Overview of the Virgo Upgrade Project

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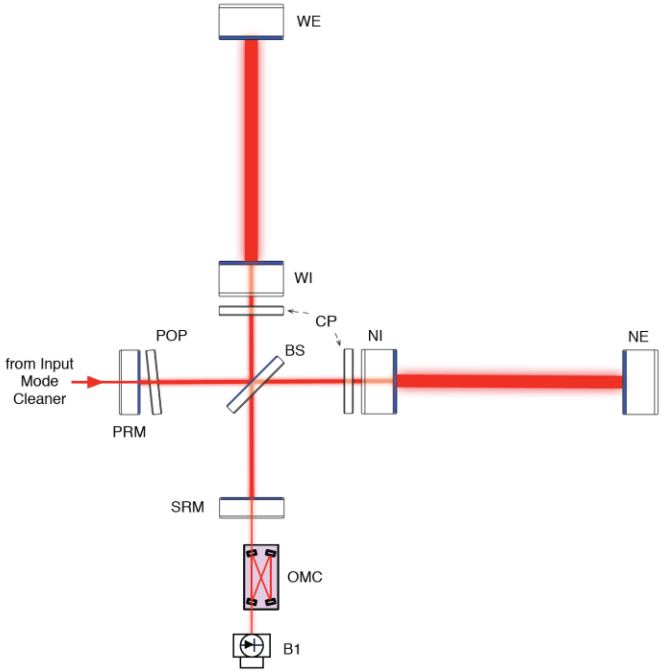
Virgo Upgrade Coordinator

Introduction

- A major upgrade of the Virgo detector since the Advanced Virgo project
  - Installation of Short Stable Cavities
  - Installation of several updates coming from O4 commissioning experience
  - Installation of some upgrades from the previous AdV+ Phase II project

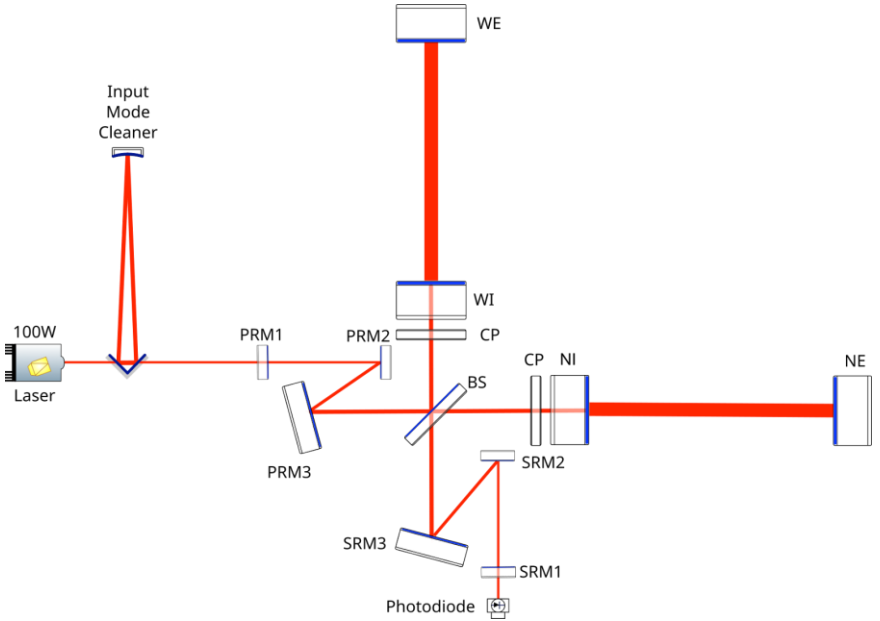
Stable recycling Cavities (SCs)



- AdV project funded and built with marginally stable recycling cavities
- Things worked «fine» as long as the ITF was only power recycled (untill end of O3)
- Addition of SRC (AdV+ Phase I project) made O4 commissioning very hard
  - Pollution of longitudinal and angular error signals from higher order optical modes
  - Unclear figures of merit for tuning the adaptive optics system
  - ***Noise limiting the O4 sensitivity carried by higher order optical modes***

