Coils
  - 6 F7 Coils
  - 8 Marionette coils
  - 4 Mirror coils
- **3 Piezos** on bottom ring
- **21 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 6 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors

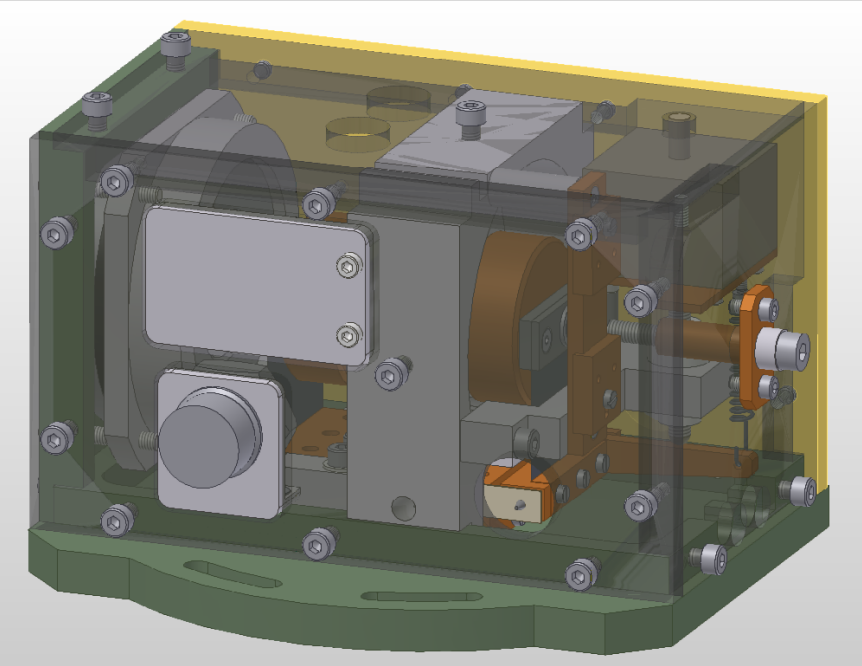


# Mechatronics in Virgo
## SA Sensors

• There is a total of 5 Accelerometer (Accs) installed on the suspension F0 of 2 different types with sensitivity of about $3*10^{-10}$ $m/s^2/sqrt(Hz)$ for $f < 3$ Hz

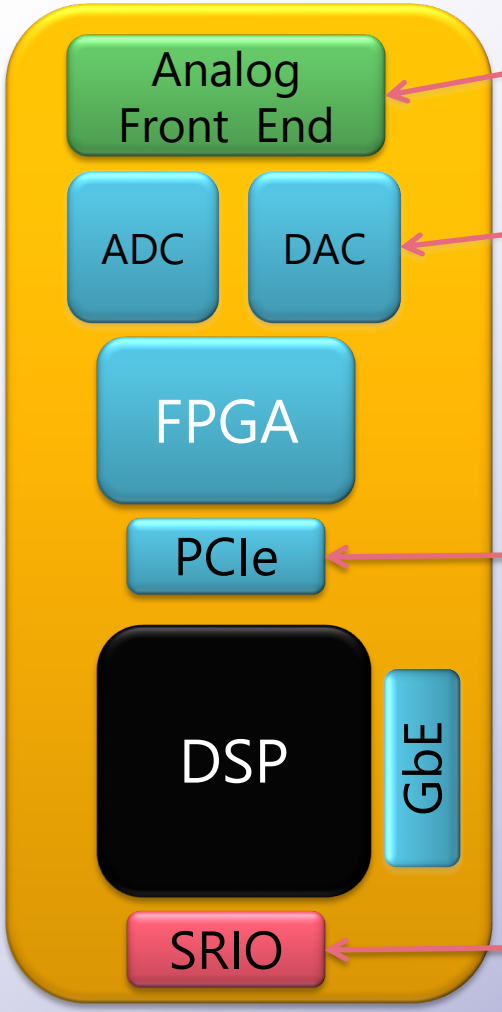
• There are 18 LVDTs installed on long tower suspensions of 3 different types with a sensitivity of about $10^{-8}$ m/sqrt(Hz) for $f > 0.1$ Hz

