ETO Design Task Force update

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on behalf of the ETO Task Force on detector layout

ET Symposium - Bologna, May 29, 2025

Scope of Task Force

Background

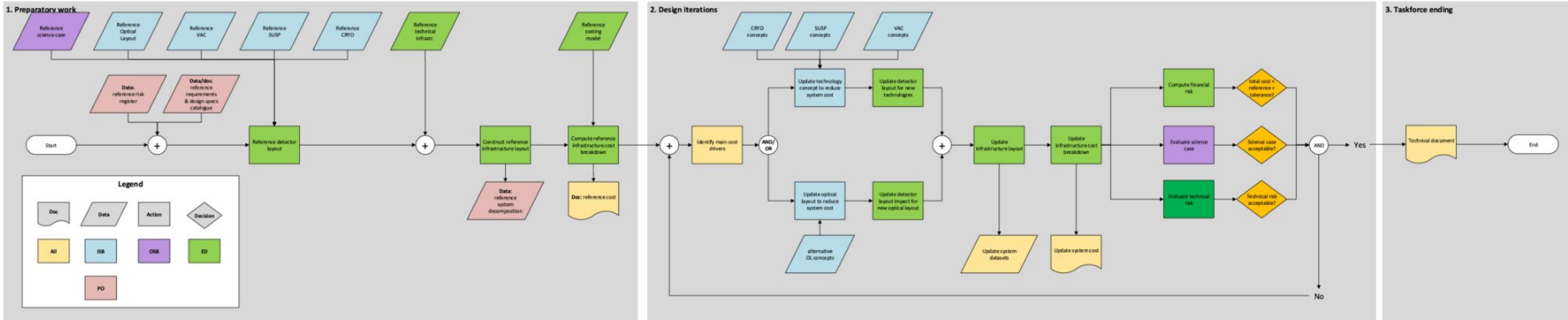
- 2020 ESFRI proposal
- 2022 CDR update
- 2024 optical layout update (ETC-ISB)
  - Triangle first, then 2L
- 2024 detector layout (ETO-ED)
  - Triangle first, then 2L
- **Informal** feedback by civil engineering experts from local teams: infrastructure to host updated detector layout would be significantly more expensive than for the ESFRI proposal