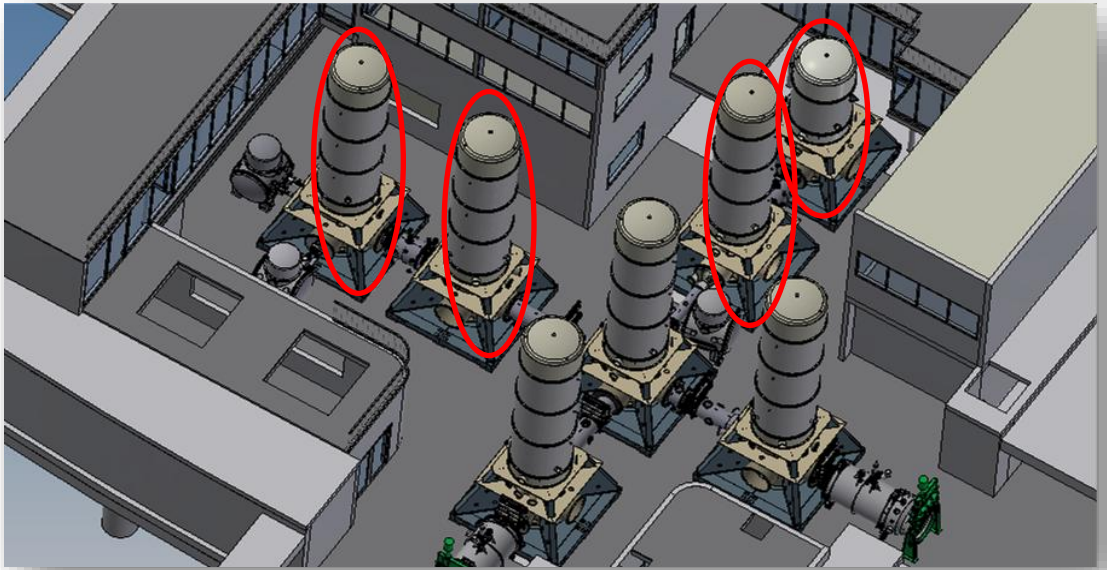
SCs Optical Design

- Designs based around solutions that allow for ~20deg Gouy phase
- Similar design already successfully implemented in LIGO and KAGRA (and planned for ET/CE)
- Stable cavities will filter out the higher order optical modes, reducing the impact of the noise they carry by more than a factor of ten



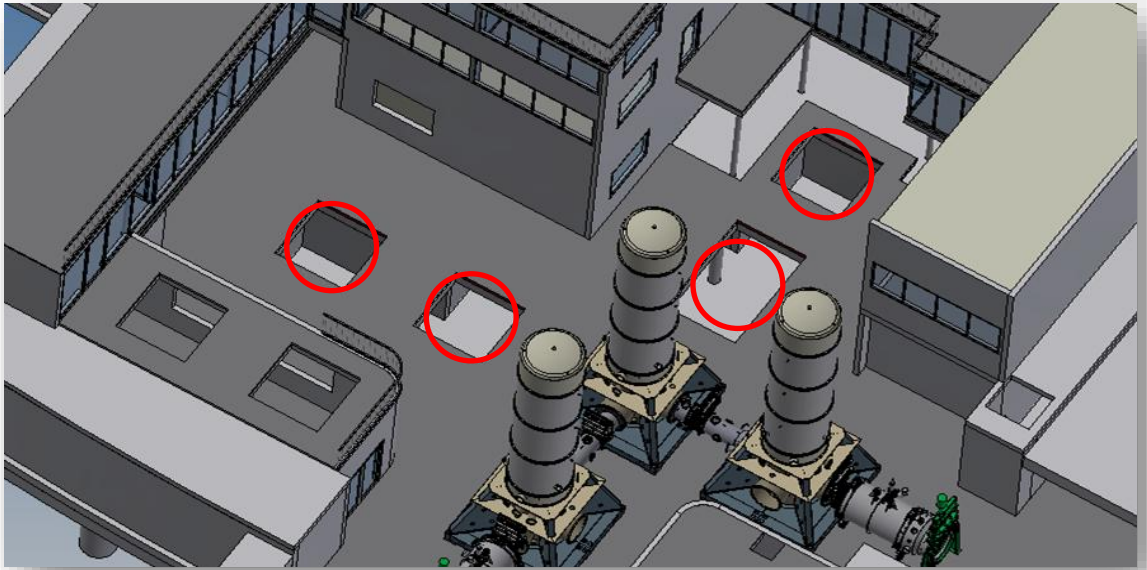
Implementing SCs

- Current central building vacuum system incompatible with SCs optical layout
- 4 towers (including their vacuum equipment, suspension and electronics, optics and benches) need to be removed



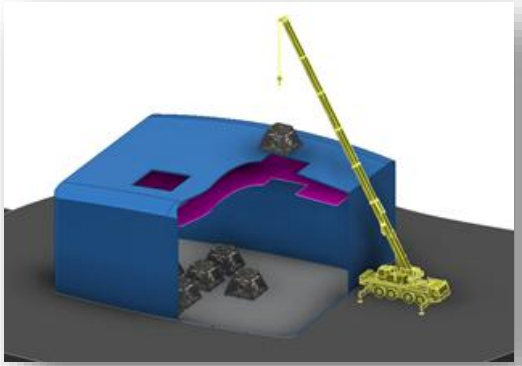
Implementing SCs

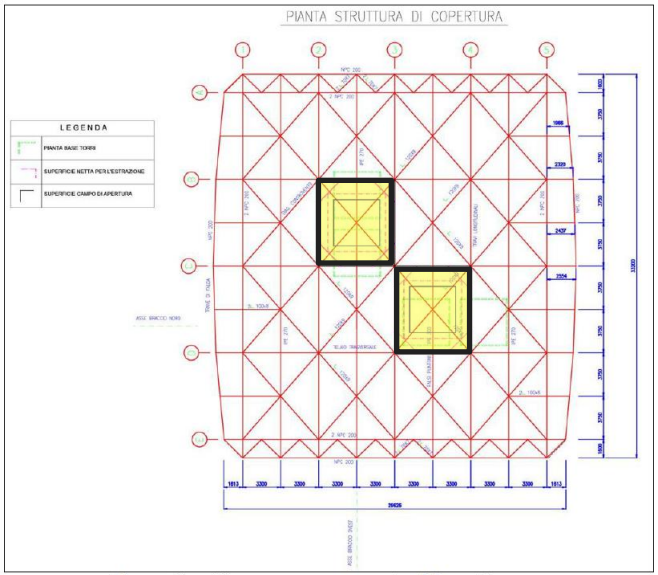
- Current central building vacuum system incompatible with SCs optical layout
- 4 towers (including their vacuum equipment) need to be removed
- Holes connecting to the undeground clean rooms have to be closed



