CAOS vacuum system

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PNRR ETIC IR0000004, “EINSTEIN TELESCOPE INFRASTRUCTURE CONSORTIUM”, CUP I53C21000420006, M 4, C 2, I 3.1

2026 May 15-16 Kagra International Workshop - Perugia

CAOS: General

CAOS is the main ETIC infrastructure, and it is under realization in Perugia, near the Engineering Department of the University. It serves as a specialized lab for testing mechanical and optical systems for the Einstein Telescope (ET).

CAOS will host:

- A seismic-isolated Fabry-Perot cavity (6.6 mt length);
- **ET's full-sized towers** – 15 mt height;
- **ET's full-sized Super Attenuators** (SAs) – 13 mt height;

CAOS will be a fertile ground to:

- Refine FEM and CFD simulations on ET full size towers;
- Explore the potentiality of the lateral entrance for the payload;
- Test Low Noise control systems;
- Test of NEG pumps in a SuperAttenuators environment;
- Test new polyurethane sealing;
- Test Improved solution on SA
- .....

- **New Collaborations**;
- **New Ideas**;

CAOS is unique Lab in the whole ET collaboration:

- ***for the size of the lab***
- ***for hosting full size ET-like towers***

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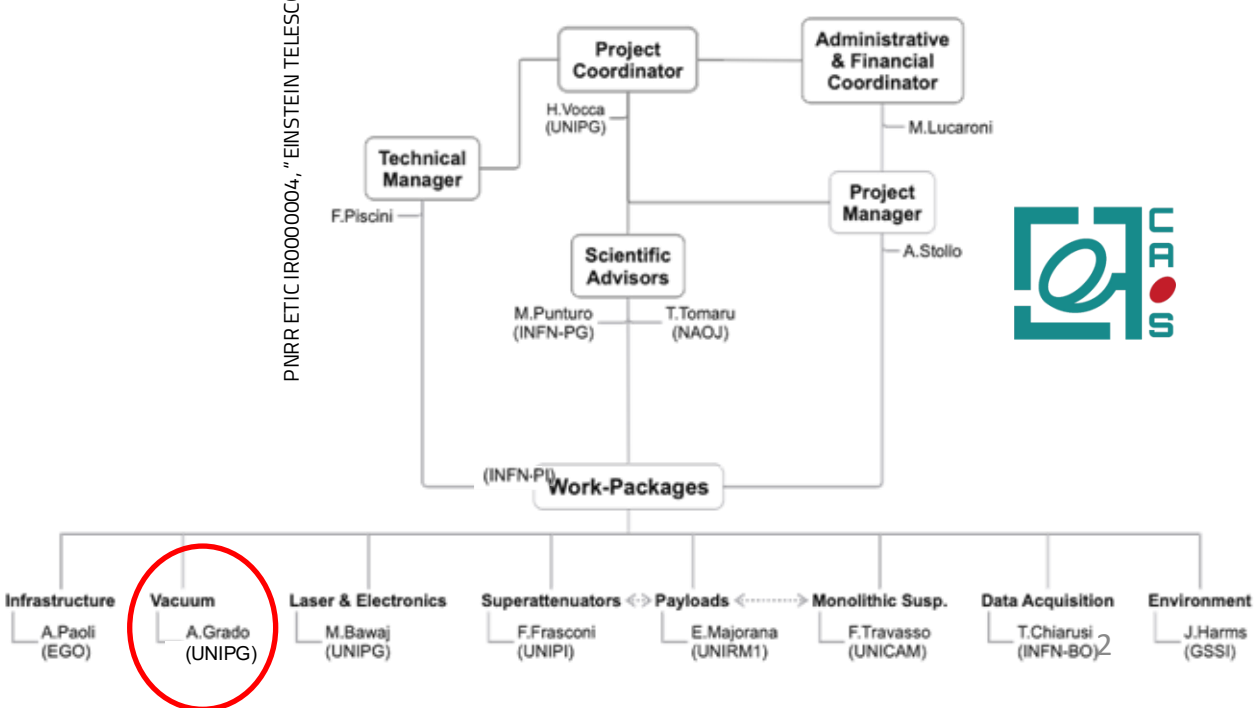
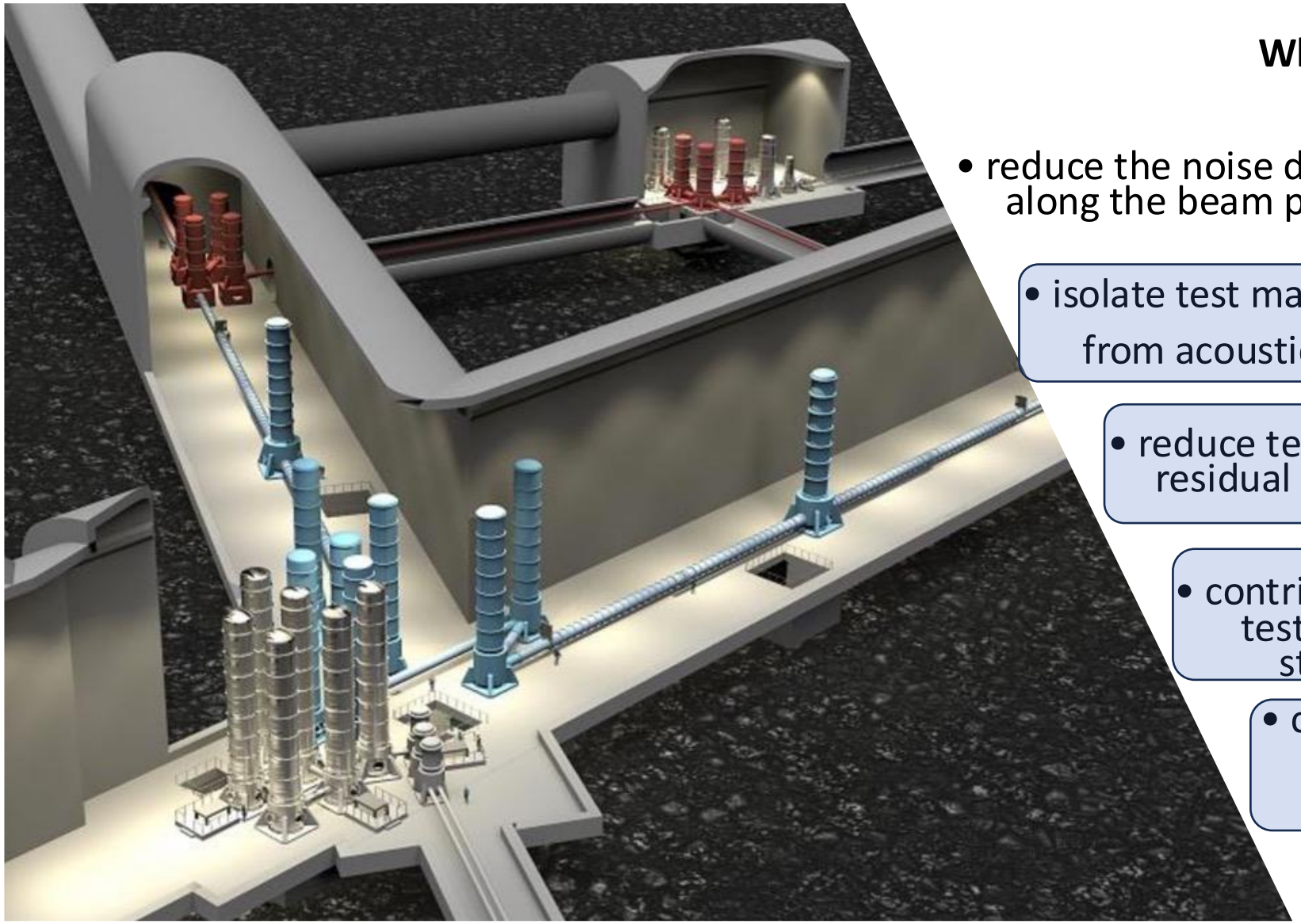


ET vacuum



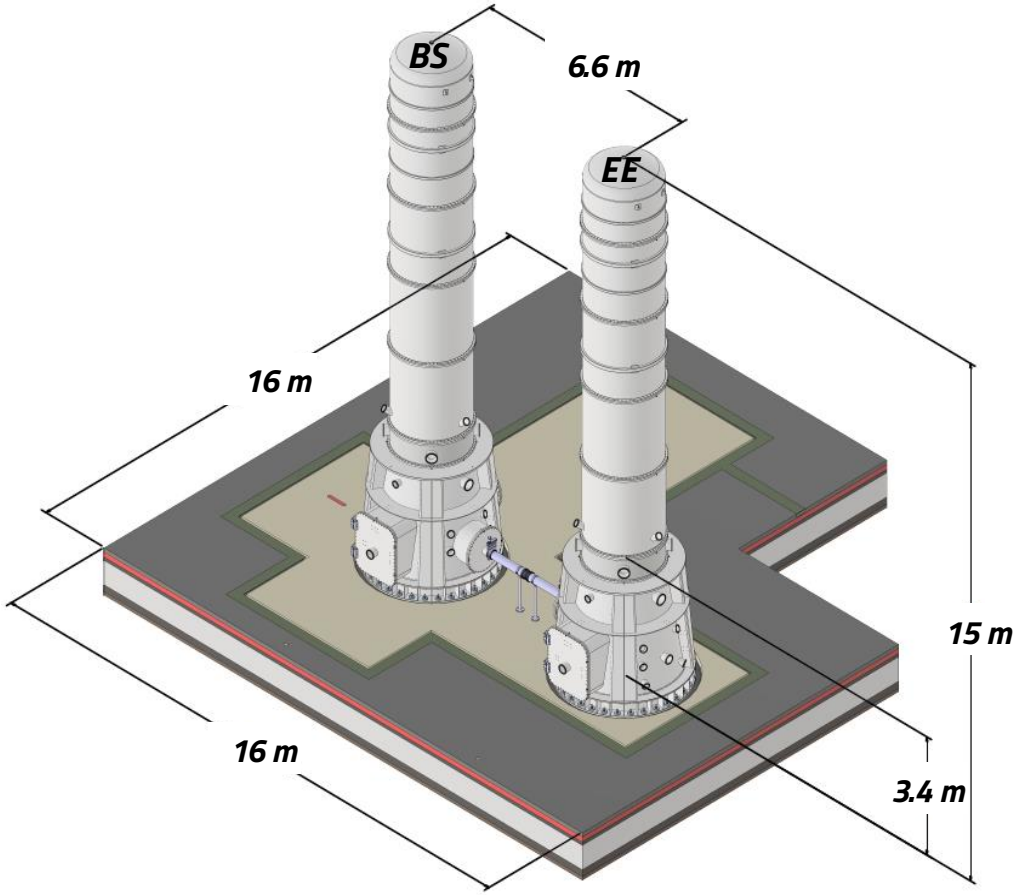
Why under vacuum?

