JENAS

Overview on GW hardware community

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September 22 2020; jo@nikhef.nl

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R. Weiss, F. Ricci, Harald Lück

Contents

Science

Gravity is a fundamental interaction with most important open scientific issues

Strong scientific interest from HEP

Advanced detectors

Quality of GW science is determined by the sensitivity of our observatories

GW and European HEP community

LIGO and Virgo are CERN-recognized experiments

MOU between CERN – INFN – Nikhef on instrumentation for Einstein Telescope

Interactions have started on R&D for vacuum instrumentation

Examples for joint R&D on instrumentation

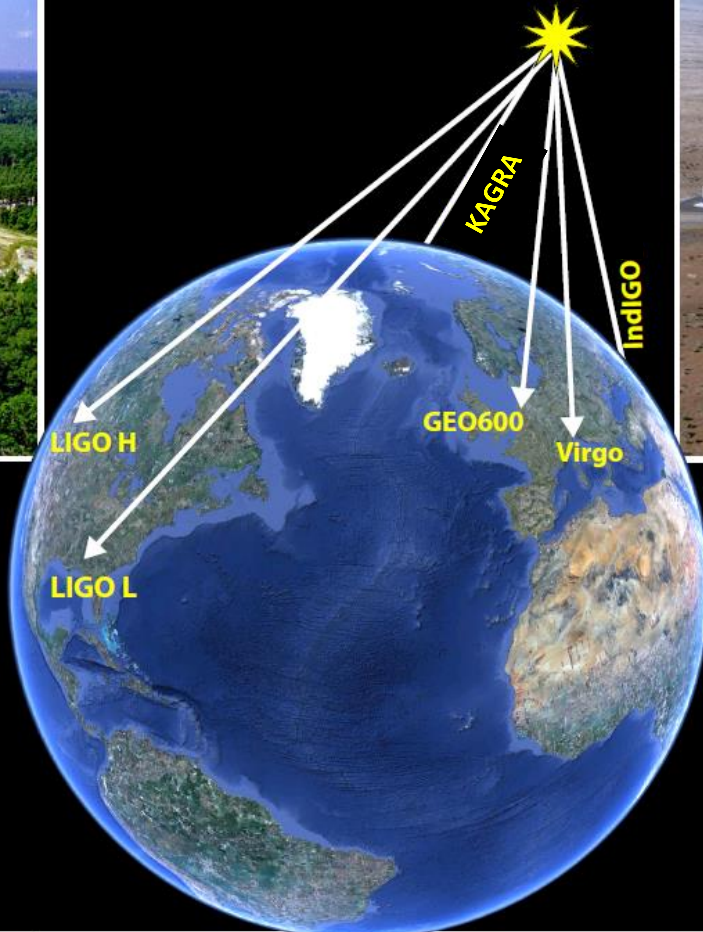
Underground construction

Vacuum beam-tube construction, cleaning & bake out procedure

Cryogenics, controls

Acknowledgments:

1. LIGO-G1900137, Mike Zucker LIGO Caltech & MIT, NSF Workshop on Large UHV Systems for Frontier Scientific Research, LIGO Livingston Observatory, 29-31 January, 2019
2. Workshop report by Fulvio Ricci, Sapienza University of Rome, ET-KAGRA-meeting-Perugia-2019
3. Virgo Vacuum System - 3G detector challenges, C. Bradaschia, A. Buggiani , A. Pasqualetti, D. Sentenac, T. Zelenova, Orosei, May 3, 2019
4. Gravitational wave detector vacuum systems, Harald Lück, Presentation at RWTH-Aachen, June 2019
5. Meeting on ET Vacuum R&D, Amsterdam, September 11, 2020

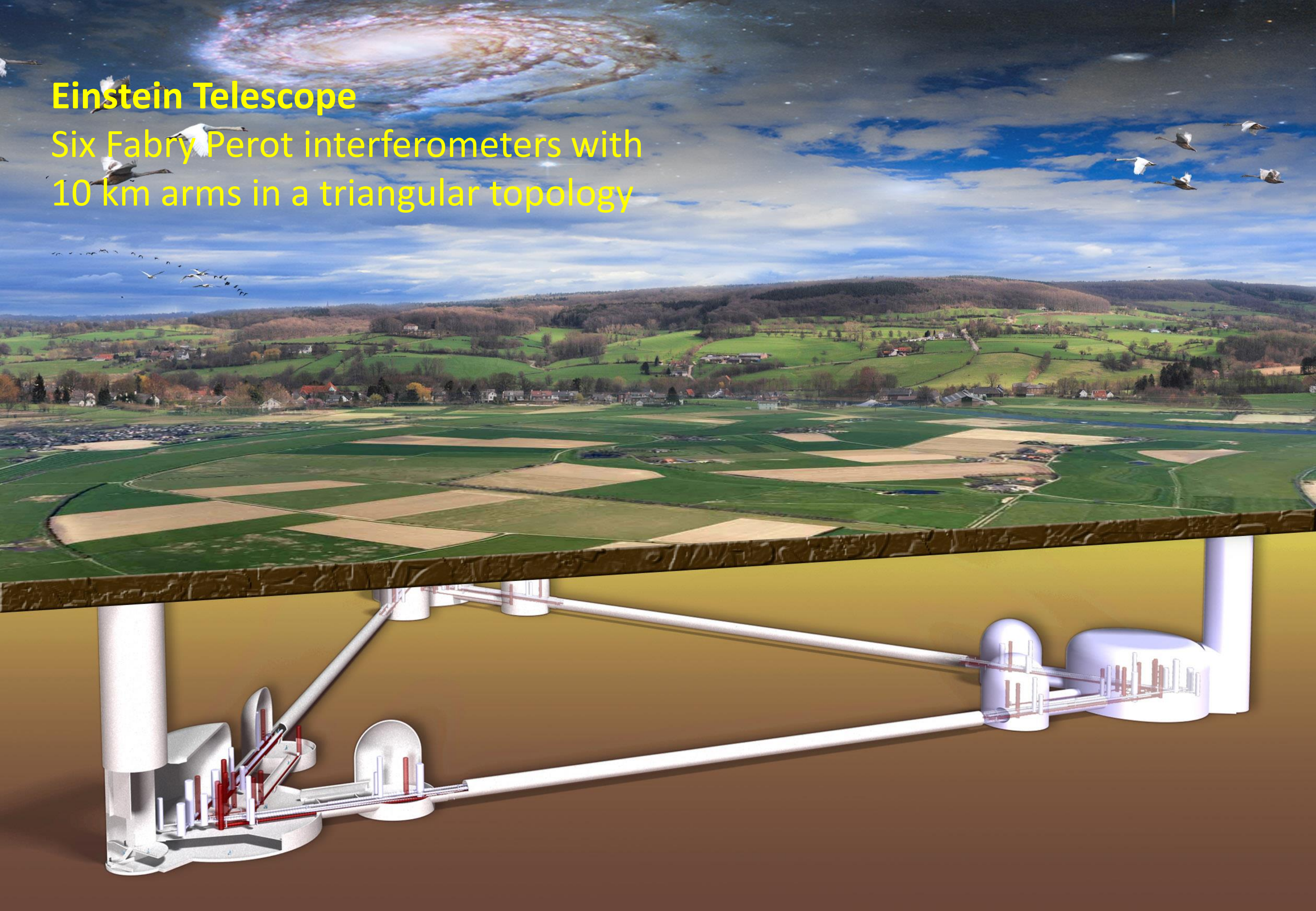


Advanced LIGO and Virgo run simultaneously

Kagra joined in 2020
LIGO India approved


LIGO Livingston, Louisiana

Virgo interferometer


Einstein Telescope
Six Fabry Perot interferometers with
10 km arms in a triangular topology

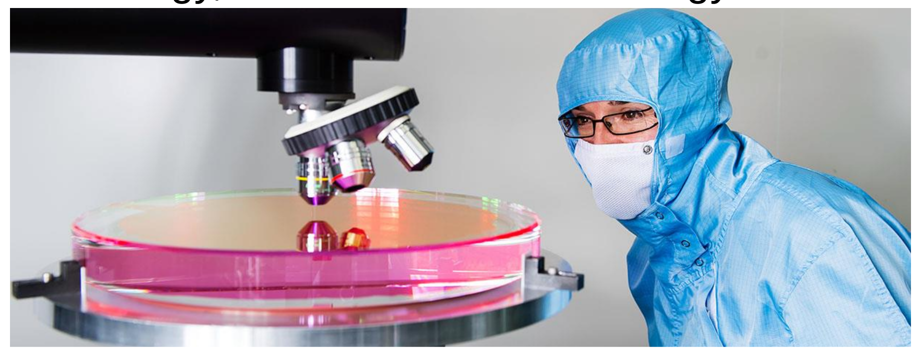
Key technologies

GW requires many of the technologies developed for particle physics: underground construction, vacuum and cryogenic technology, advanced controls

The particle physics community (e.g. CERN) has build up vast expertise in governance and implementation of big science projects. ET should build on this