Old towers removal

- The four towers will be extracted from the roof
  - Significant dismantling work is foreseen, involving the injection, detection and squeezing labs
  - De-commissionig of four superattenuators with related electronics and cabling
- Preliminary design of the infrastructural intervention is available, together with estimates of the costs, the administrative procedure timeline and the works execution duration

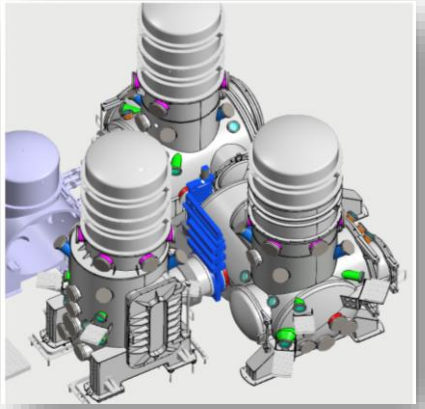


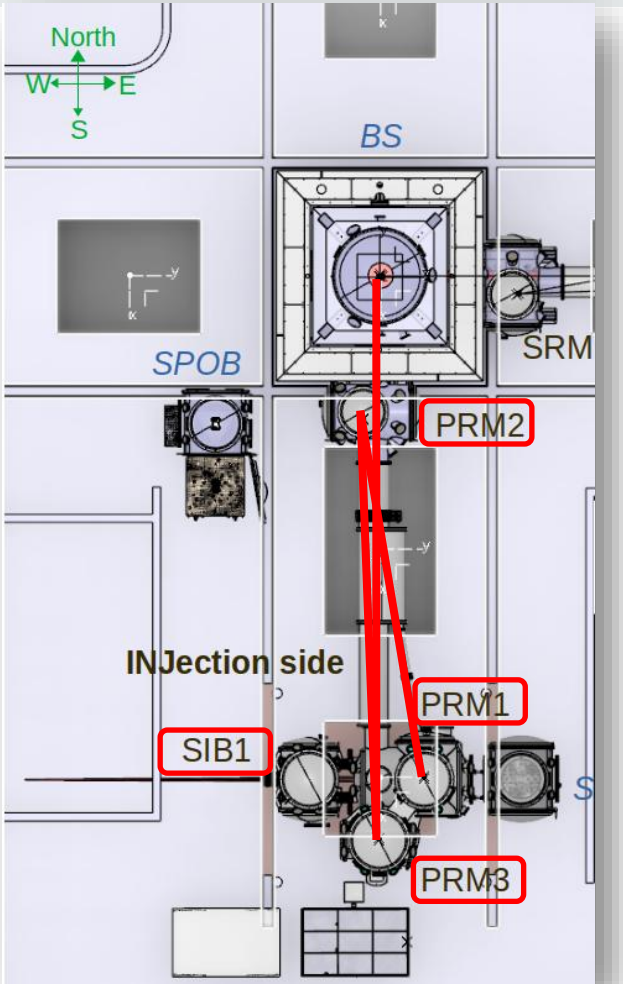


Schema unifilare della copertura con rappresentazione delle aree di intervento

Vacuum system for SCs

- 8 new 'medium-sized' chambers containing the main optics and benches. They will have UHV (ultra-high vacuum) features.
- The design of the new chambers is finalized, serving as input for the new suspension system and the optical benches





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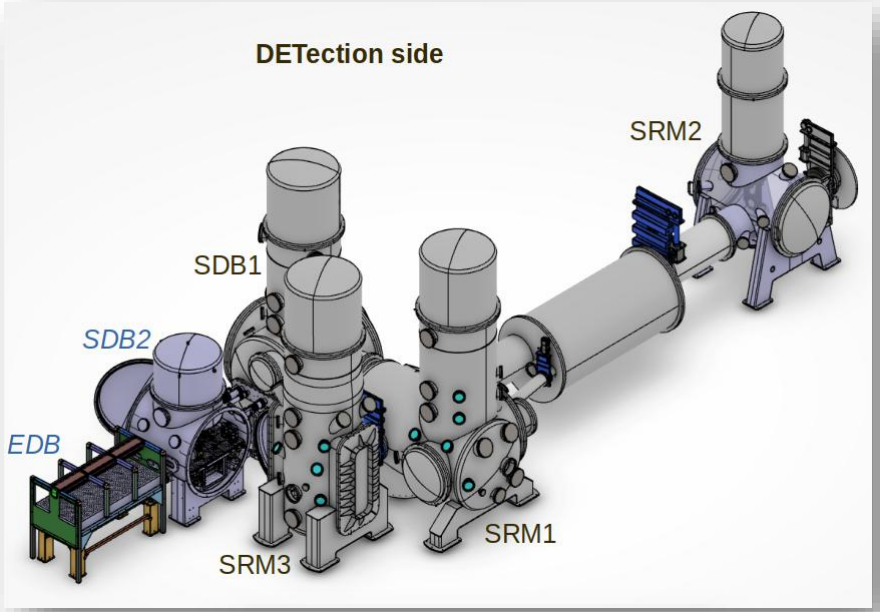
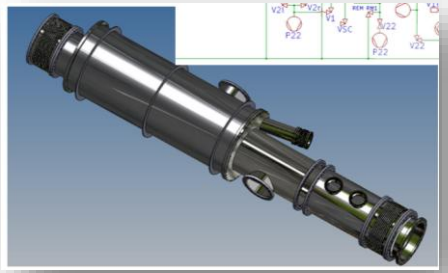
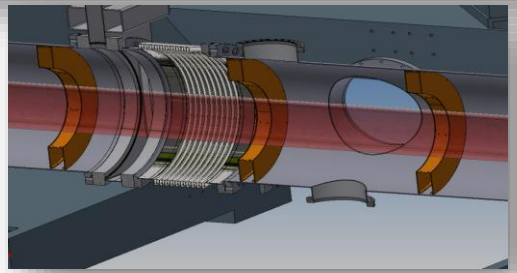
- The design of the new chambers is finalized, serving as input for the new suspension system and the optical benches
- EGO and LAPP-Annecy leading the effort