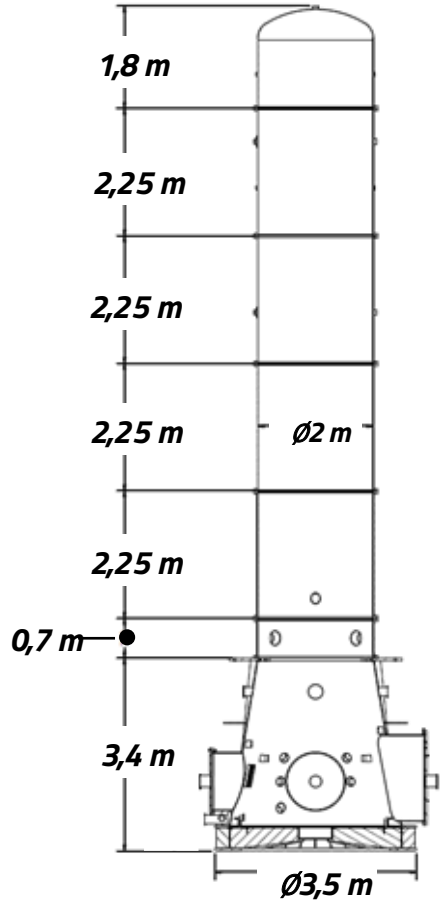
- reduce the noise due to residual gas fluctuations along the beam path to an acceptable level;
  - isolate test masses and other optical elements from acoustic noise;
  - reduce test mass motion excitation due to residual gas fluctuations,
  - contribute to thermal isolation of test masses and of their support structures;
  - contribute to preserve the cleanliness of optical elements.

CAOS: Vacuum Towers

CAOS vacuum system consists of two towers but in the future the system will be upgraded to three towers to host a Michelson interferometer.

Feature	Description
Height	14.9 m
Tower Spacing	6,6 m
Material	AISI 304 L
Operational Pressure	≤ 10^{-7} mbar *
Tower Weight	~20 ton each
Base Weight	~14.8 ton each
# Main Ferrule	4
Main Ferrule Height	2,25 m
Entrance	Lateral – 1,2 m x 1,5 m
Base Geometry	Truncated cone





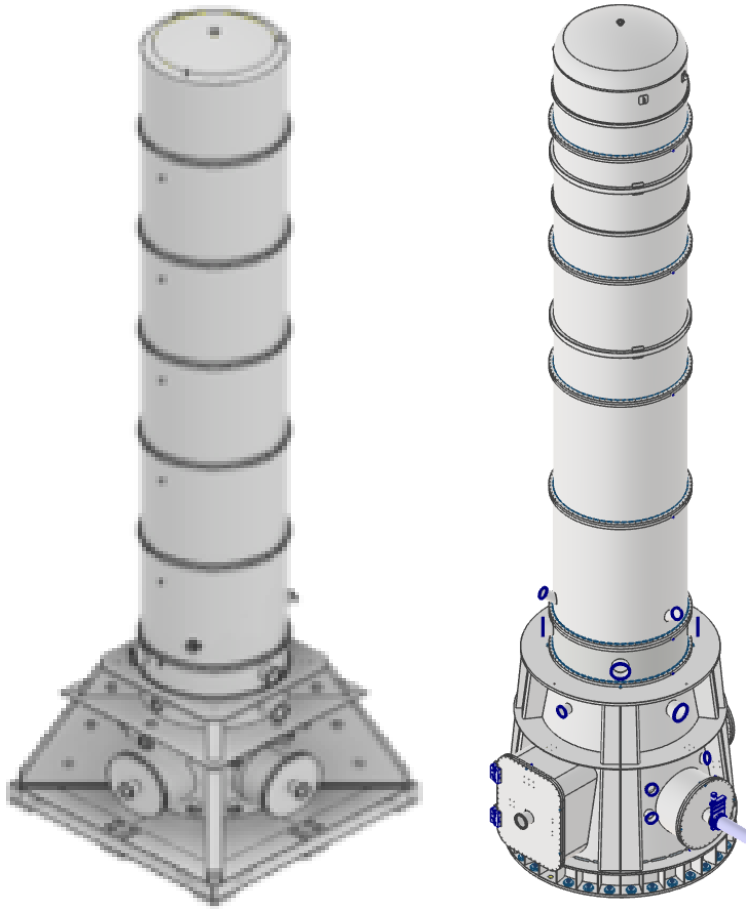
10^{-7} mbar is the initial pressure, in the base tower we foresee to go in UHV

The Virgo heritage

The starting point was the Virgo tower design tanks to Antonio Pasqualetti (EGO)

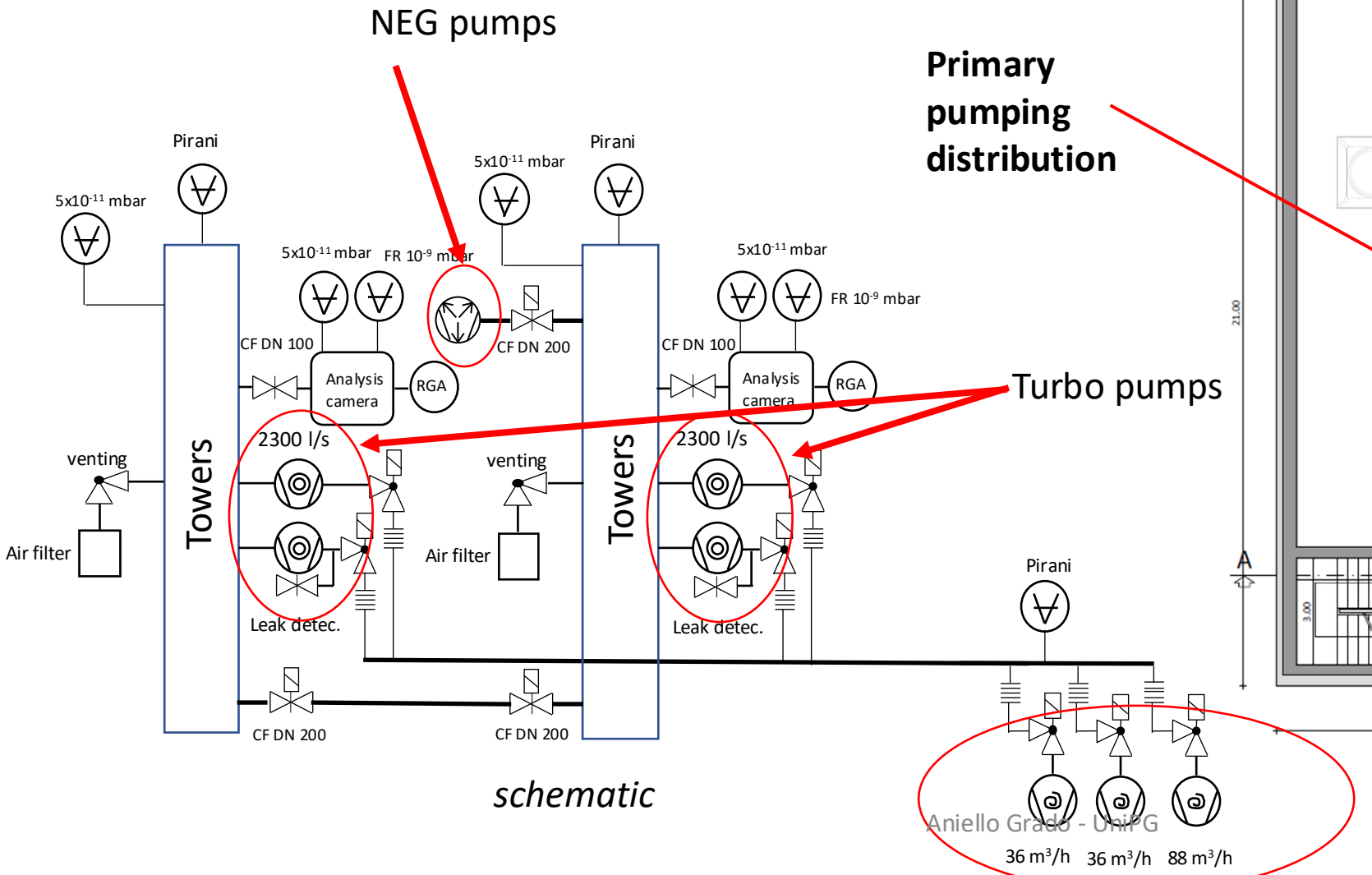
Improvement over Virgo towers

- Increased stiffeness
  - Better for Superattenuator controls
- Larger/taller base tower
  - More room for large payload
- Lateral entrance
  - Required by ET?
- Improved air inlet
  - Improve mirrors cleanless