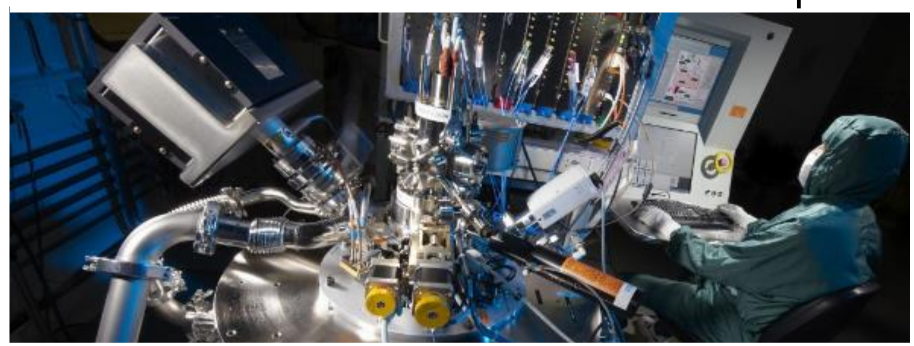
Measuring and attenuating vibrations: nano-technology, medical, defense

Optics, coatings, special materials, laser technology, semiconductor technology



Vacuum technology: ET will be one of the biggest vacuum systems worldwide

Cryogenic systems: KAGRA/ET's low frequency interferometer will feature cooled silicon optics



Underground construction

Einstein Telescope design

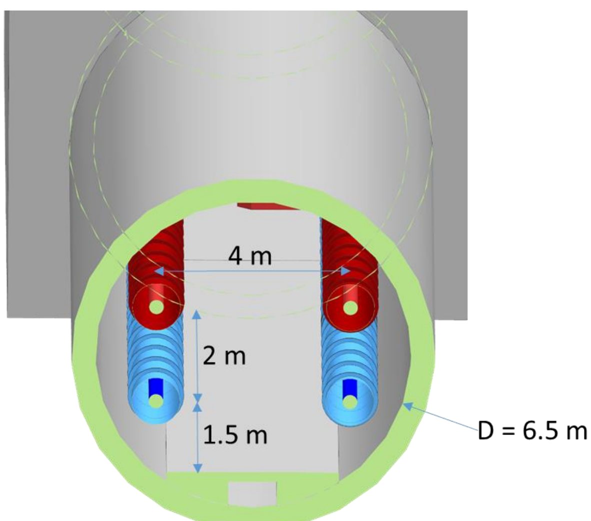
Three detectors that each consist of two interferometers: 6 ITFs in total

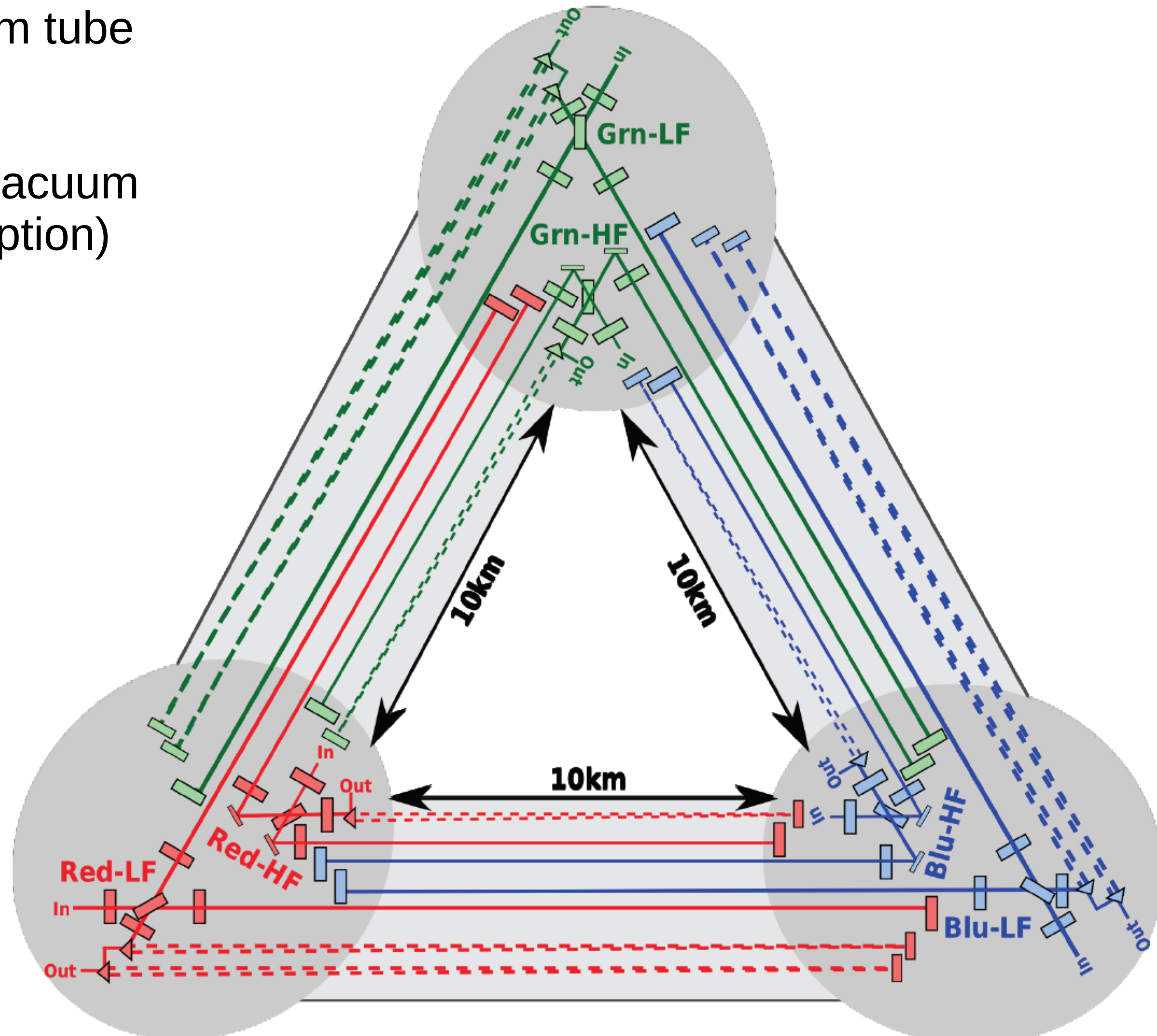
Each ITF has 20 km of main vacuum tube + several km of filter cavities

About 3 * (2 * 30 + 2) ≈ 130 km of vacuum tube of about 1 m diameter (assumption)