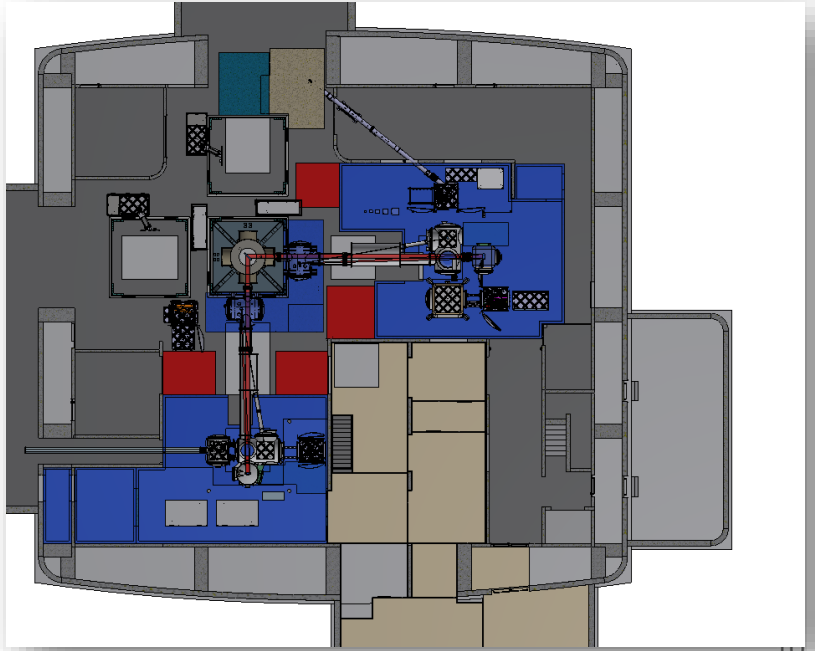






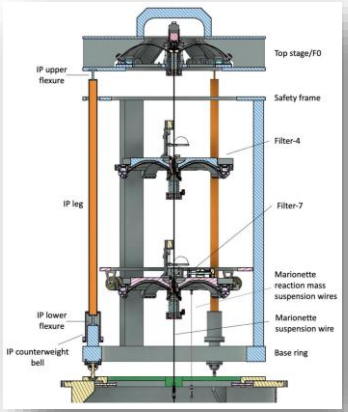
New clean rooms for inj/det Labs

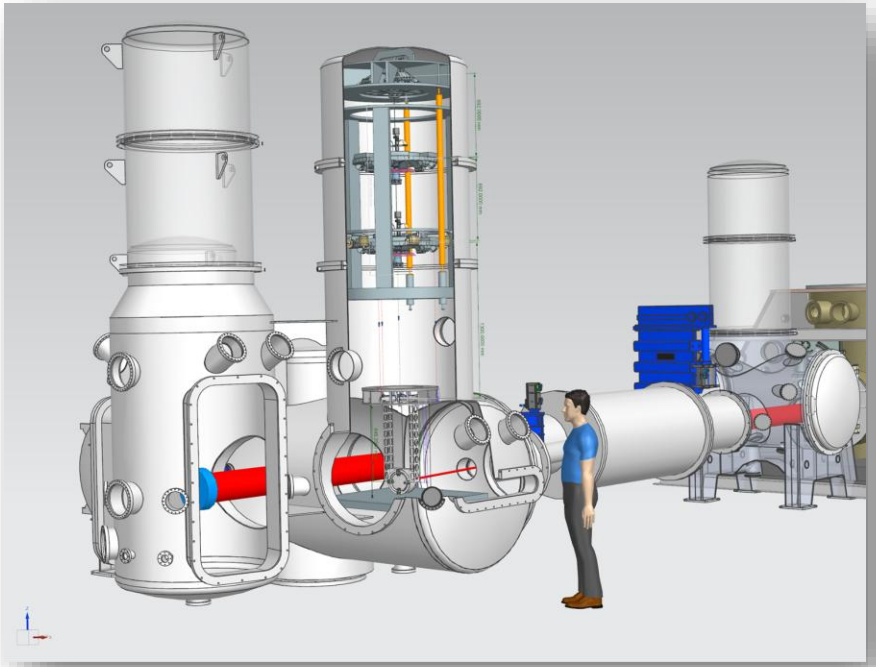
- Re-build and increase the INJ/DET clean rooms
- Upgrade of cleanliness level to allow for safe installation of in-vacuum optics and payloads
- New HVAC with improved noise performances
- Re-cable for signals and power distribution
- Major work in the O5 upgrade, both in terms of budget and schedule
- Preliminary estimates of the costs, the administrative procedure timeline (to be managed by INFN) and the works execution duration are available