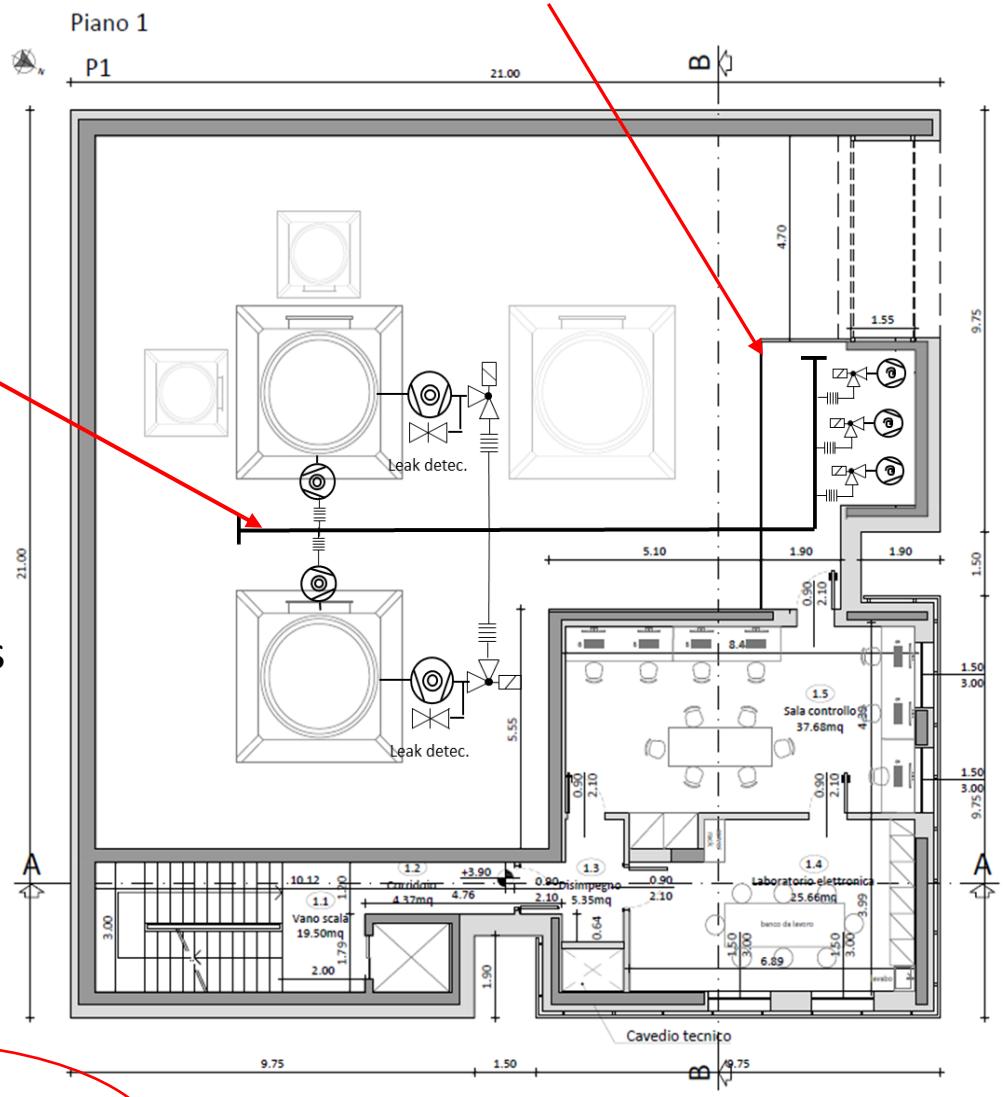


Virgo like design

CAOS vacuum layout

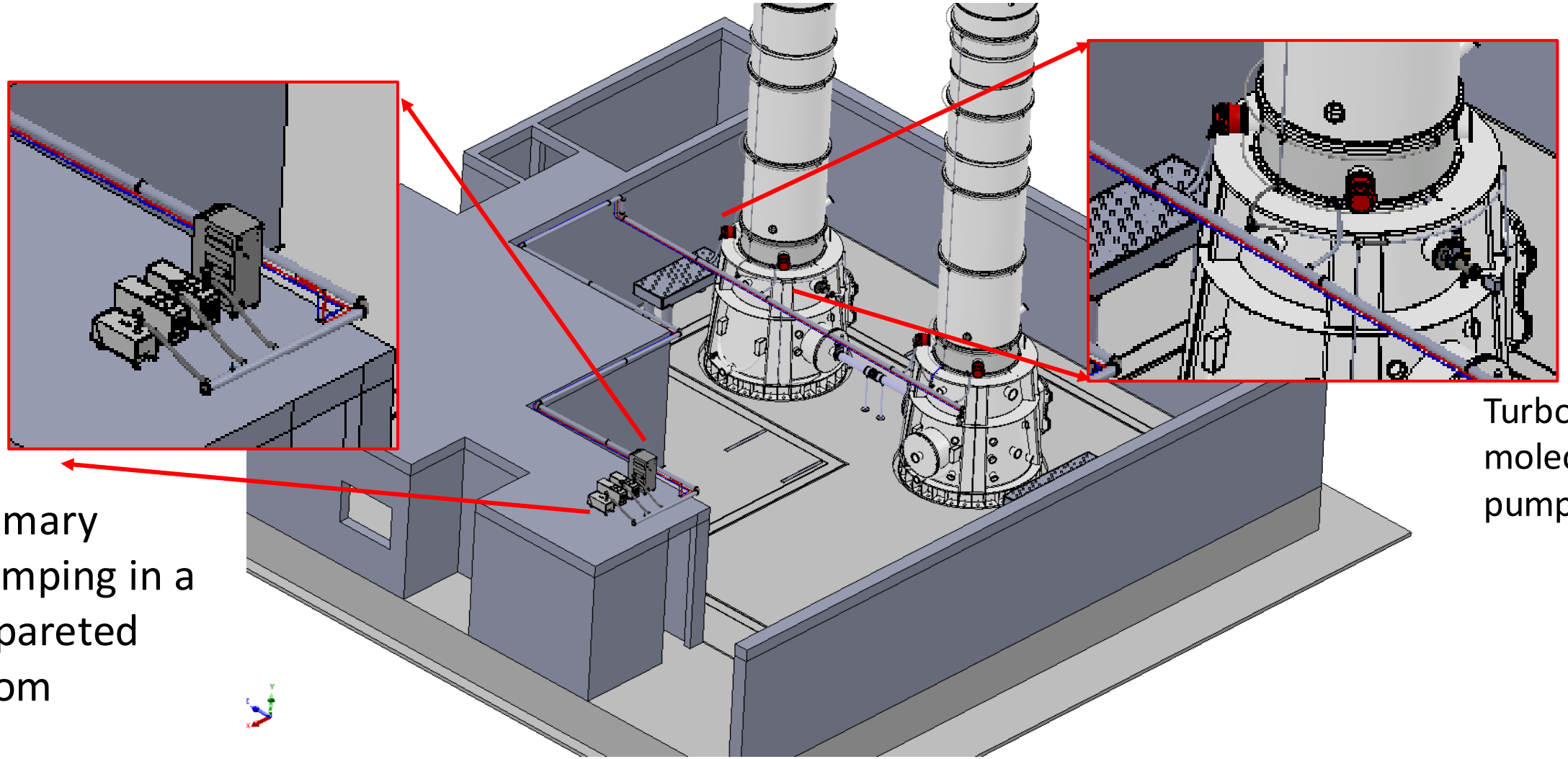


schematic



Primary pumping

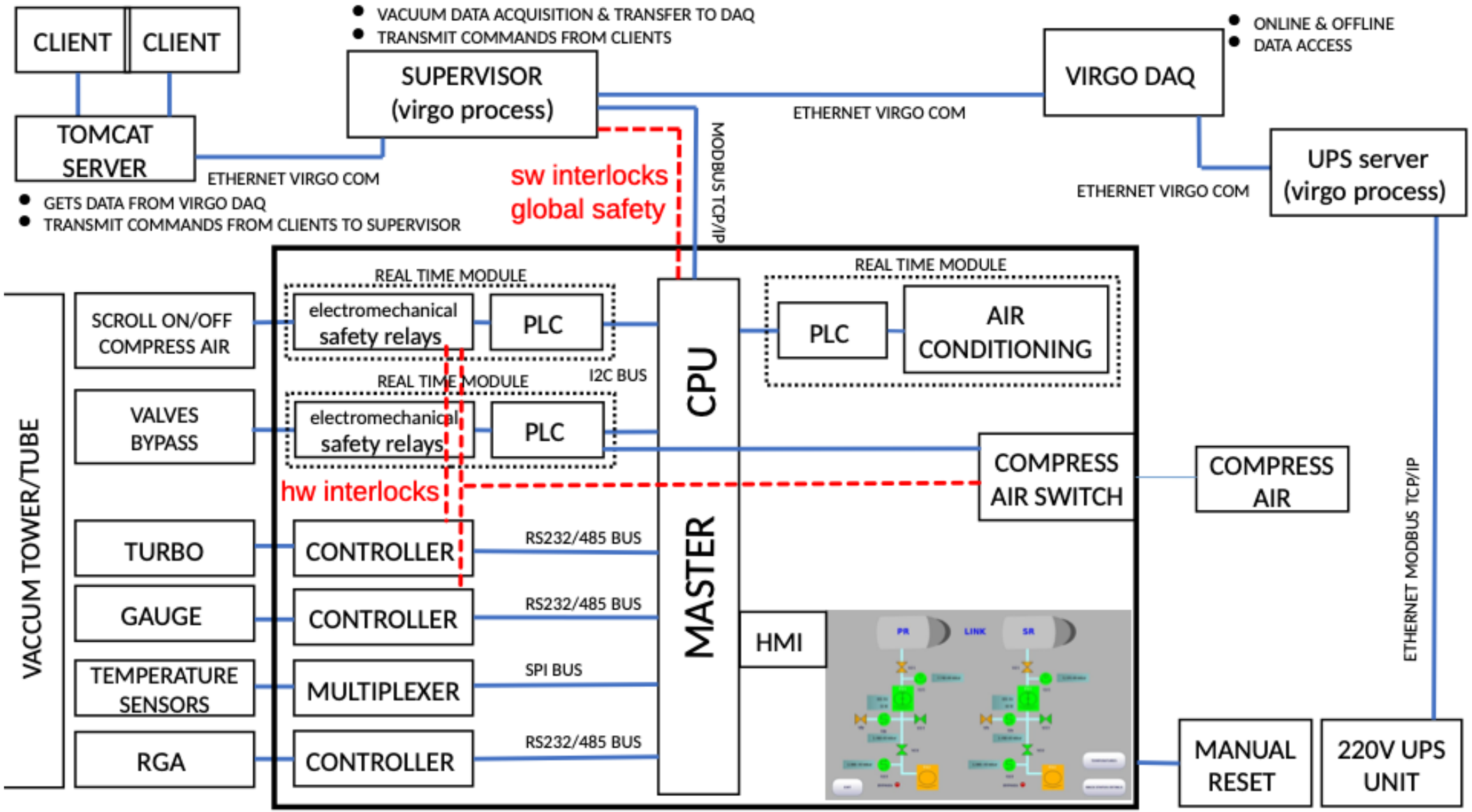
3D view of the CAOS vacuum setup



Primary pumping in a separeted room

Turbo molecolar pumps

CAOS vacuum control system: derivation from Virgo control system



Courtesy: Antonio Pasqualetti & EGO vacuum group

CAOS vacuum control system: modular system

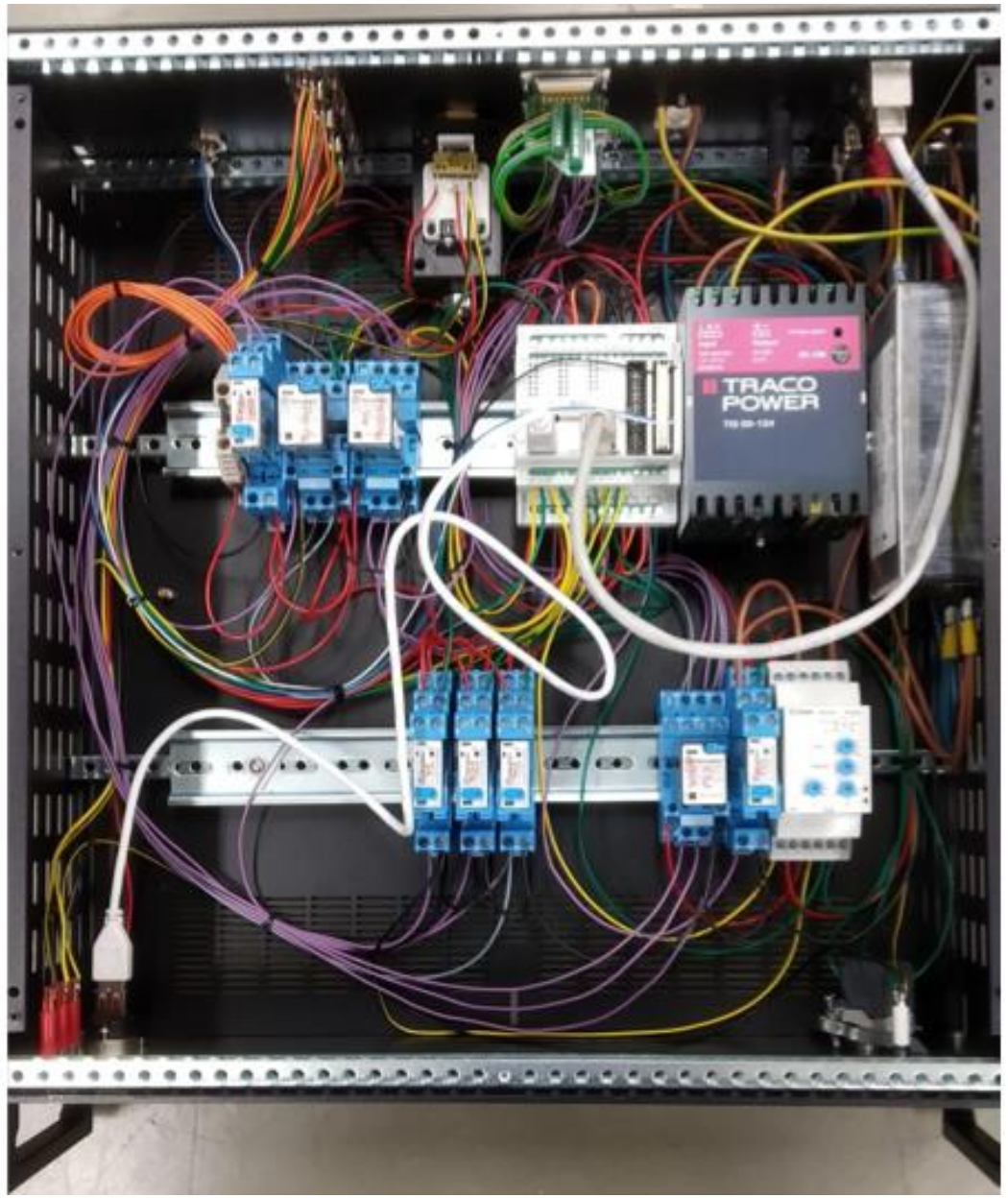
MASTER CPU

- HARDWARE MASTER CPU --> RASPBERRY 3 with OS Raspbian
- OPEN SOURCE SOFTWARE (JAVA)
- MULTI-THREADED LOOPS FOR NON CRITICAL OPERATIONS:
  - COLLECTS DATA FROM AND SENDS COMMANDS TO CONTROLLERS (RS232/RS485 BUS)
  - COLLECTS DATA FROM AND SENDS COMMANDS TO PLC MODULES (I2C BUS using 5V to 3.3V converter)
  - COLLECTS TEMPERATURE SENSOR DATA (SPI BUS)
  - SENDS DATA TO AND OPERATES VACUUM STATION FROM SUPERVISOR (MODBUS TCP/IP)
  - MANAGES HMI DISPLAY FOR LOCAL OPERATIONS

CAOS vacuum control system: modular system

PLC MODULE (STANDARD PUMPING)

- INDUSTRIAL ARDUINO BASED PLC (CONTROLLINO 12/24V))
- PLC SOFTWARE IS OPEN SOURCE (Arduino IDE / C++)
- SINGLE THREAD FOR CRITICAL OPERATIONS:
  - UPDATES ELECTROMECHANICAL RELAY STATUS