Task Force mandate

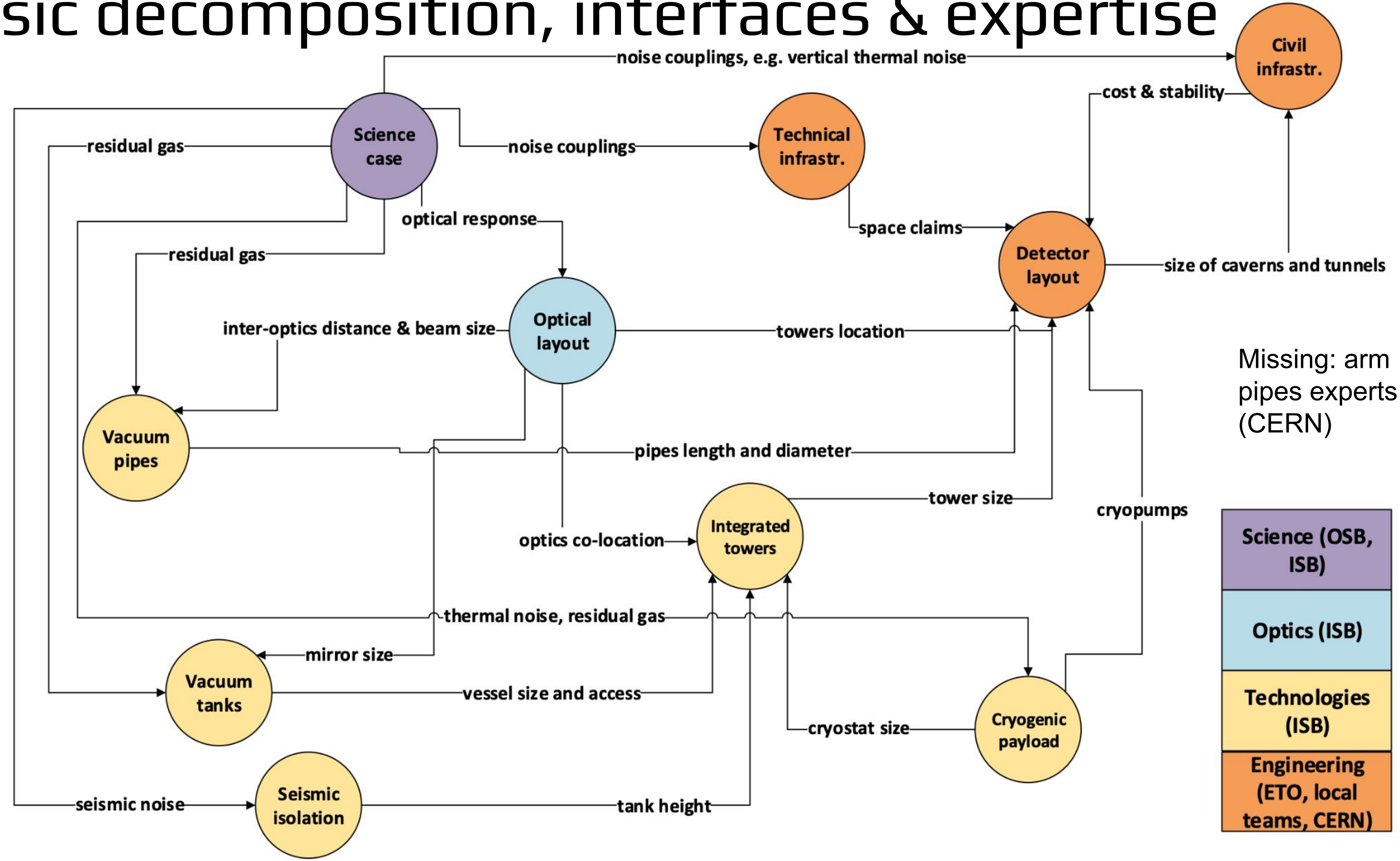
- Adapt detector layouts of ET towards an acceptable preliminary **costing** for the civil **infrastructure** (which is expected to dominate the total cost of ET)
  - for both Triangle and 2L geometries **equally** and **independently**
  - while **maintaining** ET's scientific **performance**

Task Force study logic

- Build a simplified picture of the ET detector limited to subsystems conveying major volume claims
- Develop dedicated tools for science case, detector layout, civil engineering
- Identify detector <-> infrastructure interfaces
- Identify main cost drivers for civil infrastructure
- Identify viable configurations to preserve performance and reduce cost
  - optical layout
  - critical technologies
  - independently for Triangle and 2L geometry
- comparative analysis of technical risk and infrastructure cost between identified configurations and 2024 reference



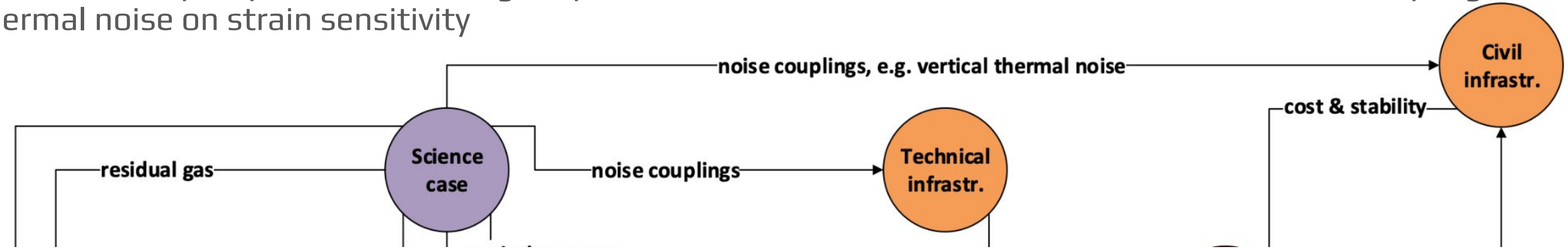
Basic decomposition, interfaces & expertise