Suspension system for SCs optics/benches

- 8 new suspension systems needed for SCs mirrors/benches
- Based on the ETPathfinder/AdV Multi-SAS technology concept



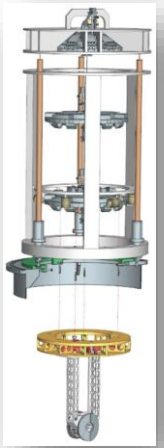


Suspension system for SCs optics/benches

- Identical upper part for all suspensions
- Lower suspension «customized» on mirror/bench
- Most innovative and challenging: SR1/SRB and PR1/PRB
- All Virgo groups with expertise in seismic isolation systems (EGO, Florence, Nikhef, Perugia, Pisa and Rome Sapienza) contributing to the activity

SIB1/SDB1

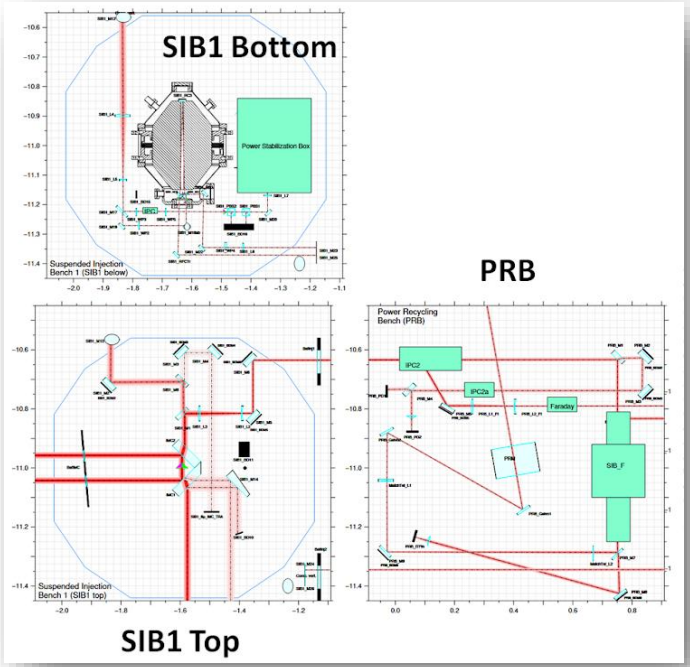
SR1/SRB
PR1/PRB



SR2/PR2

SR3/PR3

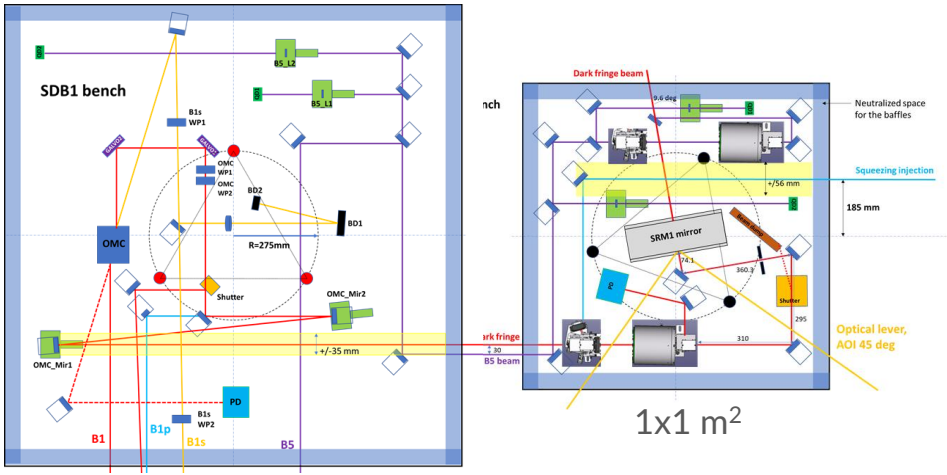
Injection system for SCs



- Bench under vacuum splitted into two:
  - Complete redesign of the in-vacuum part of the injection system
  - Keep the same general scheme with some upgrades
- Reshuffle the in-air part to adapt to the in-vacuum part
- Work ongoing on the finalization of the technical and optical design
- Other upgrades suggested by O4 commissioning include:
  - Pointing actuators towards the ITF
  - IPC upgrade: control injected power during lock acquisition
  - Faraday Isolator magnetic screening
  - New IMC end mirror payload (including a RH)

Detection system for SCs

- Two new suspended detection benches inside new vacuum chambers
  - SRB bench:
    - sharing the same suspension as SR mirror
    - hosting the Output Faraday Isolator
    - optical port for squeezing injection
  - SDB1 bench:
    - hosting the Output Mode Cleaner Cavity