  - (24V ANALOG INPUTS)
  - EXECUTES RELAY COMMANDS FROM MASTER CPU
  - (24V DIGITAL OUTPUTS)
  - CHECKS & RESETS CONTROL COMMANDS
- HARDWARE INTERLOCKS (HIGHLY CRITICAL)
  - TURBO/SCROLL/220V POWER/COMPRESS AIR FAILURES
  - PRESSURE GAUGE THRESHOLDS
  - USE SEPARATE ELECTROMECHANICAL RELAYS



CAOS vacuum control system: modular system

We decide to take advantage of the long experience and development done at EGO for Virgo.

- Avoid espensive proprietary solution
- Modular system
- Open source
- Hardware heritage based on decades of Virgo operational experience
- Ratio performace/cost very high
- Low TCO (total cost of ownership)

Tests on NEG in ET relevant environment

In order to avoid to spoil the quite ET environment the usage of quite pumps is advisable

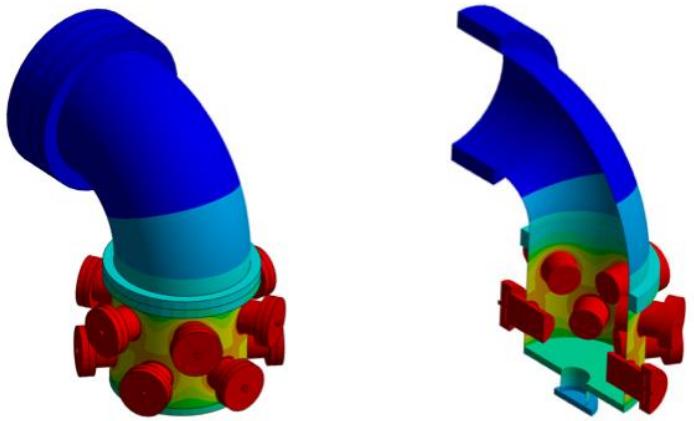
Solution: usage of Non Evaporable Getter (NEG) pumps

PRO

- High pumping speed
- Very compact
- No acoustic noise
- No mechanical vibrations

CON

- Not working for all the gas species
- Working in parallel with small ionic pump or TMP
- Working at high temperature (~ 200 deg)



The activity come from an EGO original idea

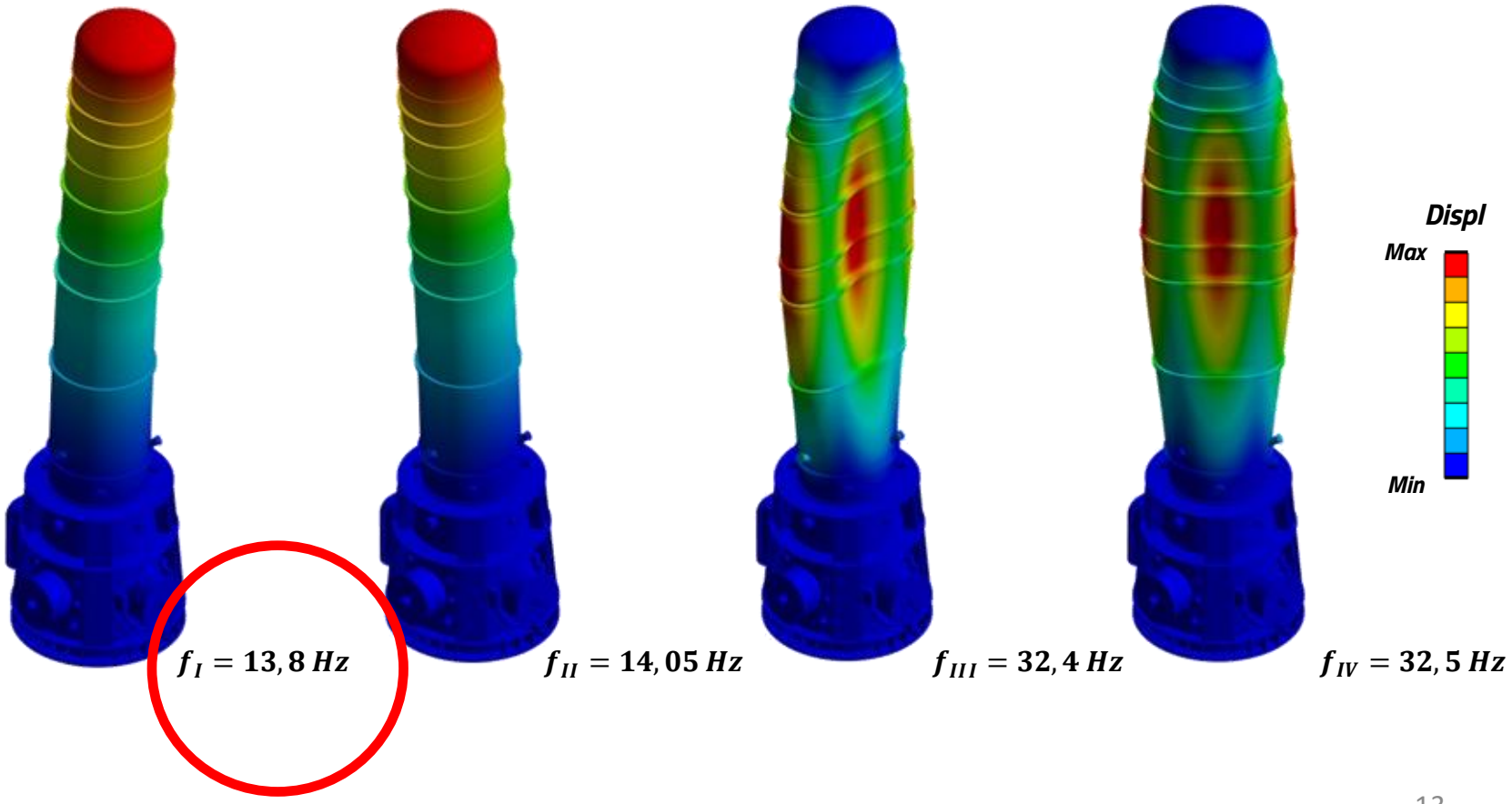
Thermal simulation of NEG pumps for AdVirgo O5.