Tunnel inner diameter: 6.5 m

Tunnel will have concrete lining

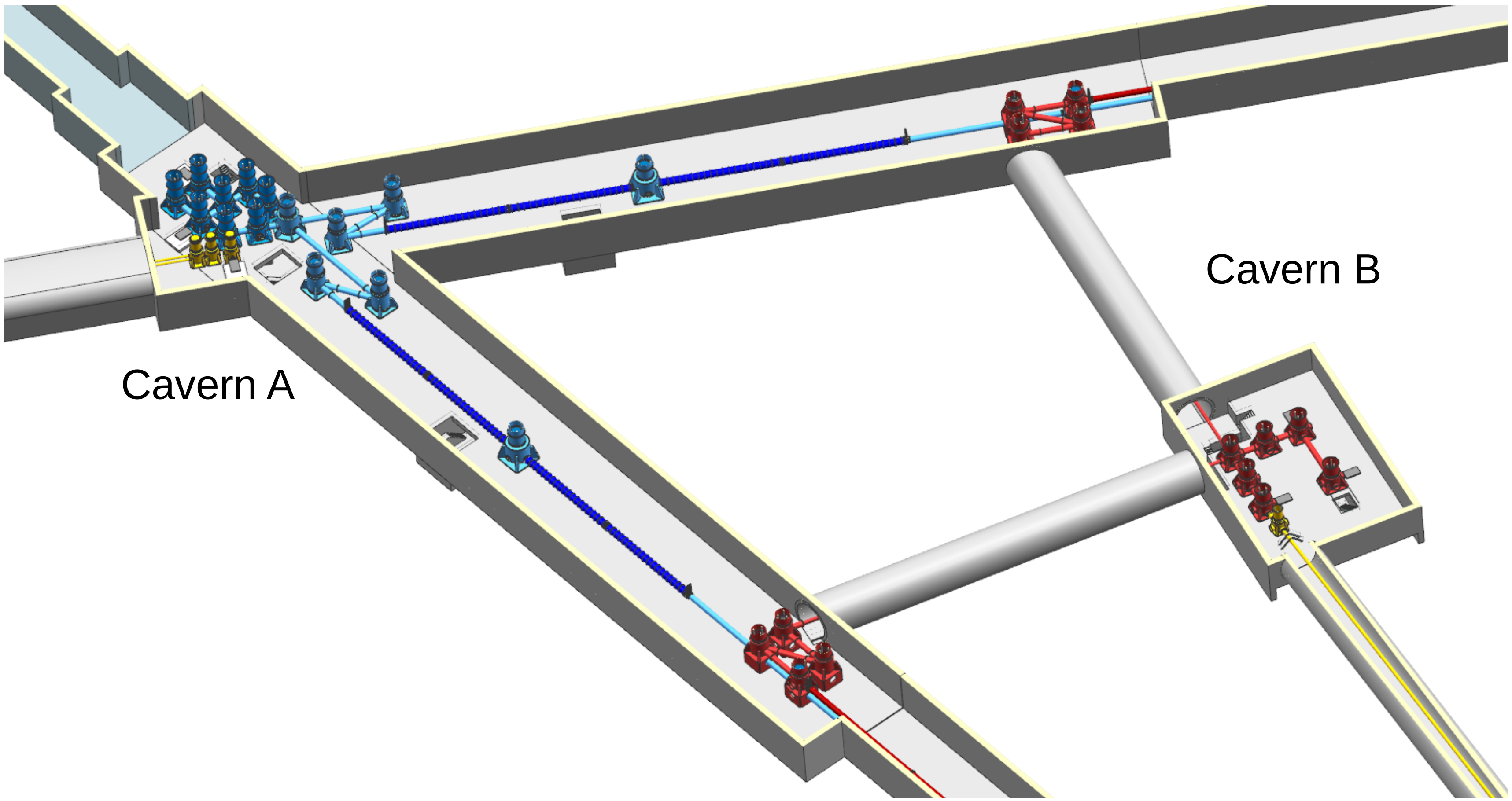




Einstein Telescope layout: corner station

Low frequency towers (blue): height = 20 m

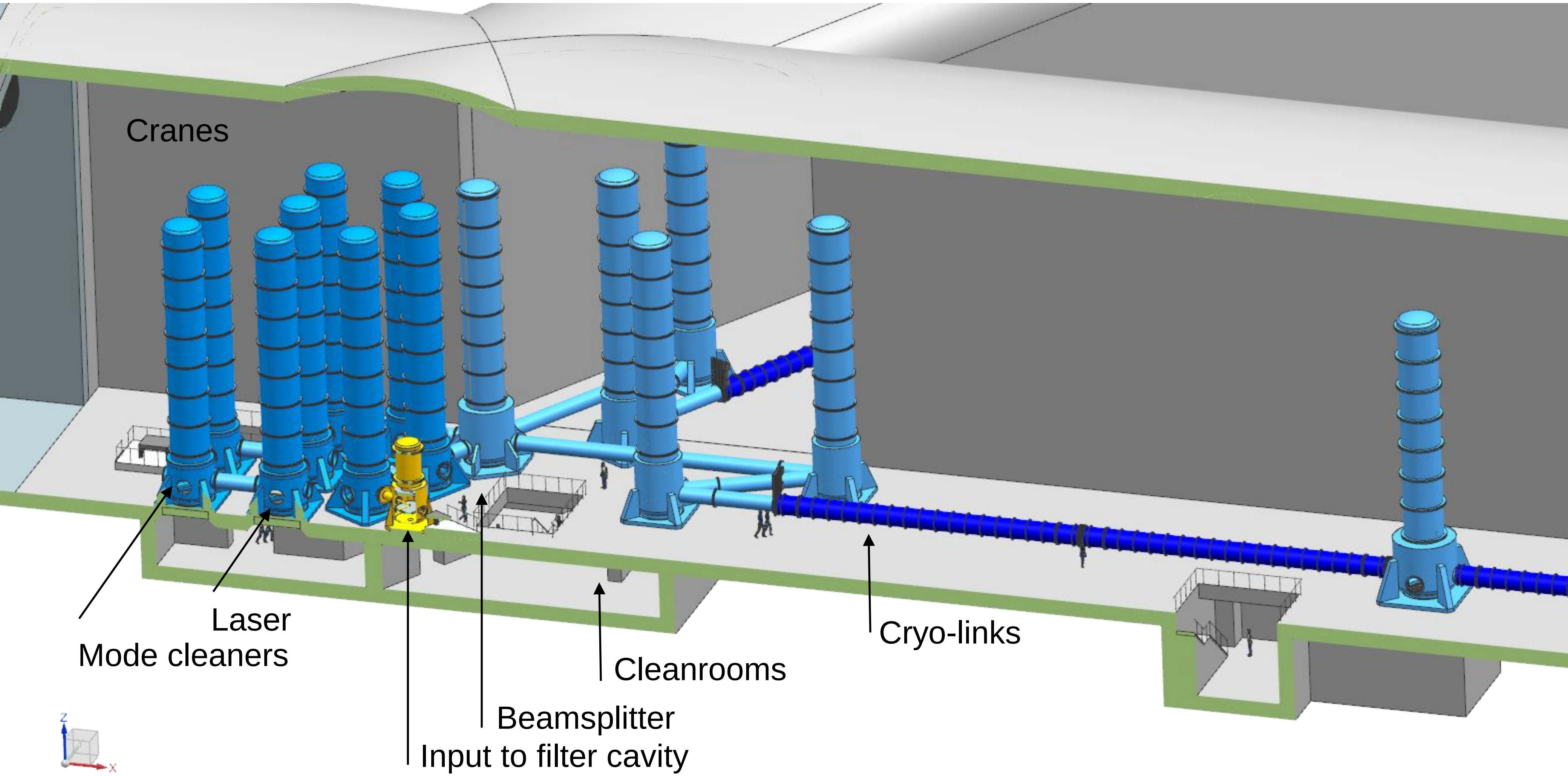
High frequency towers (red): height = 10 m



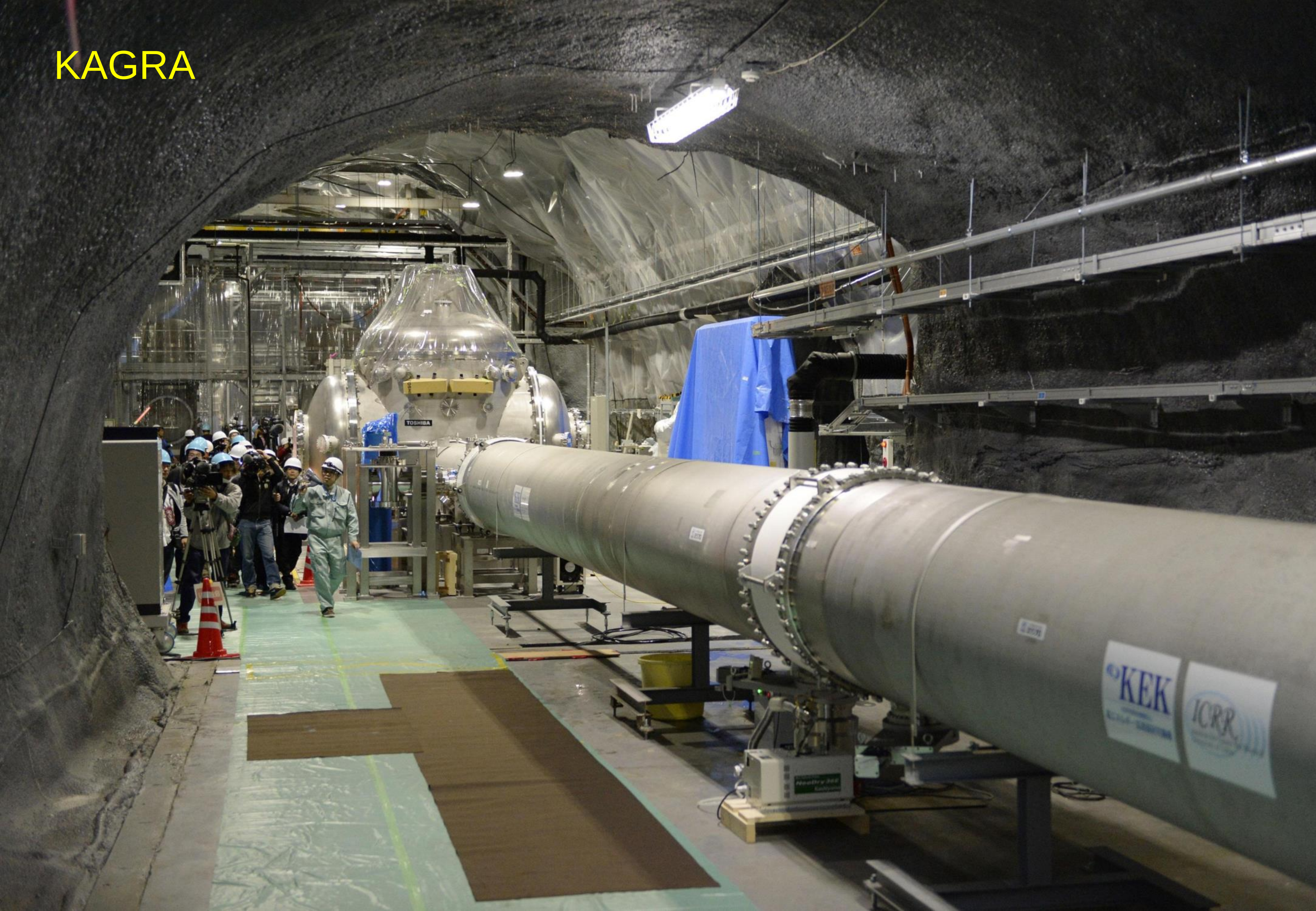
Towers for filter cavities and pick-off beams (yellow)