- Other upgrades:
- Photodiodes electronics
- Scattered light mitigation
- Adaptation of the benches to the higher input power (power distribution between sensors and electronic gains)
- New cameras to monitor the beams: replacing obsolete ones
- Picomotor driver multiplexing boards to reduce the suspended benches thermal load and the number of cables along the suspension (particularly for the new benches)

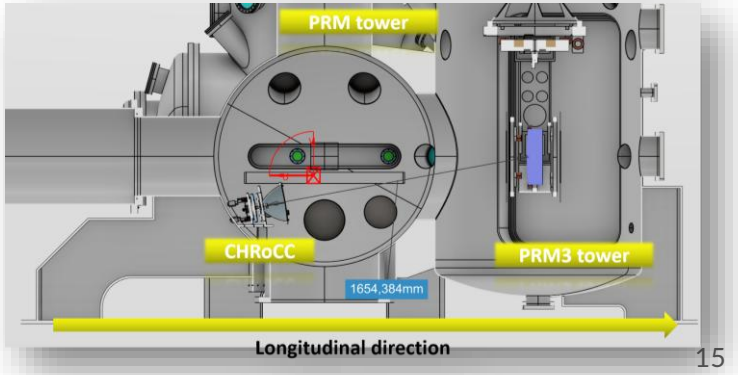
See talk by A. Daumas

Adaptive optics system for SCs

- **Ring Heaters (RH):** decrease of the RoC of PRM3 and SRM3 with a tuning capability of ~0.05%
- Each RH consists of two emitting Pyrex rings enclosed within a polished copper shield.
- Heating is generated by Joule dissipation through a helicoidal winding of NiCr flat wire.

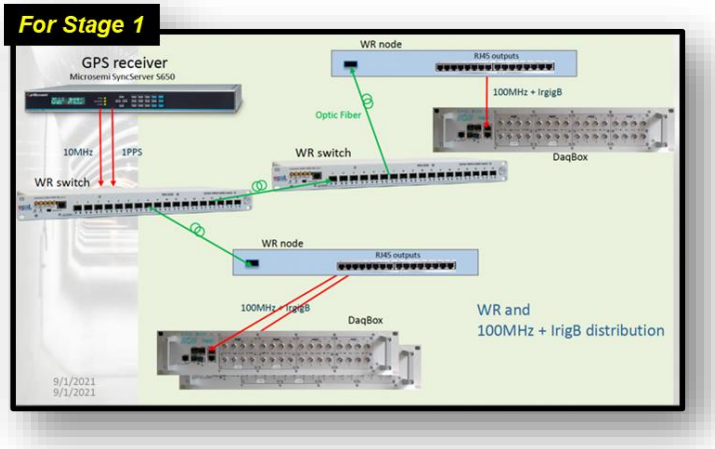
- **Central Heating Radius of Curvature Correction (CHRoCC):** increase of the RoC of PRM3 and SRM3 with a tuning capability of ~0.05%
- It consists of a ceramic heater placed inside a parabolic reflector.

RH installed around the mirror of the filter cavity



DAQ system upgrade

- **Timing distribution upgrade:** use the White Rabbit (WR) protocol developed by CERN to distribute timing in Virgo. The goal for Stage 1 is to replace the aging TDbox-based architecture.



- **Acquisition system upgrade:** produce an upgraded version of the DAQbox with embarked ADC/DAC channels, to reduce the number of different mezzanine to develop and maintain. Also produce a new version of the ADC mezzanine, and also of two other boards

⇒ DBlite will also be able to handle WR optical signal directly, along with the legacy RJ45 signal.

Seismic and infrasound system upgrade

See talk by M. Suchenek

- **Installed sensors in NEB, WEB, CEB buildings:**
  - CEB 85 (55 seismic + 30 infrasound)
  - NEB 38 (30 seismic + 8 infrasound)
  - WEB 56 (30 seismic + 26 infrasound)
  - Total 179 seismic (115) and infrasound (64) sensors

- Upgrade plan
  - Replace seismic and infrasound sensors with new version
  - Upgrade data processing architecture, synchronization
  - for eliminating the 1 Hz noise from synchronization (currently being seen in seismic data)
  - To fully exploit the new seismic sensors, with higher sensitivity of almost 10x and a wider bandwidth