• All the LVDTs are operated using a digital demodulation scheme at 320 kHz sampling frequency



# Mechatronics in Virgo

## SA Control system hardware




10 Vpp, differential I/O

6ch ADC 24bit, up to 3.84 MSPS
6ch DAC 24bit, up to 640 kSPS

**Analog and digital parts have been embedded in a single board.**

2 lanes x Gen2 PCIe (up to 10 Gbps)

Gigabit Ethernet - Control

Up to 12 modules per crate

4 lanes x SRIO (up to 20 Gbps)

RapidIO Switch

Eth

100baseT - Management

# Mechatronics in Virgo

## SA control sytem hardware


- **Electronics Design based on Texas Instruments DSP**
  - TMS320C6678
    - Eight TMS320C66x DSP Core Subsystems
    - 320 GMAC/160 GFLOP @ 1.25GHz
    - Four Lanes of SRIO 2.1 - 5 Gbaud Per Lane Full Duplex
    - Two Lanes PCIe Gen2 - 5 Gbaud Per Lane Full Duplex
    - Ethernet MAC Subsystem - Two SGMII Ports w/ 10/100/1000 Mbps operation
    - 64-Bit DDR3 Interface (DDR3-1600)

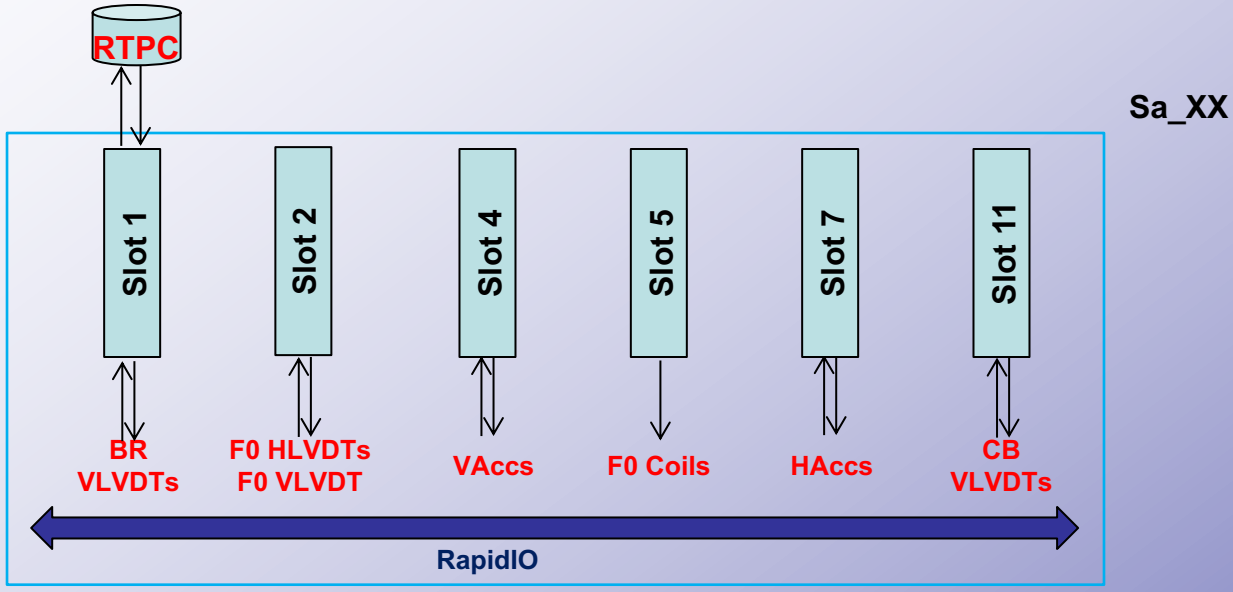
**Computing power of a high-end GPU but extremely energy efficient and specifically designed for hard real-time applications**