Corner station: cavern A

Houses the beamsplitter of the cryogenic low frequency interferometer
Towers are 20 m high. Cavern A dimensions are 20 m wide, 30 m high, 175 m long



KAGRA



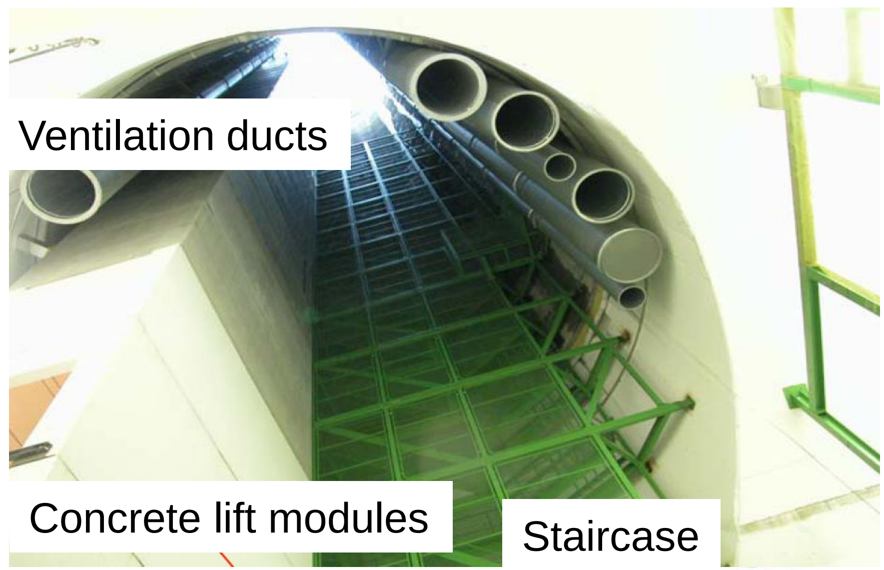
LHC underground caverns

Einstein Telescope

Cavern B: 25 m x 22 m x 38 m (about 21k m^3)