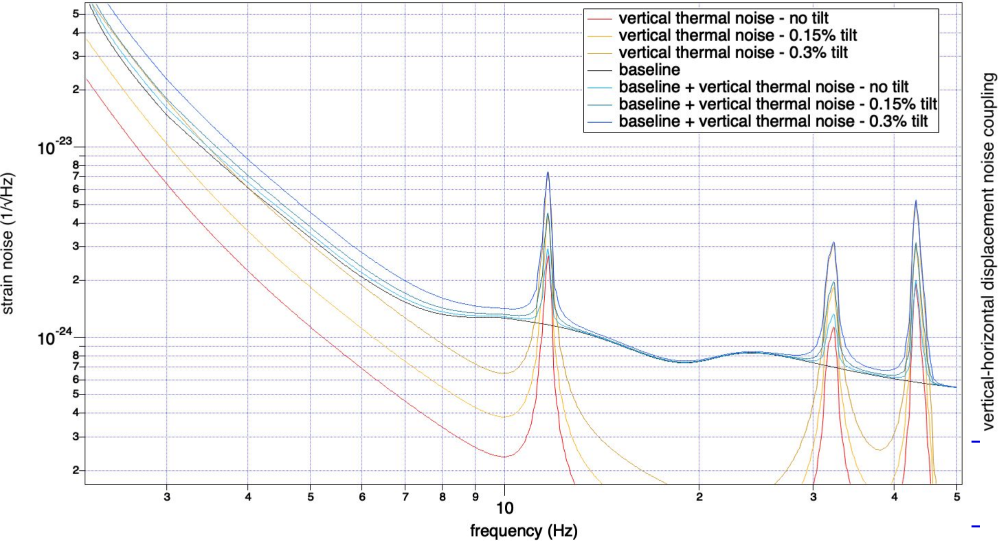


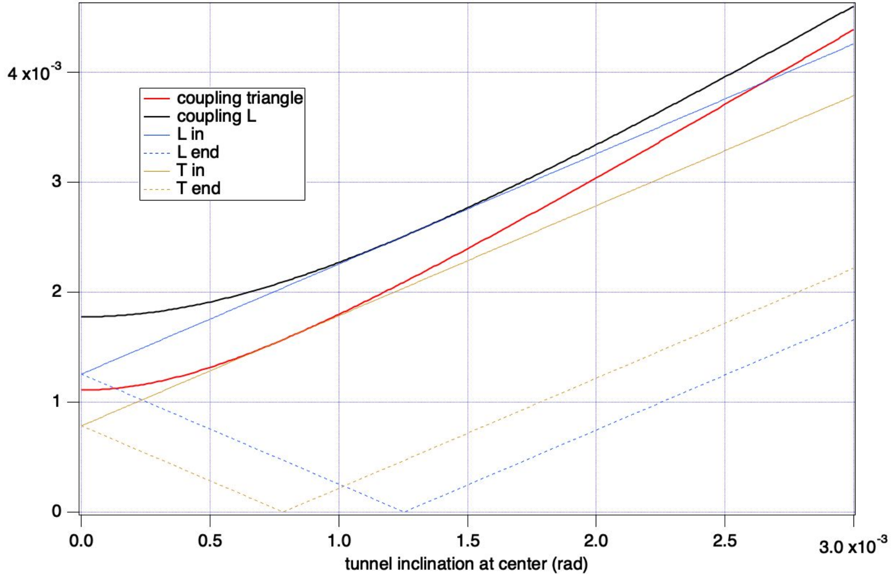
Missing: arm pipes experts (CERN)

Example of engineering requirements

- Tunnel tilt for pump-free dewatering: requirements on maximum allowed tilt (1.5 mrad) from coupling of vertical thermal noise on strain sensitivity