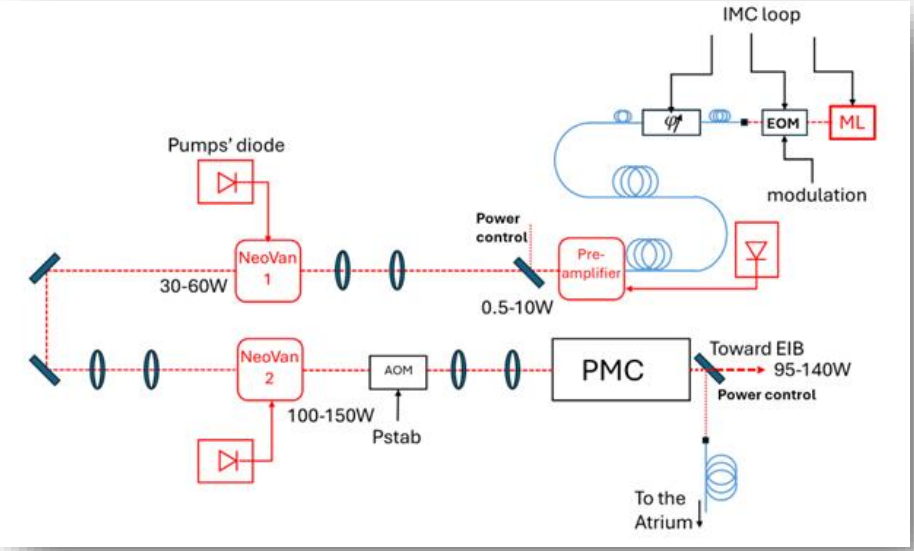
New seismic sensor

New infrasound sensors

Upgrades from O4 commissioning

- Several Subsystems realized the need for upgrades to improve perfomences and/or robustness
  - Injection
  - Detection
  - Auxiliary Laser System
  - Optical levers
  - Frequency Dependent Squeezing
  - **Pre-stabilized laser**
  - **Infrastructures modifications to mitigate environmental noise**

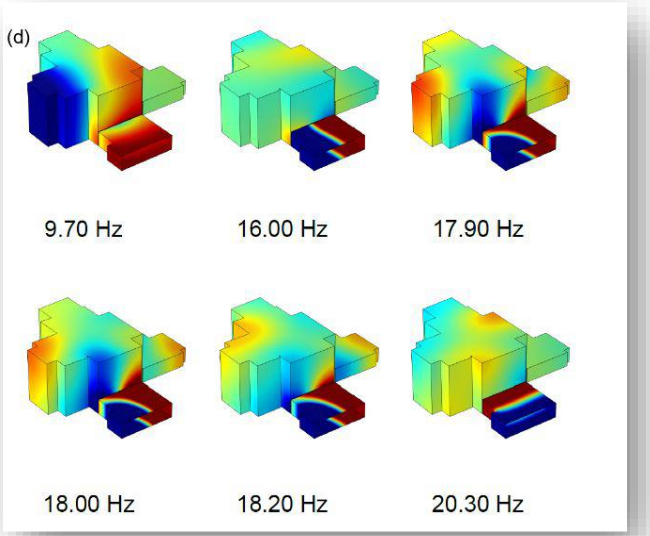
Pre-stabilized Laser



- Fiber amplifier tested during O4 commissioning: excess of high-frequency phase noise observed (lately traced to EOM electornics), limited lifetime
- Based on the LIGO PSL system: 2 solid state amplifiers for a maximum output power of 150W
- Pigtailed EOM for IMC «fast-unlocks» mitigation
- Active suspension of the laser bench: mitigation of seismic and acoustic noise coupling
- New pre-mode cleaner
- New power stabilization system
- Re-engineered electronics

Other infrastructure modifications

- Related to the reduction of plants (HVAC and power distribution) environmental noise
- HVAC terminal buildings water chillers induce a magnetic glitch at startup
- Noise mitigation in the new INJ/DET clean rooms: acoustic, seismic and magnetic
- Mitigation of magnetic noise induces by some UPS
- Terminal buildings air compressors induce a magnetic glitch at startup
- Reduction of acoustic noise at terminal buildings with soundproof racks



Upgrades from AdV+ Phase II project

- Many of the upgrades not connected with the installation of the large ETMs have been kept in the line for O5
  - New Newtonian calibrators and upgrade of photon calibrators
  - **Upgrade of timing distribution system with White Rabbit**
  - Injection/detection benches updates for handling 80 W of input power
  - New Compensation Plate, with flatter transmission map
  - **New seismic and infrasound system**
  - New control electronics for suspension control
  - Instrumented baffles on the arm cavities mirrors → See talk by M. Martinez
  - Upgraded CO2 laser projectors

Core optics management

- New ITMs
  - In operation since 2016
  - Clear evidence for point absorbers; excess of thermal noise
- New ETMs
  - Recent installations of the spares coated in 2018 left the project without **any spare**
  - Clear evidence for point absorbers
- New Beam Splitter
  - Current BS wedge is vertical, rather than horizontal → issue for future (post-O5) Balanced Homodyne Detection installation
  - Spare substrate available
- Due to extended timeline for SCs installation, coating optimization activities will go on for two more years