| Platform | | Effective Time to complete 1024 complex to complex FFT (single precision) μs | Power (Watts) | Energy per FFT (μJ) |
|---|---|---|---|---|
| GPU | nVidia Tesla C2070 | 0.16 | 225 | 36 |
| GPU | nVidia Tesla C1060 | 0.3 | 188 | 56.4 |
| GPP | Intel Xeon Core Duo @ 3 GHz | 1.8 | 95 | 171 |
| GPP | Intel Nehalam Quad Core @ 3.2 GHz | 1.2 | 130 | 156 |
| DSP | TI C6678 @ 1.2 GHz | 0.86 | 10 | 8.6 |

# Mechatronics in Virgo

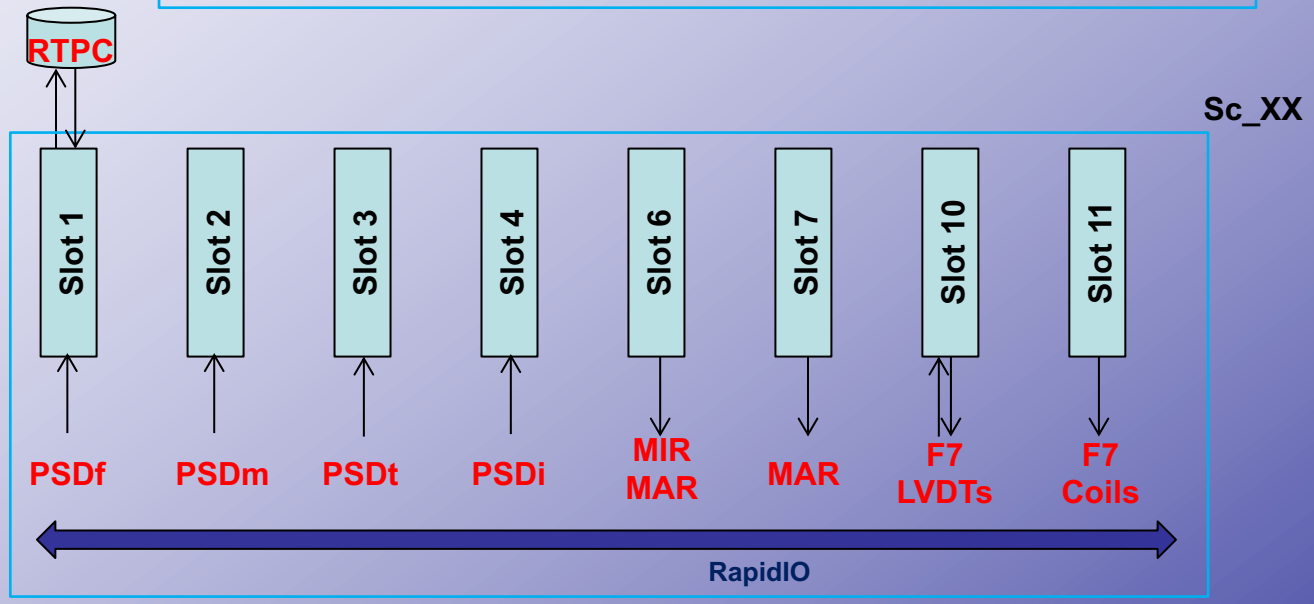
## SA control system hardware

• A total of 14 boards, each one equipped with an 8-core TMS320C6678 DSP, are connected to each long suspension:




**Total computing power of each SA :**

**> 2.2 TFLOPs !!**



# Possible contributions

• Hardware and software: new version of both hardware and software of SA real time control system

• Sensors and actuators development: hi-performance accelerometers, gyroscopes and low-noise actuators for current and future generation of GW detectors

• Technological applications of SA DSP architecture