Example - volume claims vs HFI tower height

Einstein Telescope Organisation

1. Updated L Layout

Tower Types

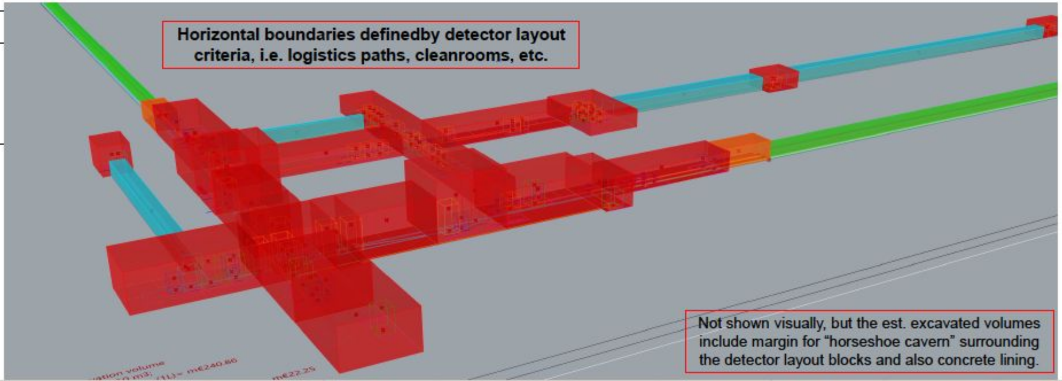
	Tot. Height (m)	Clearance (m)
T7_3m	3	2
T6_5m	5	3
HF_T6_5m	5	3
T5_6m	6	6
T4_8m	8	6
T3_10.5m	10.5	6
T1_16m	16	6

Est. total excavation volume of caverns = 321150 m3;
Est. total cost of caverns (1L)

Est. total excavation volume of conventional tunnels = 29662 m3;
Est. total cost of conventional tunnels (1L):

Est. total excavation volume of TBM tunnels = 1137241 m3;
Est. total cost of TBM tunnels (1L):

Not perfect, but close enough to previous manual work (i.e. revit block model → excel tables)



Vol & Costs (caverns)

Unit Cost (€/m3) - Cavern & Manual Excavation: 750.0

Volume (m3): 0 321150.15588

Costs (m€): 0

	Det. Layout Dimensions (LxWxH - m)	Det. Layout Volume (m3)	Est. Excav. Volume (m3)	Est. Cost (m€)
0	26.171239, 24.272008, 22	13975.027515	17607.356002	m€13.21
1	16.572008, 11.574255, 16.5	3164.842695	4450.383234	m€3.34
2	24.5, 21.296984, 16.5	8609.305692	11451.96599	m€8.59
3	24.5, 28.5, 14	9775.5	13270.886078	m€9.95
4	40.0, 21.296984, 14	11926.310915	16127.524087	m€12.10
5	11.6, 15.7, 12	2185.44	3291.303368	m€2.47
6	24.672008, 22.171239, 22	12034.197673	15252.957048	m€11.44
7	16.572008, 31.628761, 16.5	8648.50966	11548.238441	m€8.66
8	24.672008, 26.828761, 14	9266.871986	12603.508211	m€9.45
9	18.65, 55.128302, 12	12337.714017	17251.440225	m€12.94
10	24.5, 34, 14	11662.0	15745.119075	m€11.81
11	25, 15, 22	8250.0	10666.90144	m€8.00
12	16, 13, 5	1040	2056.69842	m€1.54
13	19, 47.482723, 14	12630.404223	17106.246298	m€12.83
14	23.5, 35, 8	6580.0	10267.80238	m€7.70
15	15.780648, 129.299442, 8	16323.32811	25454.290006	m€19.09
16	58.663535, 15.952074, 8	7486.440391	11774.54462	m€8.83
17	20, 11.7, 8	1872.0	3104.812063	m€2.33
18	38.1, 24.272008, 14	12946.659293	17432.201873	m€13.07
19	27, 14, 8	3024	4889.4678	m€3.67
20	11, 20, 8	1760	2933.68068	m€2.20
21	8.371239, 21.296984, 16.5	2941.655184	4208.592375	m€3.16
22	27.628761, 19.146984, 16.5	8728.622869	11617.330568	m€8.71
23	52.445298, 15.5, 8	6503.21698	10266.106114	m€7.70
24	11.2, 27.0, 12	3628.8	5343.167144	m€4.01
25	17, 14.2, 8	1931.2	3185.139024	m€2.39
26	47.482723, 19, 14	12630.404223	17106.246298	m€12.83
27	15, 25, 22	8250	10666.90144	m€8.00
28	13, 16, 5	1040	2056.69842	m€1.54
29	61.896094, 15.952074, 8	7898.968524	12412.487168	m€9.31

Vol & Costs (TBM tunnels)