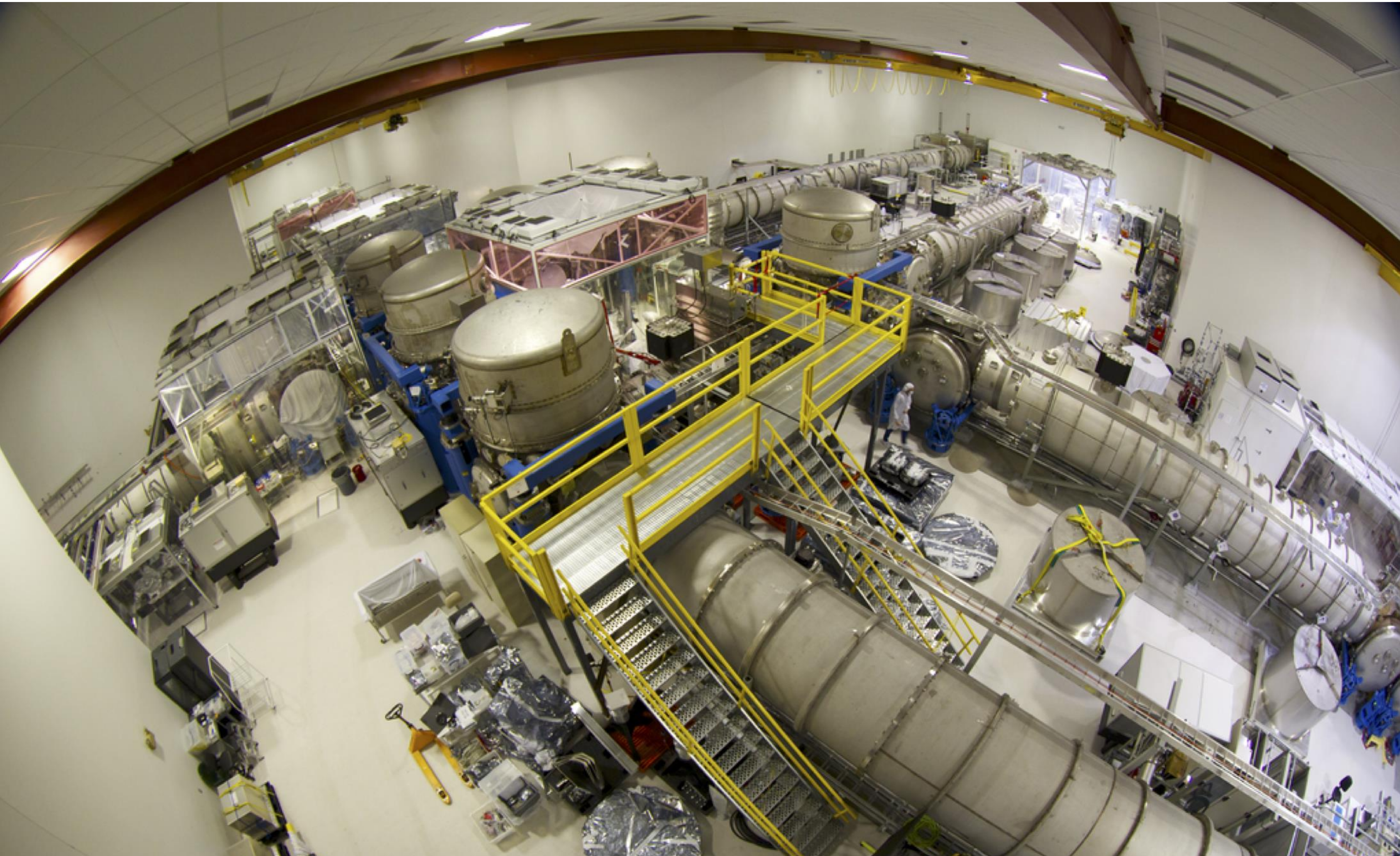
LHC project: CMS shaft

Diameter of about 20 m, while 10 m diameter is foreseen for Einstein Telescope



Vacuum system

Vacuum Equipment: LIGO Hanford corner station



Virgo vacuum system

KAGRA inauguration

Signing of the MOA with LIGO and VIRGO
Toyama, October 4, 2019

Beam tubes

304L SSt, 3.2 mm thick with external stiffeners

Raw stock air baked 36h @ 455C

Final J_{H2} < 1e-13 Tl/s/cm^2

Coil spiral-welded into 1.2m tube 16m long

method adapted from sewer pipe industry

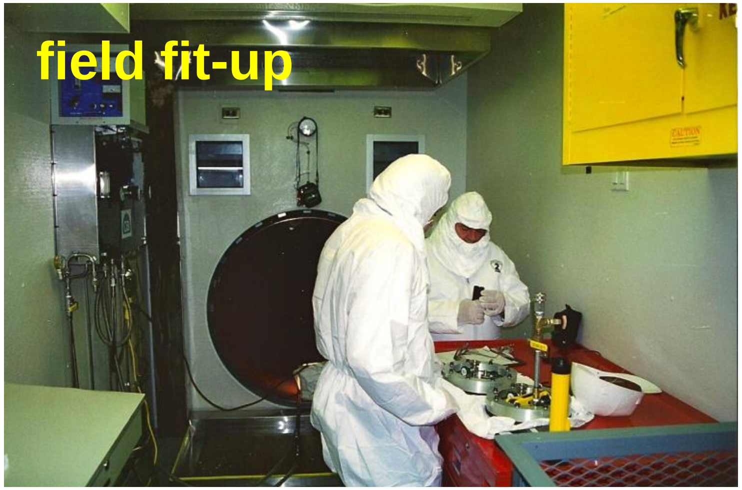
16 m sections cleaned, leak checked

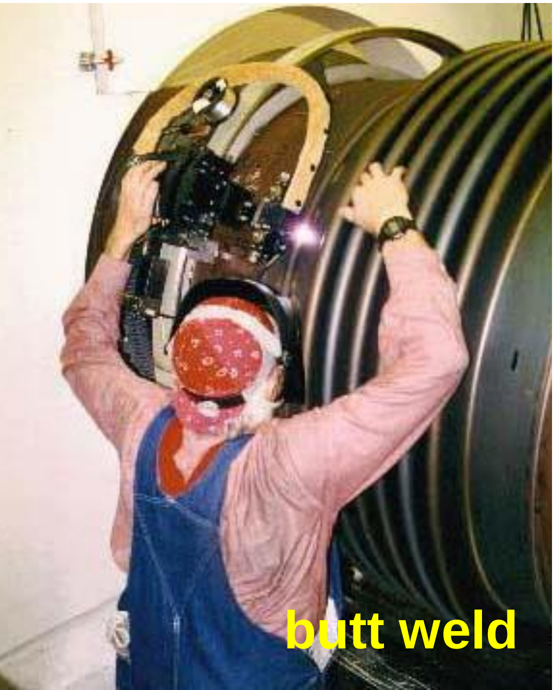
FTIR analysis to confirm HC-free

Sections field butt-welded together in travelling clean room

Over 50 linear km of weld

Beam tube field assembly



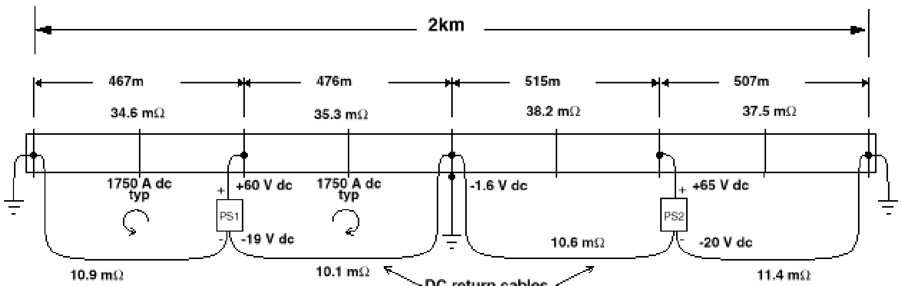


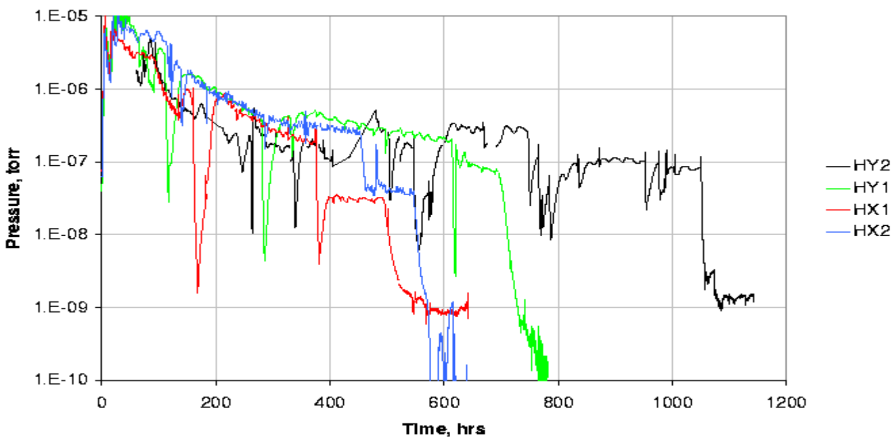
I^2R bake-out to desorb water

DC current of 2,000 A

3 weeks @ 160ºC

Final outgassing:
$J_{H20} < 2e\text{-}17$ Tl/s/cm^2





Why do we need an ultra-high vacuum system?

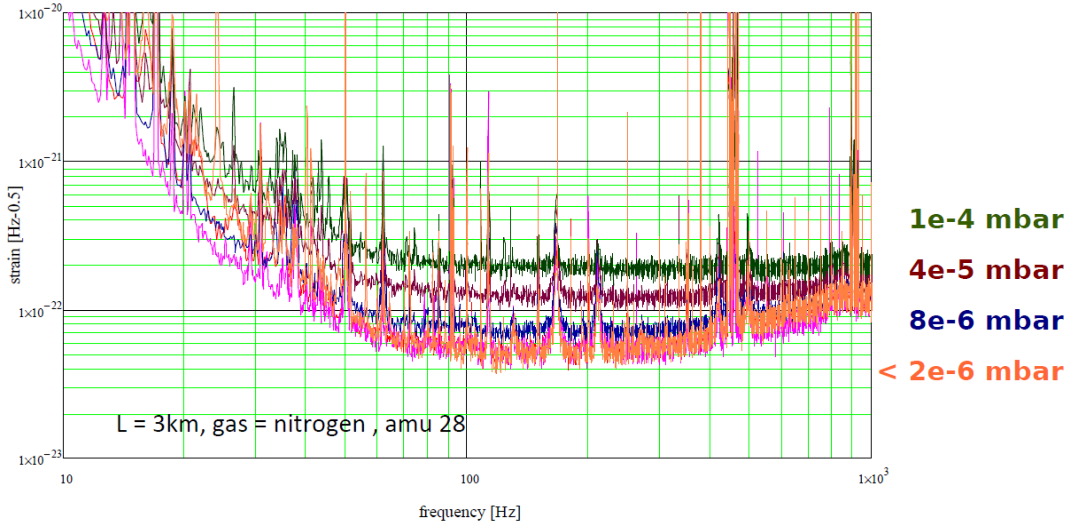
- Reduce the **phase noise due to residual gas density fluctuations** along the beam path to an acceptable level
- Isolate test masses and other optical elements from **acoustic noise**
- Reduce **test mass motion** excitation due to residual gas fluctuations
- Reduce friction losses in the mirror suspensions → **suspension thermal noise**
- Contribute to **thermal isolation of test masses** and of their support structures
- Contribute to preserve the **cleanliness** of optical elements

Virgo design values

Gas species	Pressure [mbar]	Noise [$\sqrt{\text{Hz}}$]
Hydrogen	1×10^{-9}	9.7×10^{-26}
Water	1.5×10^{-10}	2.5×10^{-25}
Air	5×10^{-10}	5.6×10^{-25}
Hydrocarbons	1×10^{-13}	2.9×10^{-26}
Total	1.7×10^{-9}	6.2×10^{-25}

Einstein Telescope aims at an order of magnitude improvement

$$S_L(f) = \frac{4\rho\,(2\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{1}{w(z)} e^{-2\pi f w(z)/v_0}\, dz$$



Fluctuations of the refractive index of residual gas limits sensitivity

Einstein Telescope vacuum system

Three detectors that each consist of two interferometers: 6 ITFs in total

Each ITF has 20 km of main vacuum tube + several km of filter cavities

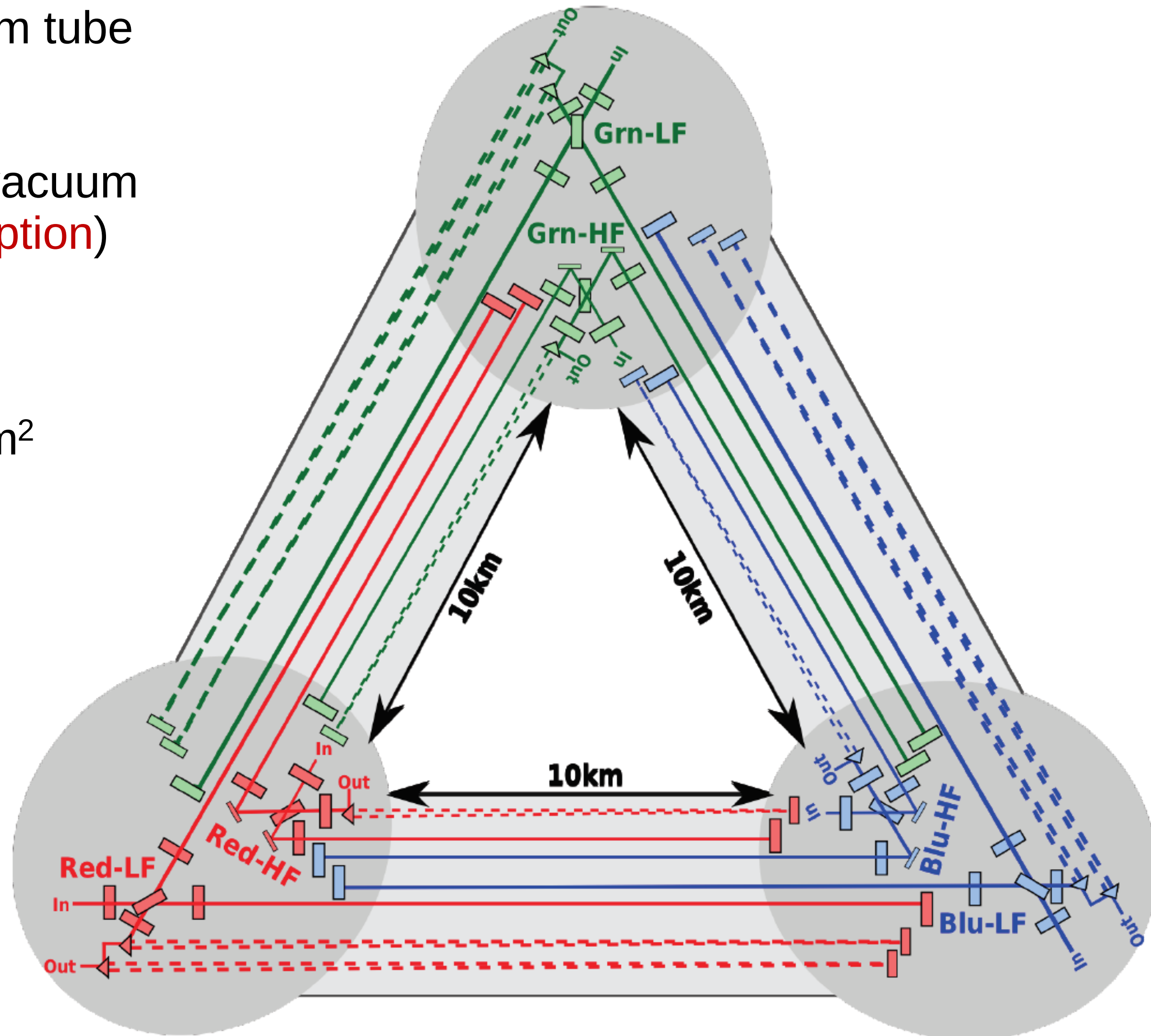
About 3 * (2 * 30 + 2) ≈ 130 km of vacuum tube of about 1 m diameter (assumption)