CAOS vacuum Towers: FEM

FEM Simulations – Modal Analysis

Extensive use of Finite Element (FE) analisys during tower design.
The goal was to *increase the stiffness* of the towers to raise the resonance frequency of the first natural mode.

A *pre-stressed* modal analysis has been done.
Several iterations to optimize shape, material thickness, flanges distribution .....



CAOS vacuum Towers: FEM

FEM Simulations – Modal Analysis

Future work

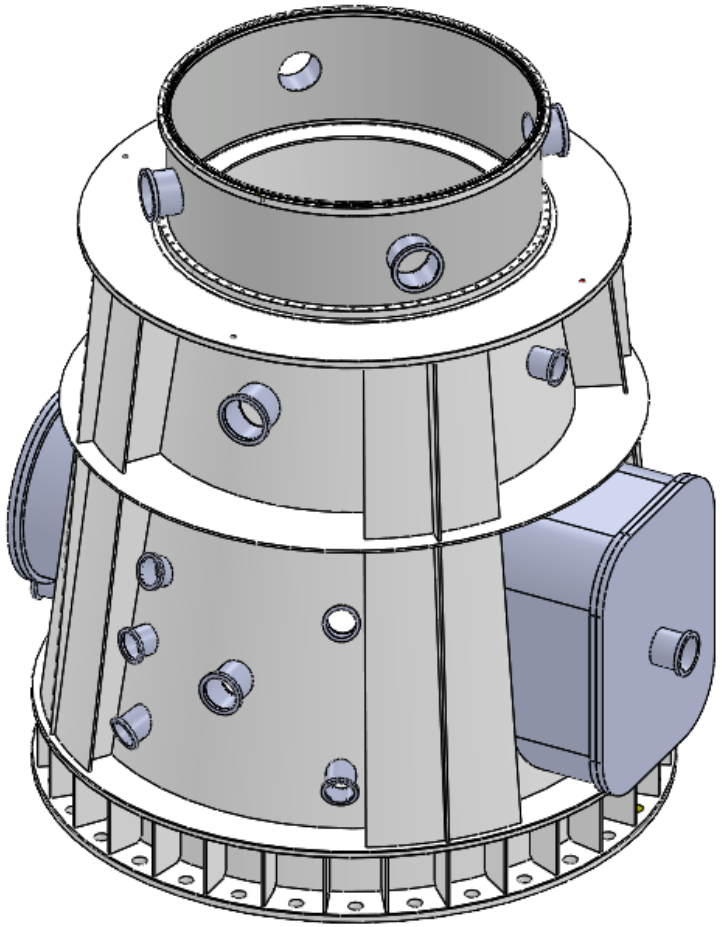
We plan to verify the simulations against a detailed measurements campain

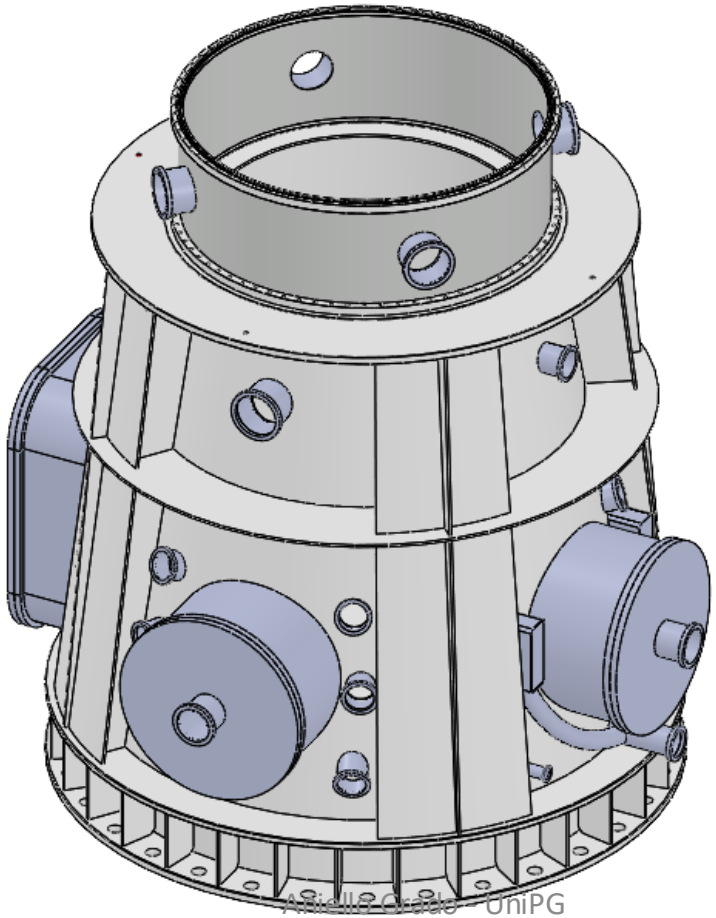
We plan to include in the FEM simulation a realistic model of all the interfaces.

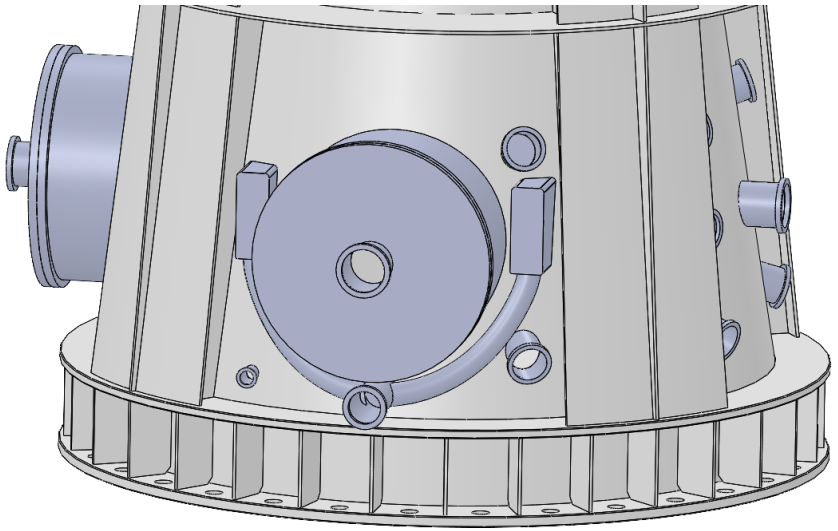
GOAL: to setup a realistic and validated simulation tool for the ET towers design

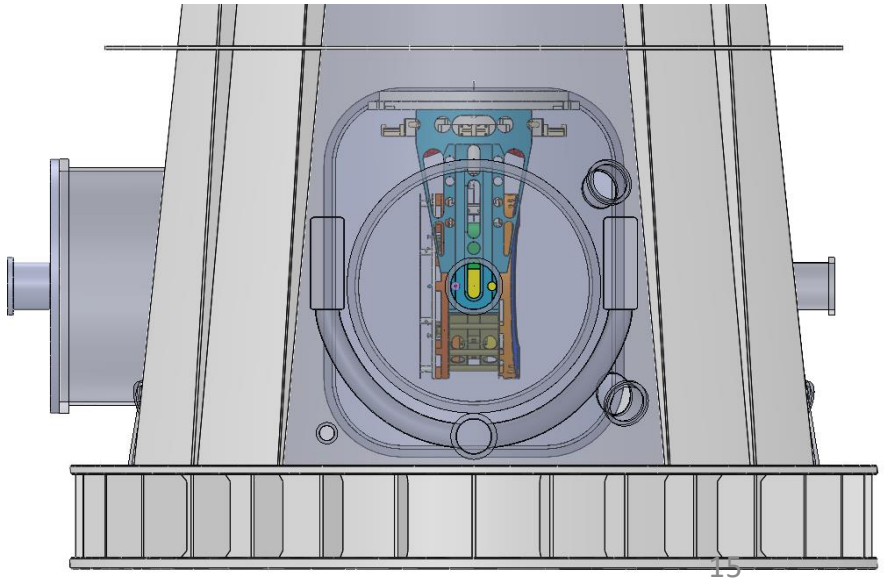
CAOS towers: viewports

In CAOS towers we added a redundant number of viewports for mirrors local control (we want to test the best configuration).