Total Excav. Vol. (m3): 0 1.1372e+6

Total Costs (m€): 0

	Envelope Dia. (m)	Length (m)	Excav. Vol. per Tunnel (m)	Unit costs (m€/km)	Costs per Tunnel (m€)
0	6.2	4959.771979	207585.467017	m€42.33/km	m€209.95
1	6.2	966.773479	40463.175511	m€42.33/km	m€40.92
2	5.8	9880	369440.616753	m€40.93/km	m€404.39
3	5.8	13899.786735	519751.597505	m€40.93/km	m€568.92

Vol & Costs (conventional tunnels)

Unit Cost (€/m3) - Cavern & Manual Excavation: 750.0

Volume (m3): 0 29661.823818

Costs (m€): 0

	Det. Layout Dimensions (LxWxH - m)	Det. Layout Volume (m3)	Est. Excav. Volume (m3)	Est. Cost (m€)
0	5.75, 102.203016, 6	3526.00406	6716.527892	m€5.04
1	58.913535, 2, 6	706.962425	1732.985233	m€1.30
2	82.496244, 9, 6	4454.797162	8050.365486	m€6.04
3	181.016247, 6.5, 6	7059.633636	13161.945207	m€9.87

Example - volume claims vs HFI tower height

3. Reverted HF towers

Tower Types

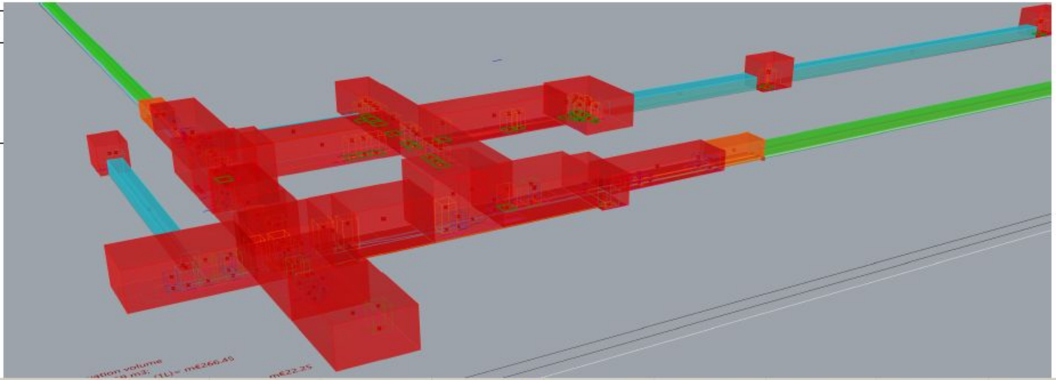
	Tot. Height (m)	Clearance (m)
T7_3m	3	2
T6_5m	5	3
HF_T6_5m	8	6
T5_6m	6	6
T4_8m	8	6
T3_10.5m	10.5	6
T1_16m	16	6

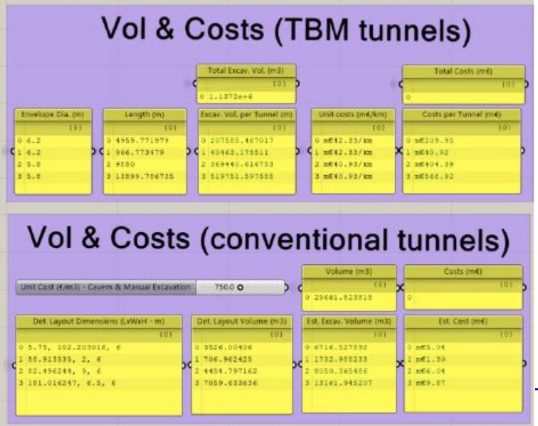
Back to previous assumption (HF_T6_5m)

Est. total excavation volume of caverns = 355269 m3; +10.6%
Est. total cost of caverns (1L):

Est. total excavation volume of conventional tunnels = 29662 m3;
Est. total cost of conventional tunnels (1L):

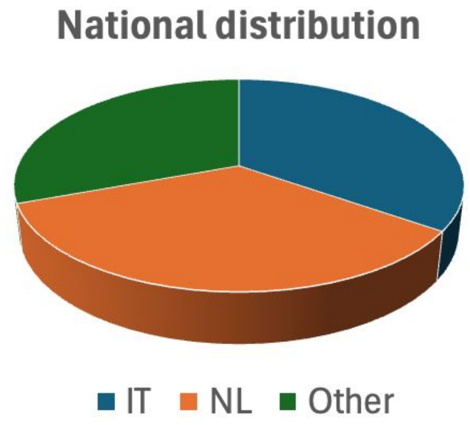
Est. total excavation volume of TBM tunnels = 1137241 m3;
Est. total cost of TBM tunnels (1L)=