Total volume: about 120,000 m³

Total surface area: about 420,000 m²

Target pressure of < 10^{-10} hPa

Hydrocarbon pressure < 10^{-14} hPa



For comparison LHC at CERN:
- **Beam tubes: 2,000 m³**
- Cryo-magnet insulation: 9,000 m³
- Cryo distribution line: 5,000 m³

Timeline Einstein Telescope

Sites qualification	now – 2023
ESFRI proposal submission	2020
ESFRI decision	2021
Research infrastructure operational design	2023 – 2025
Site decision	2025
Research infrastructure construction	2026 – 2032
Detector installation	2030 – 2034
Operation	2035

Underground construction and vacuum represent > 85% of the cost of ET

Preparation phase

Activity	Cost [M€]	Actualised cost [M€]	Start	End	Note
Site Qualification	15	14	2019	2022	Complex series of activities, going in parallel in the two candidate site, aiming to the qualification of the sites (compliance with the stringent ET requirements)
Funding schemes for the two sites	0	0	2019	2023	Definition of the two funding schemes for the two candidate sites. Interaction and negotiation between countries
Site Comparison	1	1	2022	2023	Evaluation of the two candidatures, using also external panels, experts and companies
RI Technical Design completion	38	31	2023	2025	Completion of the preliminary design, realisation of the definitive and operative design by specialised external companies.
Governance definition -ERIC	1	1	2021	2024	Study and definition of the governance structure of ET
Land acquisition	19	15	2023	2025	Acquisition of the land for the excavation and for the realisation of the surface infrastructures
Funding schemes for the two sites	0	0,0	2019	2023	Activity addressed to the definition of the financial schemes for the two candidatures
Technology development	95	81	2019	2028	R&D activity addressed to the development of the technologies needed for ET. This activity is already started since years and it is partially based on the technology developed for the upgrade of the current detectors
Detector design completion	2	2	2022	2025	Completion of the detector design after the selection of the site
Tot	171	145			

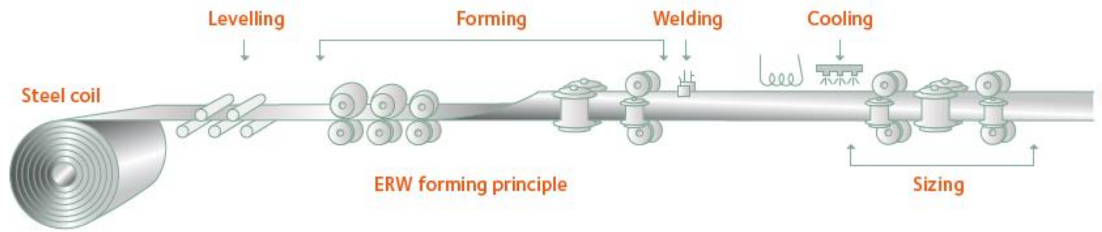
Construction phase

Activity	Cost [M€]	Actualised cost [M€]	Start	End	Note
Infrastructure costs	932	635			
Excavation	781	540	2026	2031	Excavation of the underground tunnels with TBMs and of the caverns. Cost based on the evaluation by two independent external companies
Direction of the civil works	9	6	2025	2032	Evaluation based on the 1% of the underground and surface infrastructures realisation cost
Civil works in surface	98	62	2028	2033	Realisation of the technical and civil infrastructures on the surface. Cost evaluation based on the Conceptual Design study
Services underground (ventilation, …)	44	27	2030	2033	Technical infrastructures serving the underground facilities and apparatuses
Detector costs	804	552			
Vacuum system	566	391	2026	2031	Vacuum plant, pumps and pipes
Optics and Laser	125	86	2026	2031	Main mirrors, auxiliary optics and lasers
Suspension system	48	33	2026	2031	Filtering and suspension systems
Cryogenics	45	31	2026	2031	Cryogenic plants
ET installation	20	11	2032	2035	Contracts and activities for the installation of the ET components
Total	1736	1187			

Overview of possibilities for joint research

Minimizing cost and impact of construction

Local factory for beam tube production: about 8,000 segments (16 m)



Courtesy of Corinth Pipeworks

ourtesy of SCC Nigeria

Courtesy of Corinth Pipeworks (Greece)

Pickled and oiled coils ready for overseas shipment (Fos-sur-Mer)

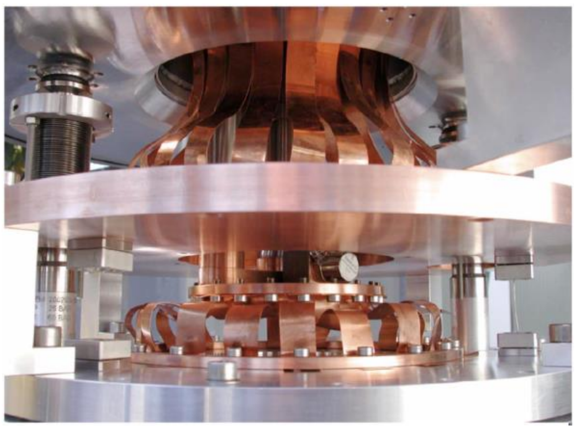
SAWH API 5L pipes being inspected during the coating operation.

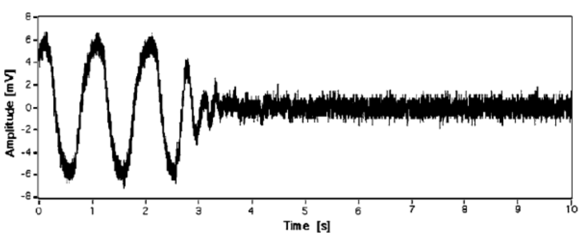
Creating a smart infrastructure

Minimizing the effects of the infrastructure on our measurements

- Low noise equipment: HVAC systems, (water) pumps, vacuum equipment, electronics, acoustic isolation, …
- Temperature stability

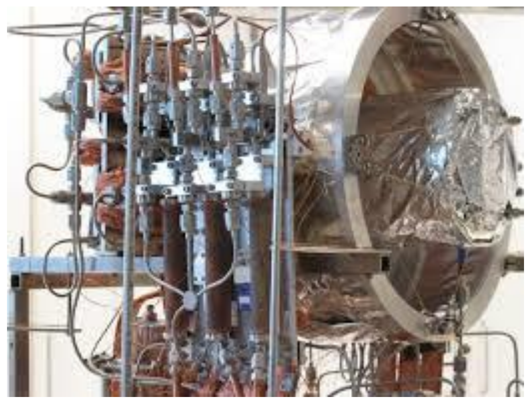
Pulse tube cooling





S. Caparrelli et al., Rev. Sci. Instrum. **77**, 095102 2006

Vibration-Free Cooling Technology to Replace Mechanical Compressors in Sensitive Space Applications



Marcel ter Brake et al., Thema-bijeenkomst “Thermal Challenges”, Mikrocentrum Veldhoven, 15 mei 2019

Cleanroom facilities

Optical surfaces are illuminated with up to 200 kW/cm^2 in current interferometers

Even low-level contaminants can result in laser damage to optics

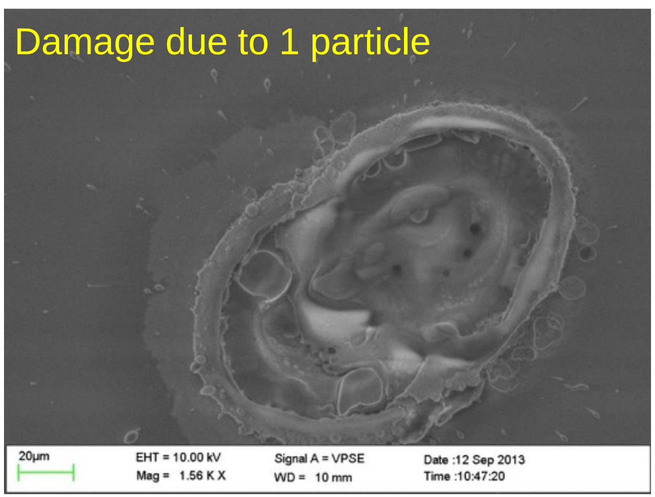
Requirements for absorption on cavity surfaces: 0.5 ppm per surface with 0.1 for contamination