CAOS towers: mirrors dust contamination

During assembly or maintenance the mirror is exposed to dust contamination

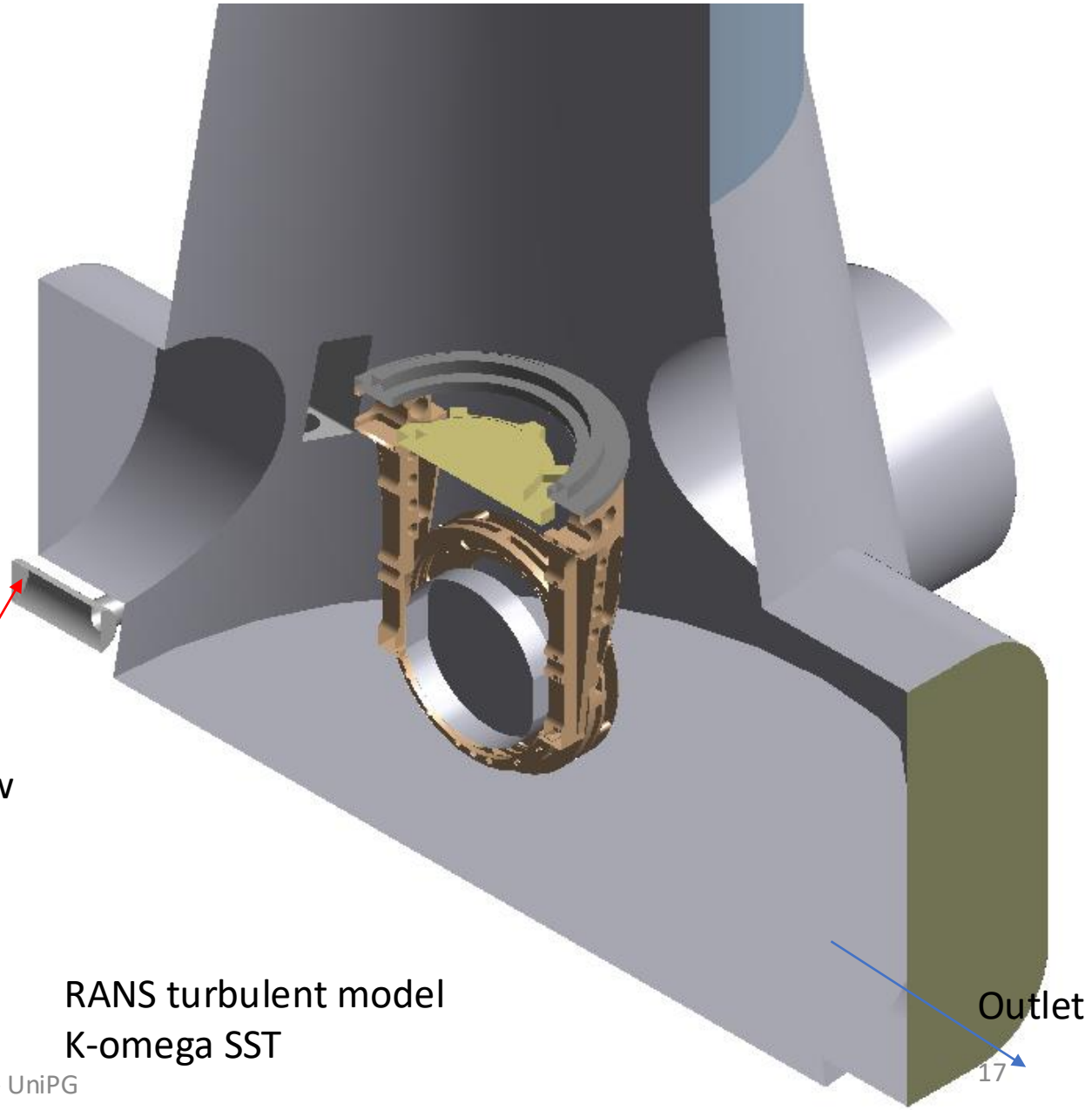
We consider an air flux parallel to the mirror surface that contains dust particles.
The possible forces between dust and mirror are:

- **Gravitational force**
- **Electrostatic force**
- **Van der Waals force**

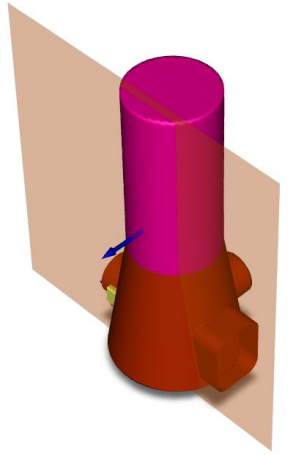
Using CFD we studied the speed of a 1 micro diameter dust particle such that the drag force is > of the actraction forces mirror-dust.
At 0.1 micron distance an air speed of 5m/s is enough to avoid contamination