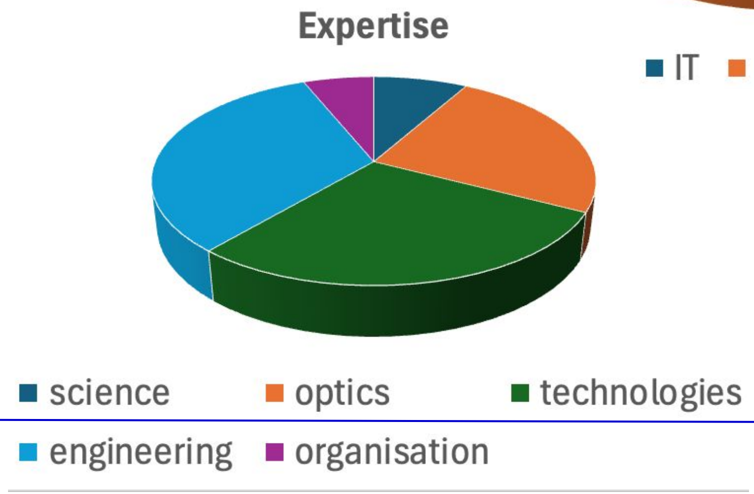




Task Force composition

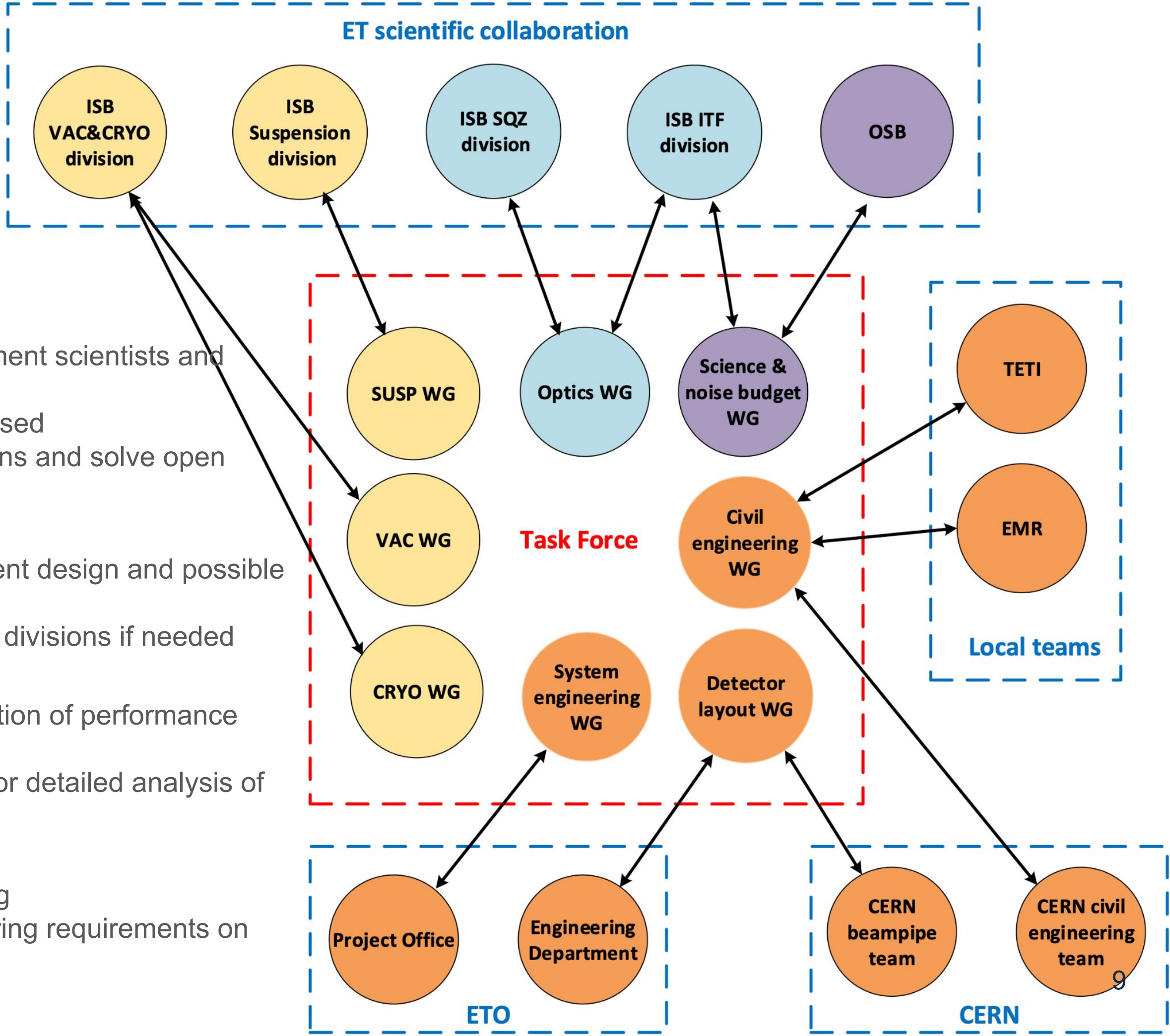
- 24 core team members
- 25 consultants
- National distribution
  - 35% from Italy
  - 35% from Netherland & Belgium
  - 30% from other countries
- Expertise distribution
  - 8% science case & noise budget (ETC ISB & OSB)
  - 24% optics (ETC ISB)
  - 29% instrument technologies (ETC ISB)
  - 33% engineering (ETO PD, ETO PO, local teams, CERN)
  - 6% organisation & management (ETO)