LIGO vacuum chambers operate in an ISO 5 (Class 100) environment

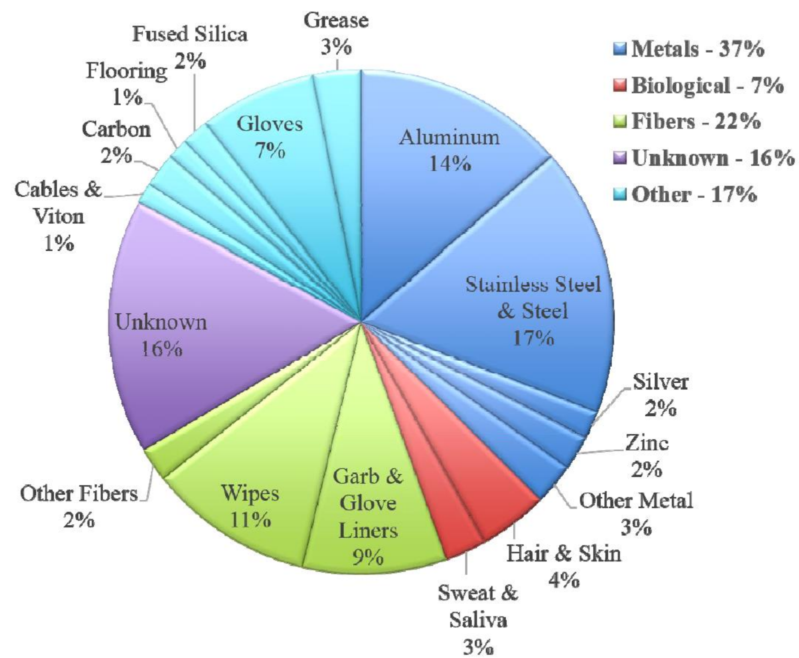
Materials: LIGO Vacuum Compatible Materials List, NASA outgassing specifications

IEST-STD-CC1246 standardizes the criteria for PCLs

Witness wafers, “FBI” samples, …



Molecular analysis of specimens collected with FBI sample tool in vacuum chambers



Two concentric tube design

Option of an independent inner and out vacuum space

Sealed inner UHV vacuum tube, concentrically disposed inside an independent outer “guard” vacuum tube

Discussions with **coating suppliers and manufacturers**

Metal oxides, carbides, nitrides, aluminides, oxynitrides, and others, use to **reduce corrosion by creating barrier layers** against incoming oxidizing species at the surface. These barriers may reduce the outgassing of lighter molecular gases released from the deeper metal layers

Diamond-like carbon (DLC) coating

About 100 times better than stainless steel surfaces

Takahashi et al. (Vacuum **73** 145 (2004))

Outgassing rates from **unbaked** DLC coating

1.9 x 10^{-11} Torr liter s^{-1} cm^{-2} after 10 hours

3.0 x 10^{-12} Torr liter s^{-1} cm^{-2} after 50 hours

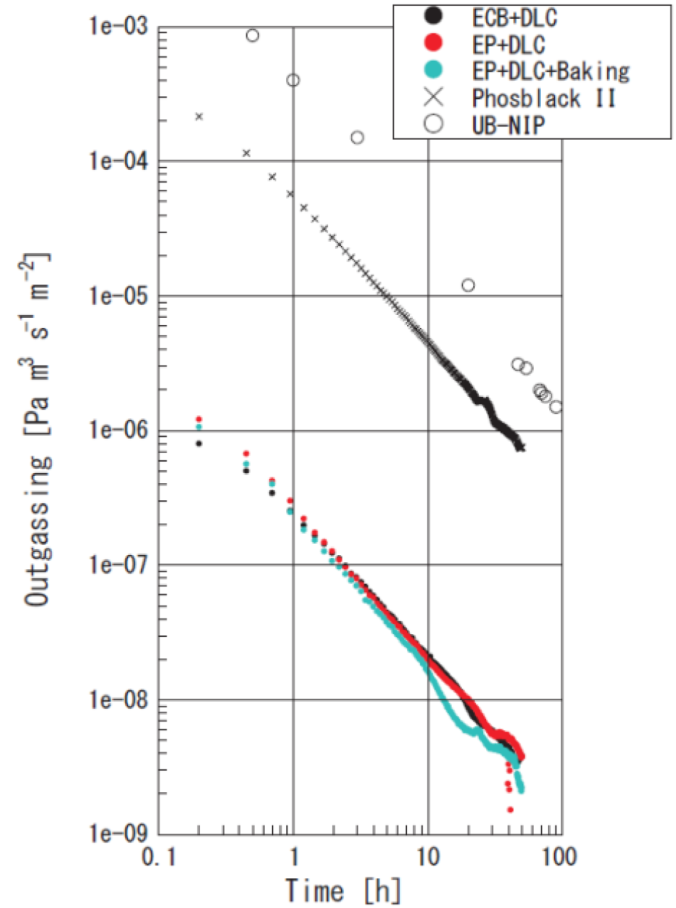
Diamond-Like Carbon film (by Nanotec)

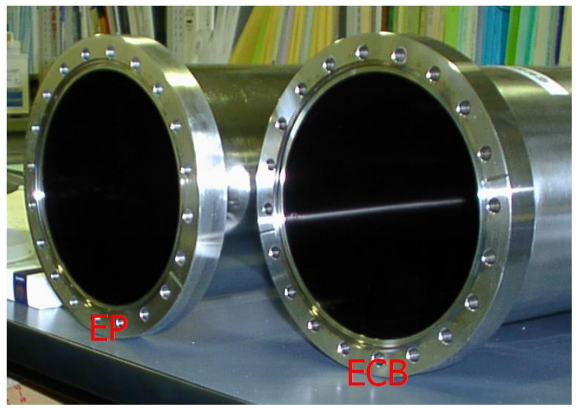
DC plasma CVD: 500 V, 120 mA

Thickness: ~1μm

Sample: SS304 pipe (150mmφ x 1m)
+EP or ECB
+Baking only for EP (215℃, 23h)

Outgassing measurement: conductance-modulation method





Recent study comparing SSt and mild steel

Potential for significant cost savings

Park, Ha and Cho[1] published a study in 2015 carefully looking at both total and hydrogen outgassing from three grades of structural mild steels and a typical UHV quality 304 stainless steel. Confirmed by CERN studies

They find that with reasonable care of the vacuum facing surface, total outgassing rates are 3 to 30 times more than stainless steel

Measured hydrogen outgassing rates was 20 x lower than stainless steels after a modest 150°C (48h) pre-treatment for both metals

Attribute this reduction to modern mild steel making techniques that reduces both bulk carbon and hydrogen (Ruhrstahl-Hereaus process)

Development of such a process would require a cooperative arrangement between a steel-mill and research labs! Potential advantages for the 3G detector and for the companies involved in a new technological development

Thermal outgassing rates of low-carbon steels

Chongdo Park and Taekyun Ha
Pohang Accelerator Laboratory, 80 Jigok-Ro 127 Beon-Gil, Pohang, Gyeongbuk 37673, Korea

Boklae Cho[a)]
Korea Research Institute of Standards and Science, 267 Gajeong-Ro, Yuseong-Gu, Daejeon 34113, Korea

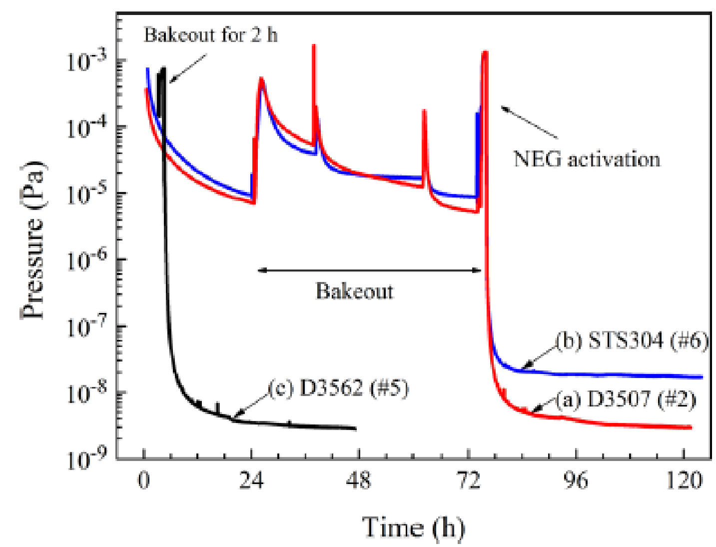
(Received 22 July 2015; accepted 13 November 2015; published 2 December 2015)

Outgassing rates of three low-carbon steels were measured using rate-of-rise and throughput methods. Outgassing rates of water vapor during pump-down were higher than those of stainless steels, probably due to the nature of native surface oxide layer. However, hydrogen outgassing rates without a high temperature pretreatment were as low as (1–4) × 10^{-10} Pa m^3 s^{-1} m^{-2}, which is much lower than that of untreated stainless steels. No dramatic reduction was observed in H_2 outgassing after vacuum annealing at 850 °C for 12 h, suggesting that the low-carbon steels had been fully degassed during the steelmaking processes. This may be due to the use of the Ruhrstahl-Hausen vacuum process during steel refining instead of an older process, such as argon-oxygen decarburization. The extremely low H_2 outgassing rate from low-carbon steels makes them applicable for use in ultrahigh vacuum or even extreme high vacuum applications, particularly where magnetic field shielding is needed.