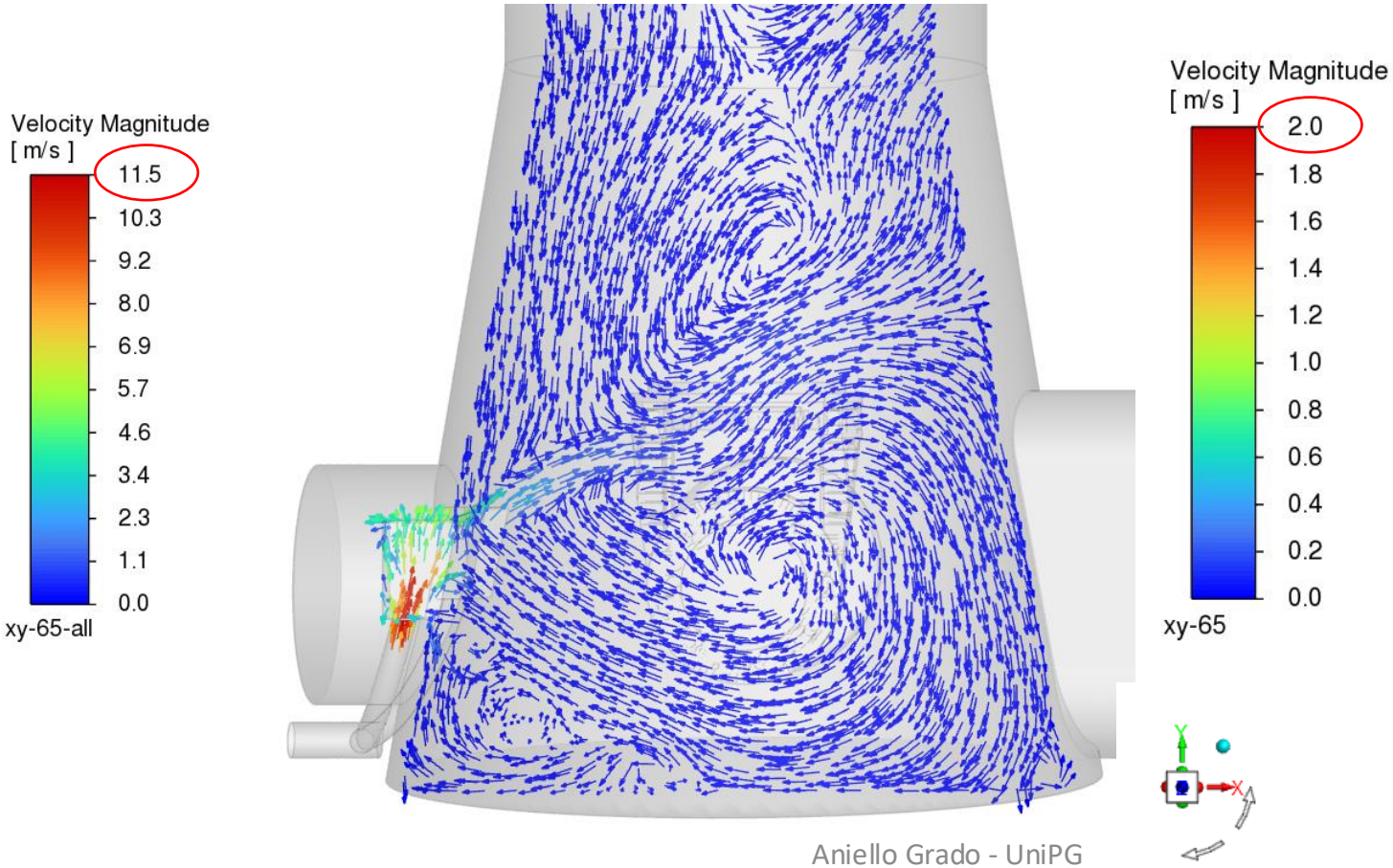
CAOS towers: air inlet

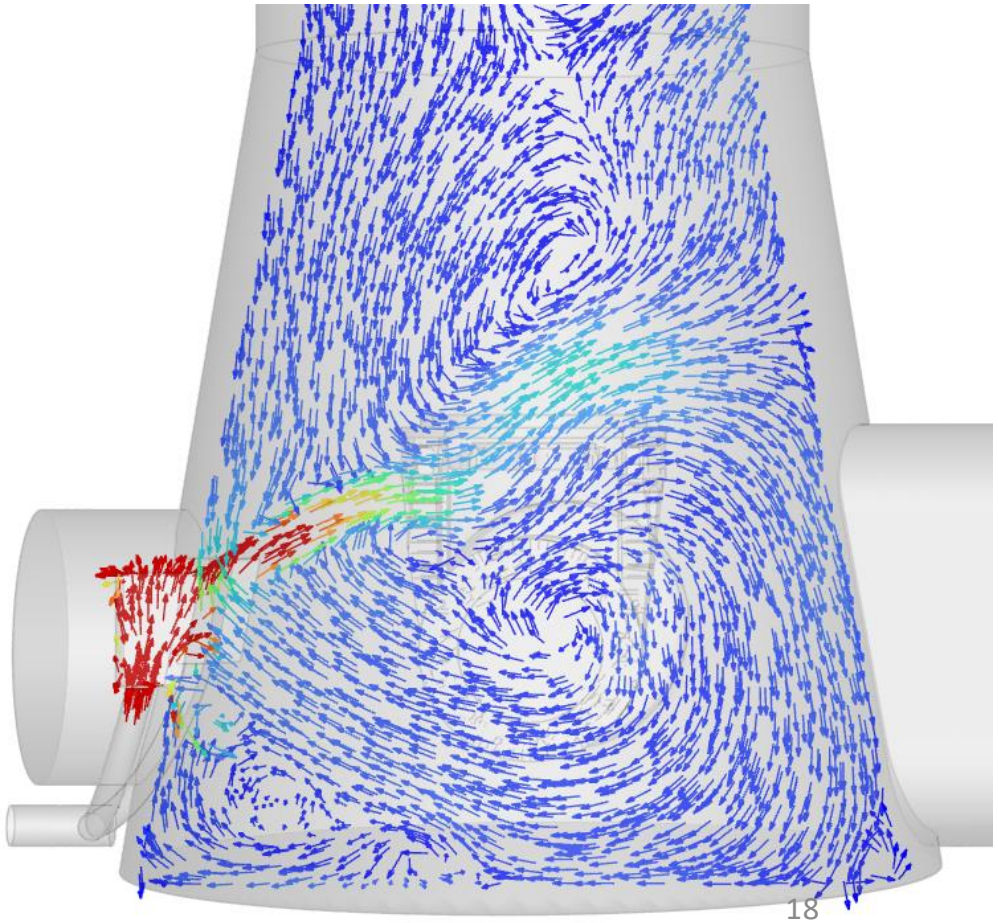
The lateral entrance and the increased number of viewports, forced us to modify the air inlet configuration.
CFD simulation to optimize
Air inlet position, size and inlet air speed