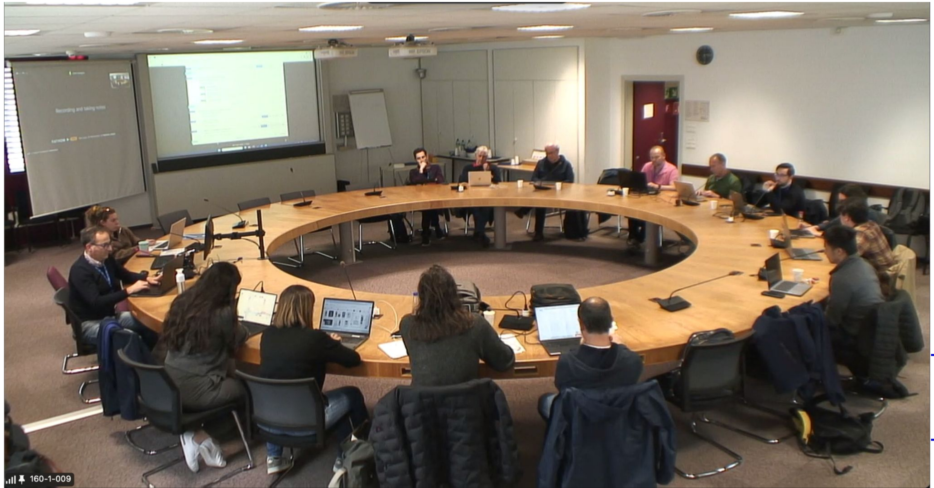
Working groups and external interactions

- Plenary Task Force meetings bring together instrument scientists and engineers;
  - outcome include design options to be analysed
  - asynchronous work to analyse design options and solve open questions for next iteration
- Task Force members from ISB
  - provide information about baseline instrument design and possible alternative options
  - share part of the open questions within ISB divisions if needed
- OSB liaisons
  - Provide prompt feedback for coarse evaluation of performance risk during configuration search
  - Carry out extensive analysis work to OSB for detailed analysis of science case on selected options
- Local teams liaisons
  - Share and refine criteria for civil engineering
  - Identify and discuss most relevant engineering requirements on infrastructure



Overview of Task Force work

- Started on January 2025
- Weekly plenary meetings - minutes on ET Wiki
- Aperiodic meetings with subgroups of experts (~2/week)
- In-person workshops - minutes on ET Wiki
  - 1st workshop - methods consolidation & 2L layout update - Pisa, February 18÷20
  - 2nd workshop - 2L layout consolidation - Amsterdam, March 18÷20
  - 3rd workshop - Triangle layout update - CERN May 5÷7
- Output delivered to external review team on 23/05
  - available on Gitlab to ETC
  - final version after review ~end of June



