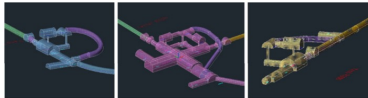


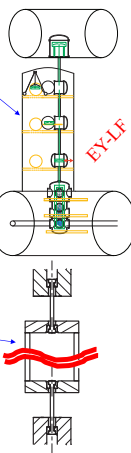
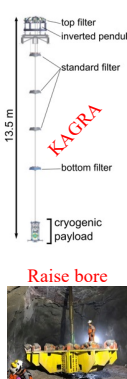
History of double tunnel structure

The KAGRA double tunnel structure was required by the necessity to separate the head of the seismic attenuation chain from the cryostat and declutter the space around the cryostat and test masses.



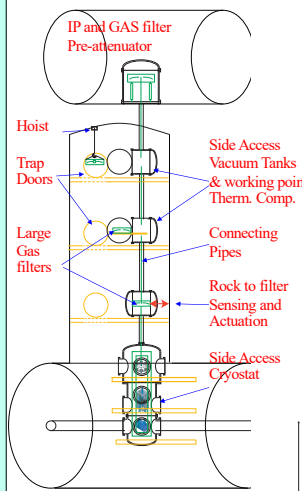
Double tunnel structure advantages, disadvantages and solutions

- Easier and safer side access for test mass, filters and the pre-attenuator
- The cryostat, decluttered of IP structures, is smaller and suspensions can be assembled directly from a clean room in the tunnel
- More stable, less tilt sensitive, short inverted pendulum pre-attenuator
- Longer and lower frequency pendulums
- In KAGRA it was extremely difficult to access, install and tune the standard filters inside a narrow well**
- A wide raise-bore well, with floors and side flange vacuum chambers provides easy and safe access. No need of large cranes.
- The optics positioning can be adjusted by $\pm 1-2$ m within the well
- The yaw frequency was excessively low**
- The long wires suspension are replaced with short ones and long, light tubes, which are rigid in torsion

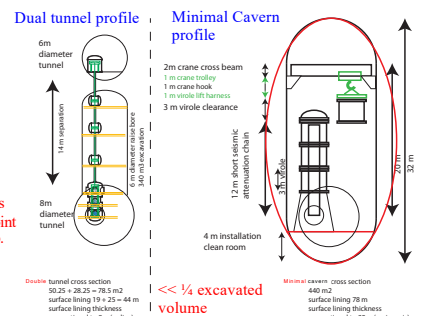


Side access filter assembly

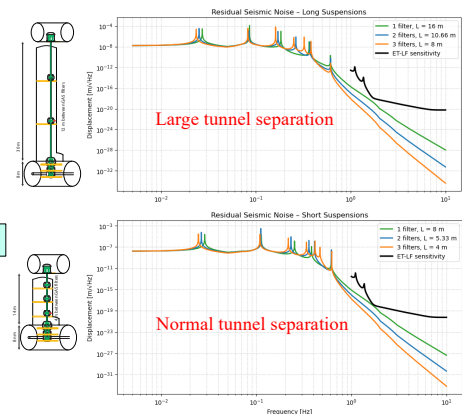
- The GAS filters will be more than 1.5 m in diameter and weight at least 200 kg to support the larger mirrors.
- Floors in the well will allow installation of **side-access vacuum chambers** connected via small diameter vertical tubes
- Individual vacuum tanks kept at the best working point temperature
- a hoist operating through **trap-doors** **replace the large crane**
- Installation and maintenance of the filters will be safe and easy with side access



Both tunnels can fit within the profile of the cavern

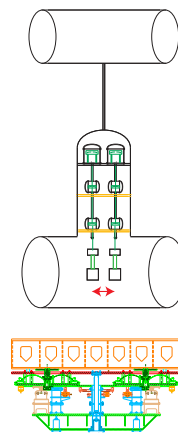


Wider separation between tunnels brings better noise performance practically at no added cost



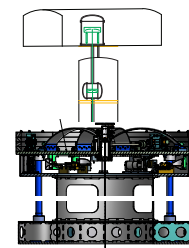
Shorter attenuation chains and positioning flexibility

- Lower requirement optical elements can be housed in inexpensive, shorter raise bore wells
- Still reducing clutter around the beam line
- Allows for meters of positioning freedom for mirrors within the well
- Provide easier access to components
- Lower-weight optical elements can use smaller GAS filters and vacuum tanks
- Optical tables still supported from below



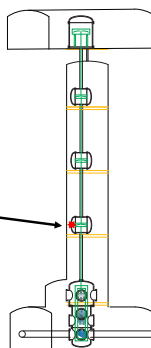
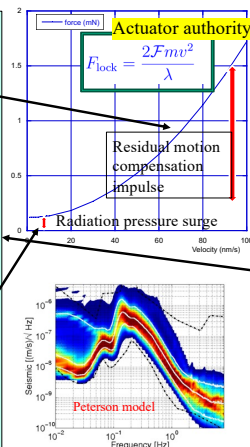
KAGRA-like IP, GAS preattenuators

- Inverted pendulum sitting on rock are much less sensitive to tilt
- IP movement due to seismic tilt motion can be easily compensated with soft actuators



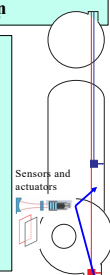
Pendulum mode damping for easier interferometer lock acquisition

- Most of the actuator authority required for interferometer lock comes from the **residual pendulum velocity** of the seismic attenuation chain
- Sensor-actuator feedback between the bottom filter and the nearby rock wall** can damp the velocity to less than 10 nm/s
- Only radiation pressure surge remains
- Lock can be acquired with minimal authority and therefore less actuation noise



Rock Tiltmeter for IP and Newtonian Noise subtraction

- The rock motion can be optically measured against **two different-length pendulums**.
- The pendulum resonances are damped with a very narrow bandwidth feedback to $< 10^{-13}$ m/(s $\sqrt{\text{Hz}}$) ($<$ Peterson's model)
- The differential signal is the rock tilt (for IP drift correction)**
- The average signal is the horizontal motion
- Tilt-subtracted **rock motion measurements** at the end stations and at the escape routes along the beamline **measure the fluctuating rock density** between the mirrors for **Newtonian Noise Subtraction**



Conclusions

- Maintain flexibility & improve the science case
- Important control advantages** deriving from the stability of the rock
- Longer pendulums drive the residual seismic motion out of the picture
- Low-noise seismic motion sensing available for **Newtonian Noise subtraction**
- Safer and easier side-access installation** from intermediate floors
- Decluttered** space around the **cryostat** for better implementation
- Shorter wells and seismic attenuation chains for less demanding optics
- Allows work on an interferometer without affecting performance of the other
- Input/output or quantum squeezing optics housed on separate tunnels
- Two or more times less expensive than the large caverns.**