[http://dx.doi.org/10.1116/1.4936840]

q_{H2} = 2.6 x 10^{-10} Pa m^3 s^{-1} m^{-2} mild vs. 5.1 x 10^{-9} Pa m^3 s^{-1} m^{-2} SSt304
0.048 ppm (mild steel) vs 1.64 ppm (SSt304)

C. Park, T. Ha, and B. Cho, Journal of Vacuum Science and Technology **A34**, (2016) 021601-1



CERN-GW R&D program together with industry

Participants from steel and car industry

Tata Steel Ijmuiden
Producer of low carbon steel
Vacuum treatment to de-hydronize
Enamel coatings

VDL Group
International industrial and manufacturing company
Car industry, CERN CLIC cavities

Settles
Focus on the creation of new technology, manufacturing processes and/or equipment

Potential participants

Allseas Group S.A.
Major offshore pipelay and subsea construction company
Coatings on steel
Oil & gas industry

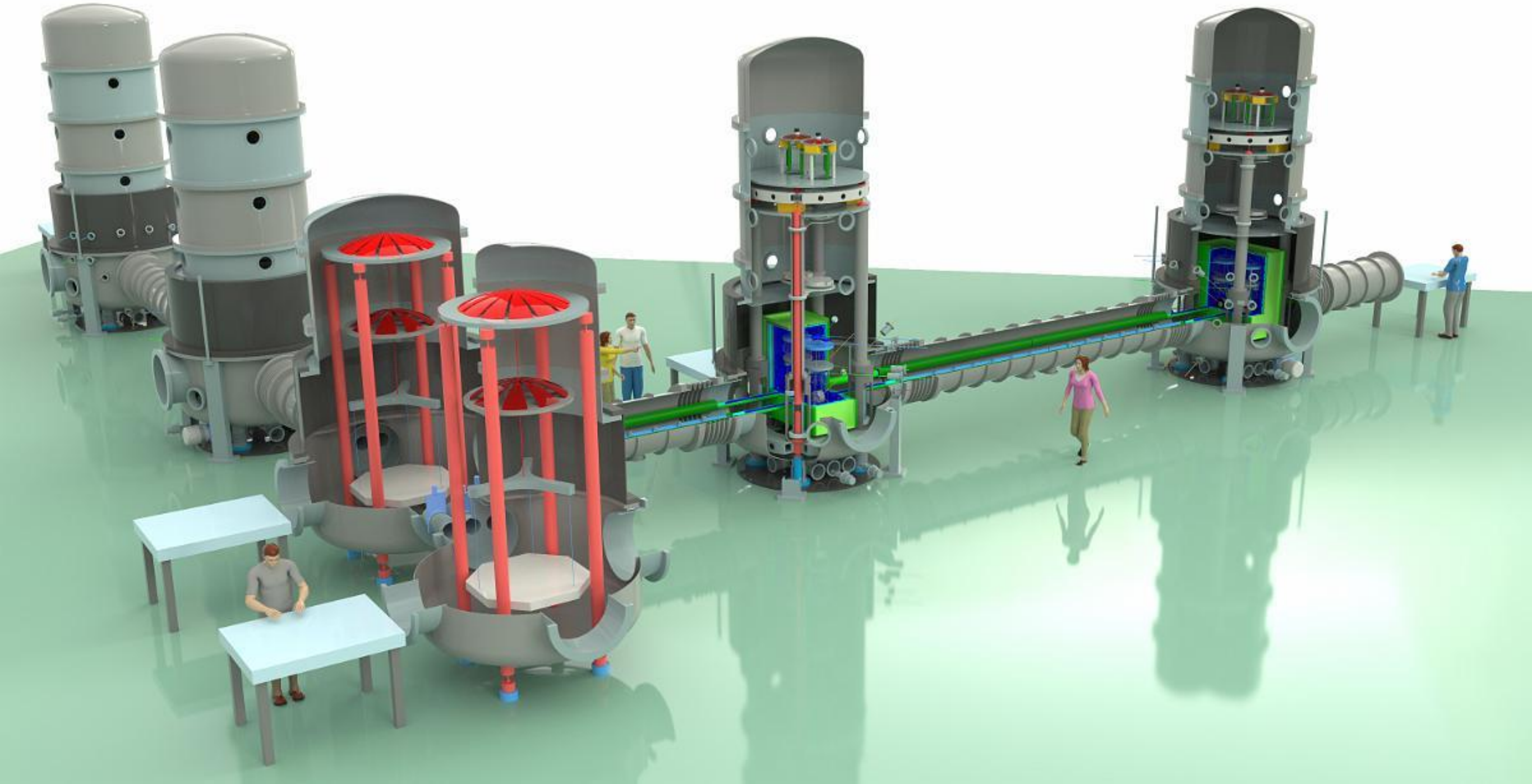
Numerous issues: construction, assembly, valves, pumping, …

Connections to other innovative activities
Hyperloop project, fuel cells, …

Test facility: ET Pathfinder UMaastricht

Test facility: ET Pathfinder UMaastricht

Possibility to accommodate realistic vacuum vessels



Gravitational waves, CERN and JENAS

MOU in place to foster a strong CERN role in our quest for Einstein Telescope. Use JENAS initiative to strengthen the effort on joint R&D for current and future GW detectors → contact these Collaborations

Science

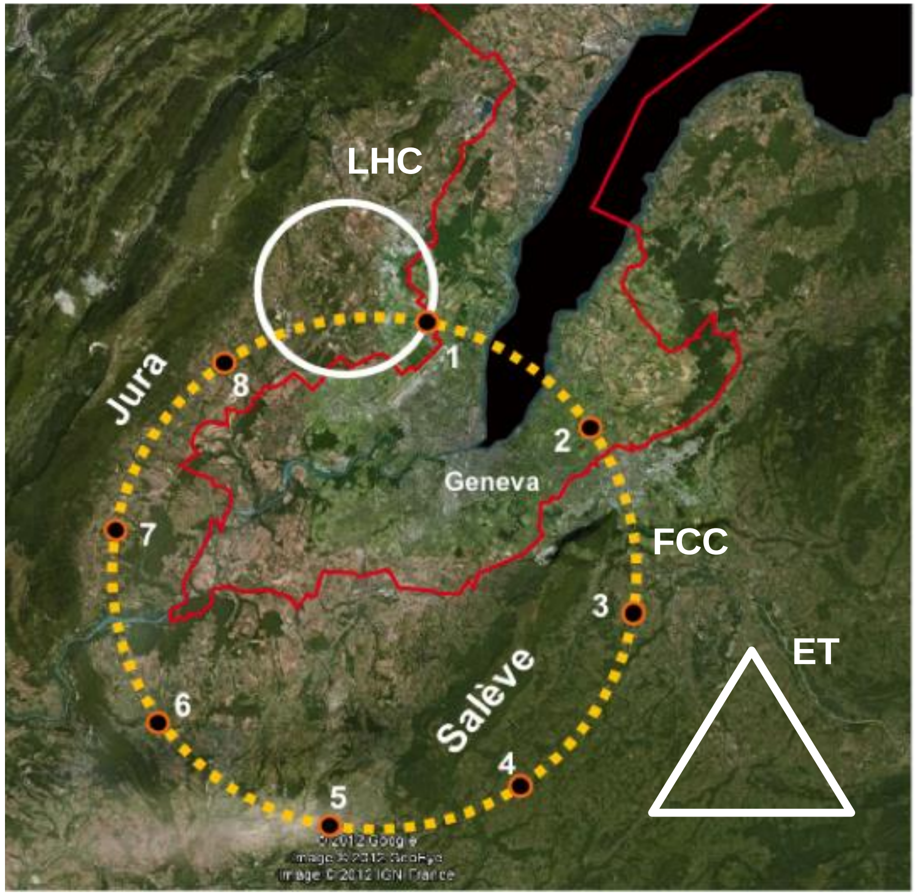
- Gravity is a fundamental interaction with most important open scientific issues
- GWs are the dynamical part of gravity
- Strong scientific interest from HEP

Time window

- ET Preparatory phase
- CERN projects

Instrumentation R&D

- Vacuum infrastructure
- Underground construction
- Cryogenics
- Controls



Thanks for your attention! Questions?