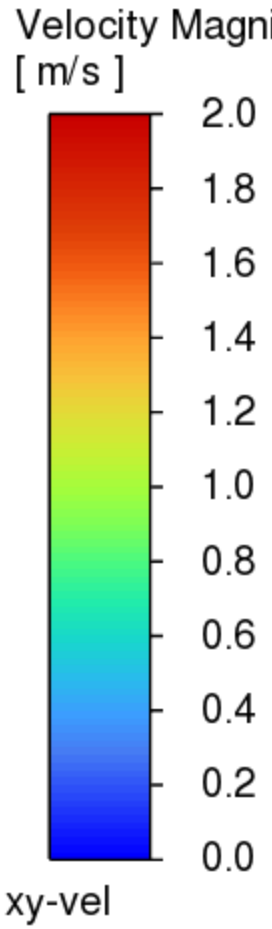
Velocity field

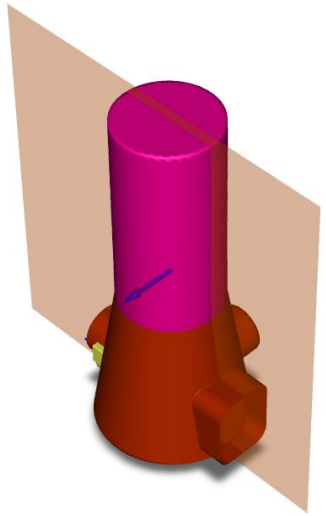


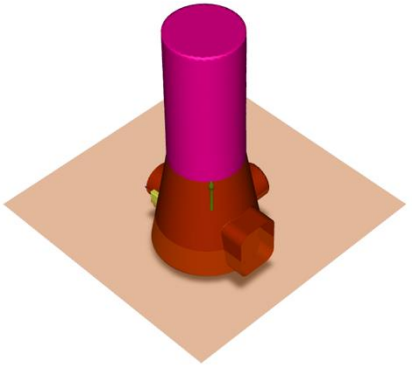


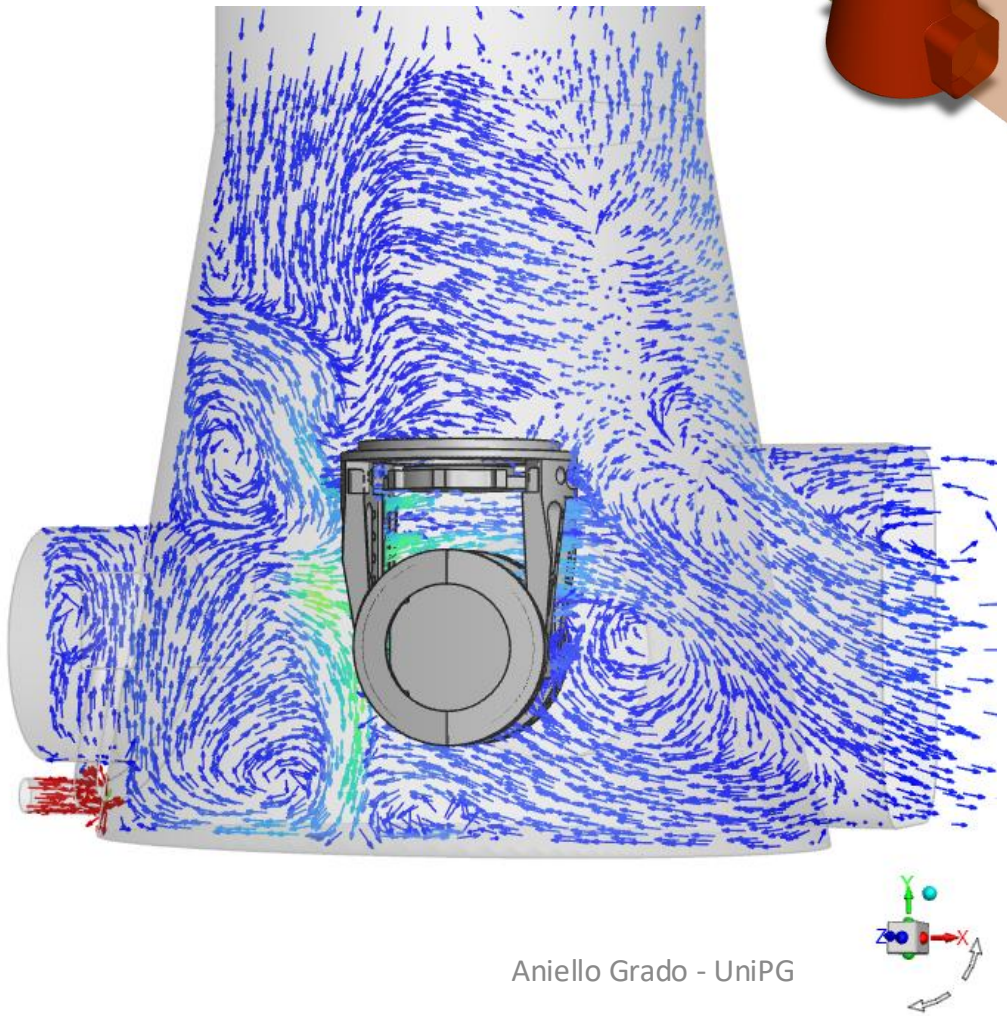


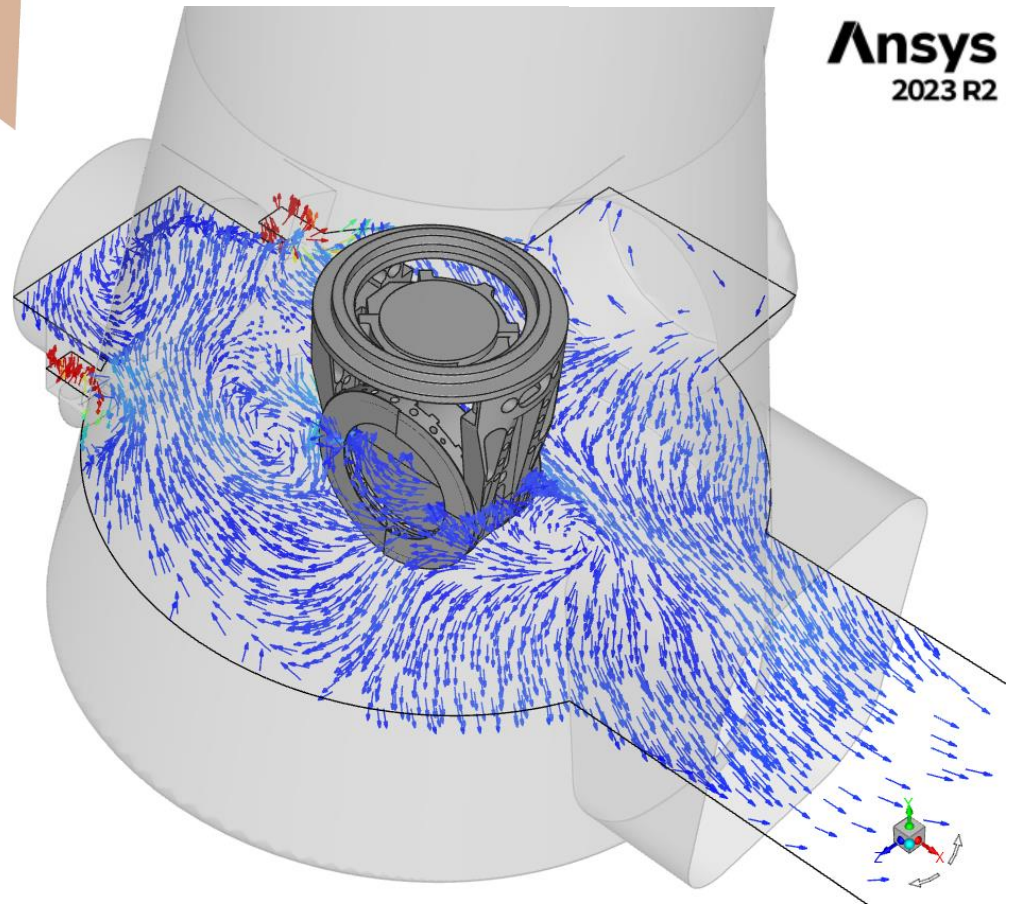
Velocity fields



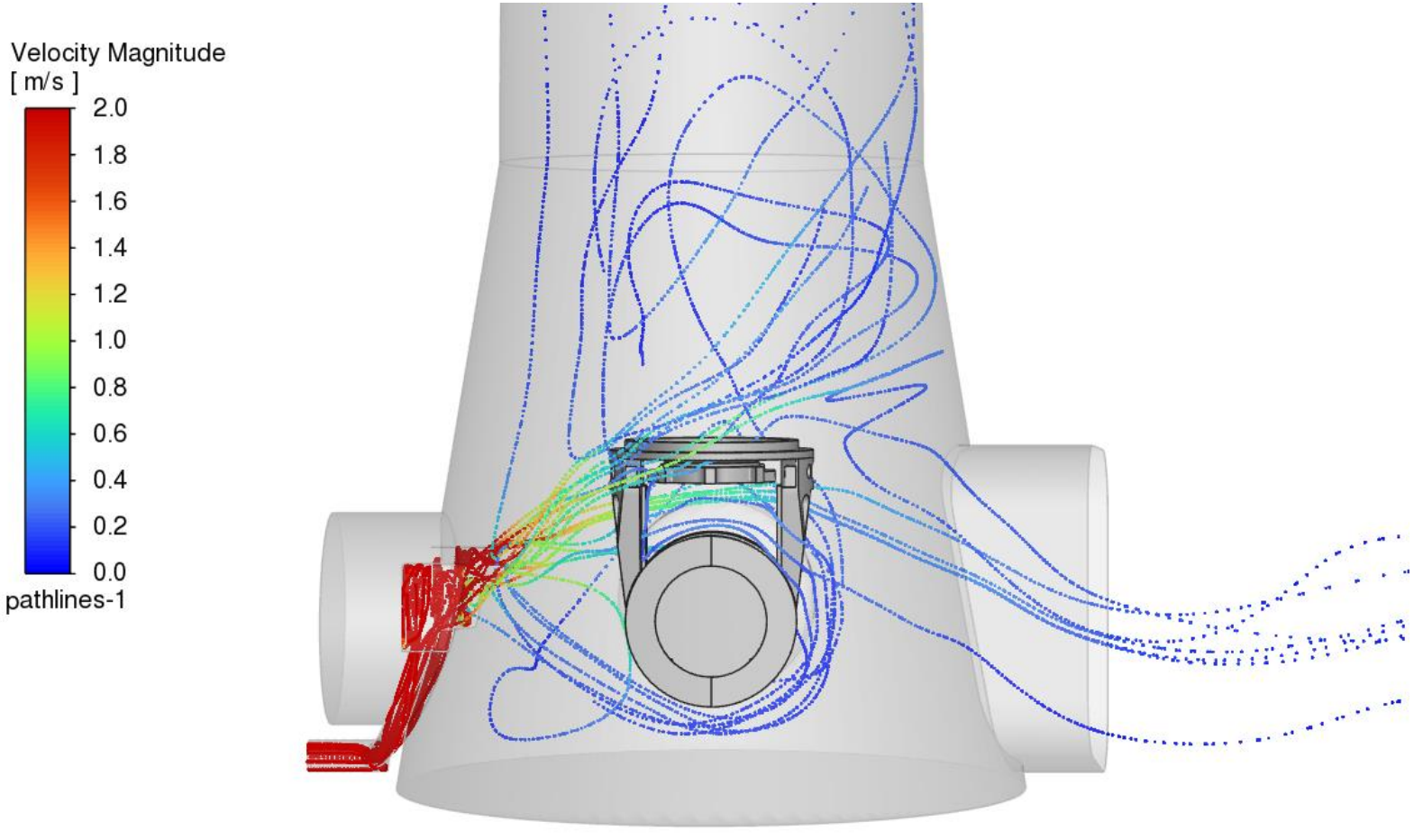


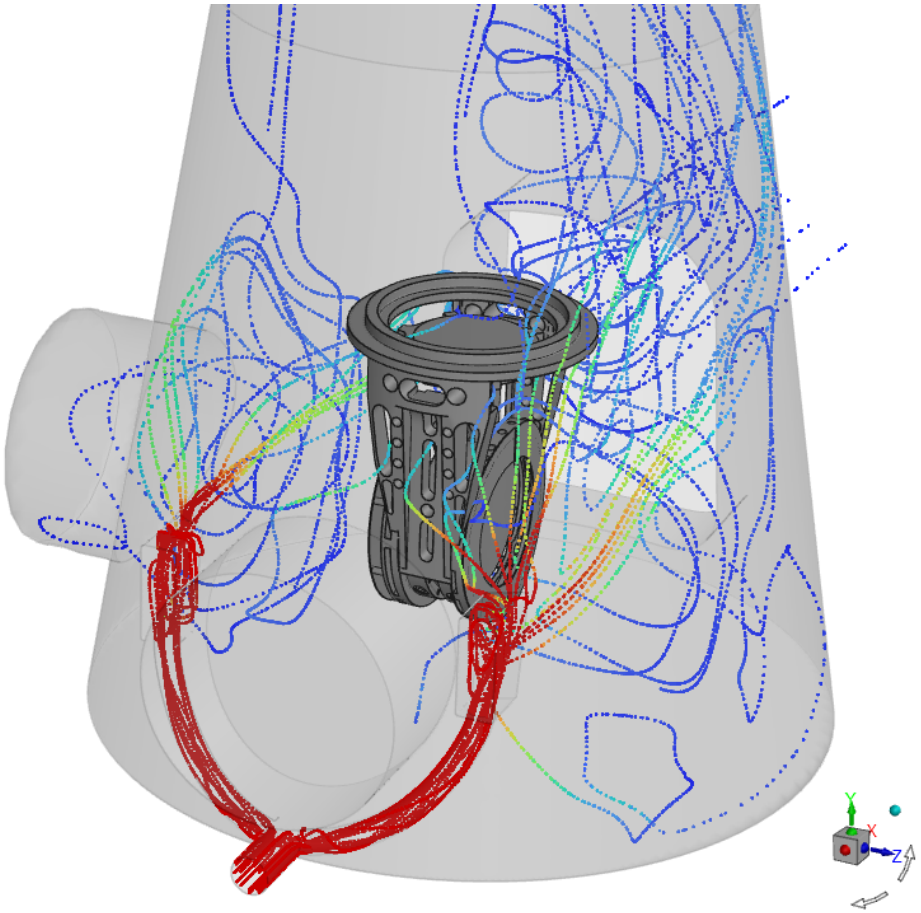






Pathlines

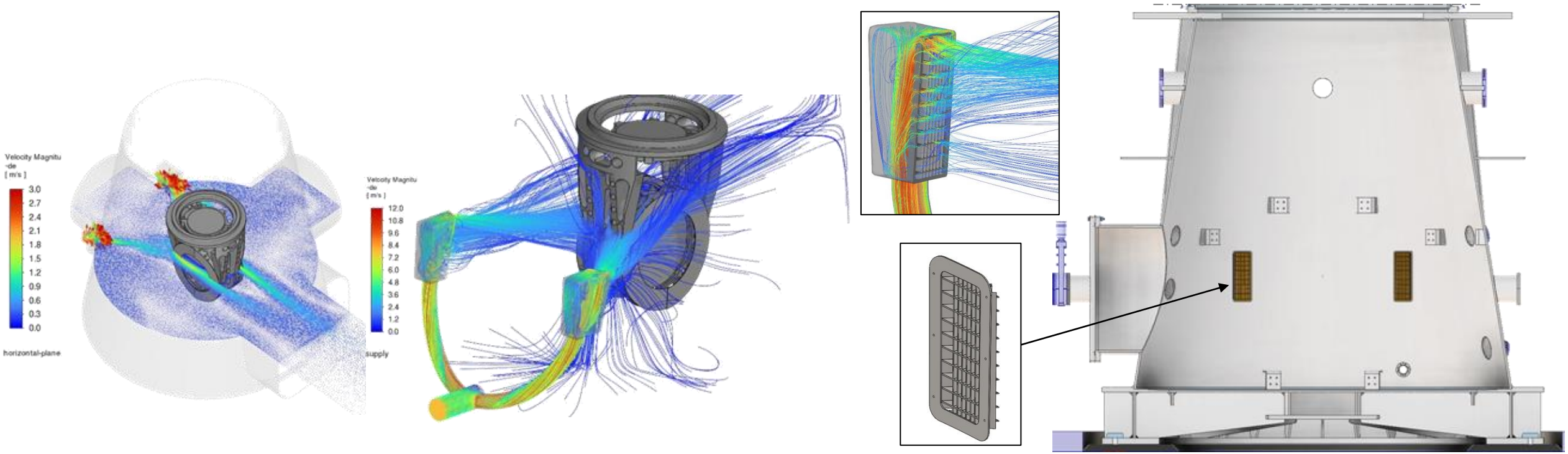

Velocity Magnitude
[m/s]
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
pathlines-1



CAOS: air inlet

CFD Simulations

A lot of work has been done taking advantage of CFD simulations to develop an aeration system that provides an air blade around the mirror to limit the deposition of contaminants during maintenance.



First base tower delivered on 03/04/2026

THANKS

Thanks to all the colleagues involved in the project

Giovanni Ambrosi - INFN-PG
Francesco Bianchi – INFN-PG
Marco Bizzarri – Unipg
Monique Bossi – INFN PG
Gabriele Capoccia – INFN-PG
Carlo Fabozzi – EGO
Luca Francescon – EGO
Franco Frasconi – INFN-PI
Antonio Iannuzzo – INFN-LNG
Ettore Majorana – Uni Sapienza
Andrea Paoli - EGO
Antonio Pasqualetti - EGO
Michele Punturo – INFN-PG
Riccardo Romboli - EGO
Daniel Sentenac – EGO
Alessio Stollo - UniPG
Helios Vocca - UNIPG

The acoustic noise

The vacuum towers have also the function of isolating the mirrors from acoustic noise.

Acoustic noise can become a significant issue for the Einstein Telescope because mechanical resonances excited by acoustic noise may couple to the detector and affect its sensitivity.

CAOS represents an ***ideal test bed*** to study this problem well in advance.

We can investigate both passive and active solutions to mitigate, or potentially completely solve, these issues and experimentally validate them at CAOS in a relevant ET-like environment.