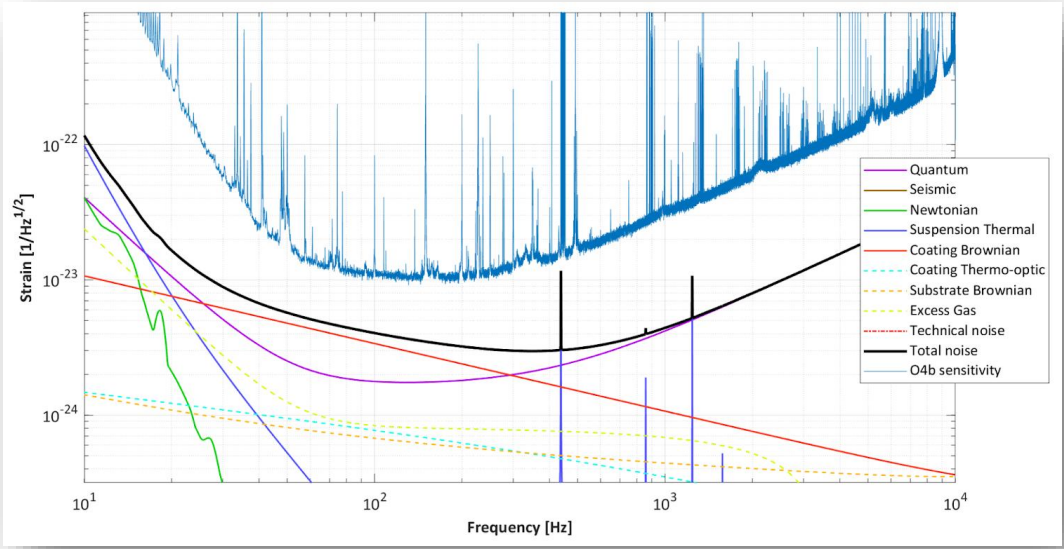
Staged upgrade plan

- Three Project Stages for two installation steps, interleaved by commissioning + possible observing run
- Stage-0 – funding approval March 2026:
  - Preparatory activities for Stable Cavities: infrastructural works administrative procedures, recycling cavities suspensions prototypes, vacuum chambers and mirrors
  - Production of new electronics for suspension control
- Stage-1 – funding approval March 2027:
  - Main target: install stable cavities + replace Input Test Masses and Beam Splitter
  - Input power ≤ 25 W, 3-4 dB of Frequency Dependent Squeezing
  - Sensitivity range: 90-130 Mpc (depends mostly on low frequency noise)
- Stage-2 – funding approval March 2029:
  - Main target: replace End Test Masses, install high-power laser
  - Increase input power ≥ 40 W, 4-6 dB of Frequency Dependent Squeezing
  - Sensitivity range: 120-160 Mpc (depends mostly on low frequency noise and coating thermal noise)

Design configuration and sensitivity

- Maximum achievable sensitivity

Parameter	Value
Recycling cavity	Short Stable
FP cavity power	380 kW
SQZ measured	6.0 dB
Coating	TiO2:GeO2
BNS range	170 Mpc
BBH range	2.0 Gpc

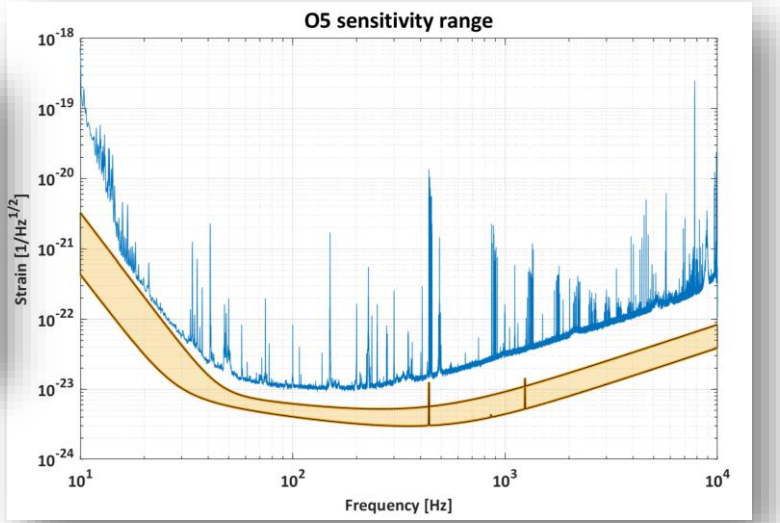


Design configuration and sensitivity

- However, due to the unavoidable uncertainties in the final configuration, more conservative estimates have been made

Parameter	O4b	Stage 1	Stage 2
Power injected	17 W	25 W	40–80 W
Signal recycling	Yes	Yes	Yes
Squeezing type	FIS	FDS	FDS
Squeezing detected level	0 dB [a]	4.5 dB	5.3 dB
Mirror thermal noise @ 100 Hz	$< 6 \times 10^{-24}/\sqrt{\text{Hz}}$ [12]	$4.8 \times 10^{-24}/\sqrt{\text{Hz}}$	$3.4 \times 10^{-24}/\sqrt{\text{Hz}}$
Technical noise @ 20 Hz	$3 \times 10^{-22}/\sqrt{\text{Hz}}$	$(2 \times 10^{-22}$–$2.6 \times 10^{-23})/\sqrt{\text{Hz}}$	$(2 \times 10^{-22}$–$2.6 \times 10^{-23})/\sqrt{\text{Hz}}$
BNS range	55 Mpc	90–130 Mpc	120–160 Mpc

[a] During the commissioning phase in preparation for O4b, the detected squeezing was 2 dB [11]. Following the misalignment of the signal recycling mirror, it dropped to 0 dB.



Strain ASCII files will be available at VIR-0797B-25 (public link)

Conclusions

- Virgo O5 upgrade is a huge enterprise, involving also infrastructural modifications to the Central Building
  - Many Subsystems involved in the installation of stable recycling cavities
  - Several upgrades are «inspired» by the O4 commissioning phase

- This upgrade will boost the Virgo sensitivity, reducing the current gap with LIGO and improving the localization of astrophysical sources and enabling multi-messenger observations together with LIGO and KAGRA