System decomposition - output tables

- TAB5: Civil Functional Volumes output table
- TAB3: ET-L Optical Layout output table
- TAB1: System Decomposition output table
- 20250506_18:22 Copy of TAB3: ET-L Optical Layout out
- 20250506_16:39 Copy of TAB3: ET-L Optical Layout out
- TAB6: ET Sensitivity and Noise Budget output table
- TAB4: Technical Infrastructure output table
- TAB2: Integrated Towers output table

TAB6: ET Sensitivity and Noise Budget output table

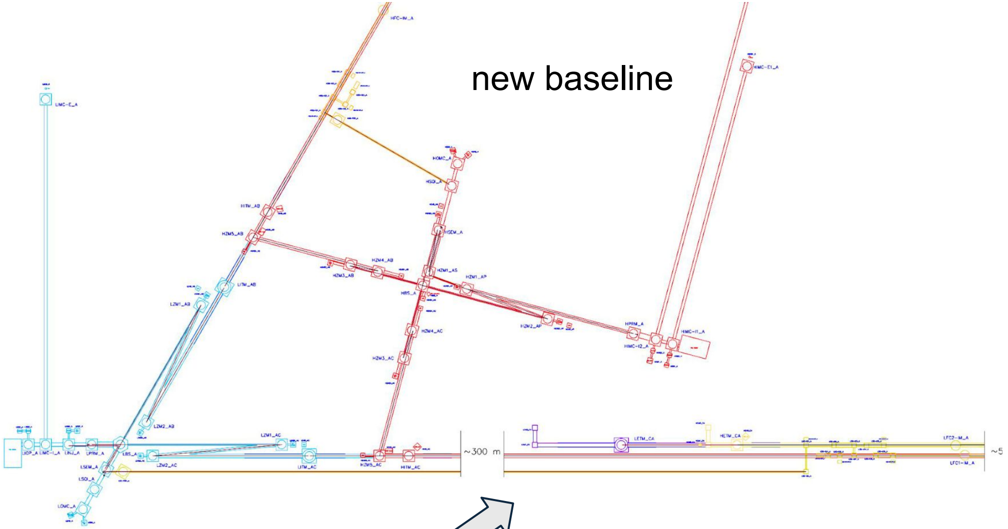
	System ID	System Name	Type	#	Parameter ID	Parent ID(s)	Parameter	Readiness	Specification/Requirement	Tolerance	Rationale
2	SYS_003	HFI	REQ	0300	REQ0300	REQ0001	HF_sens_full		The HF detector sensitivity levels shall remain equal to or below the reference Taskforce HF_sens curve		Reference to [src:Taskforce_sensitivity_curves]. The HF sensitivity curve is 'sum' of individual noise contributions
3	SYS_003	HFI	REQ	0301	REQ0301	REQ0300	HF_sens_quantum		The sum of noise contributions with a source in Quantum domain shall remain equal to or below the reference Taskforce HF_sens_quantum curve		Reference to [src:Taskforce_sensitivity_curves]. The HF sensitivity curve for quantum noise is the 'sum' of individual noise contributions (in power spectral densities)
4	SYS_003	HFI	SPC	0300	SPC0300	REQ0301	HF_sens_quantum_RelASSqz		The designed contribution to quantum noise of the squeezed vacuur		Reference to [src:qauntum_noise curve]. This curve corresponds to the contribution from (squeezed) quantum vacuum coming from the squeezer
5	SYS_003	HFI	SPC	0301	SPC0301	REQ0301	HF_sens_quantum_RelASMisrotation		The designed contribution to quantum noise due to misrotation of the		Reference to [src:qauntum_noise curve]. This curve corresponds to the contribution anti-squeezing coupled into the signal quadrature due to misrotation of the squeezing ellipse from the optimal angle
6	SYS_003	HFI	SPC	0302	SPC0302	REQ0301	HF_sens_quantum_XiDephase		The designed contribution to quantum noise due to the dephasing at FC/IFO is defined by the corresponding sensitivity curve		
7	SYS_003	HFI	SPC	0303	SPC0303	REQ0301	HF_sens_quantum_XiBroadBand		The designed contribution to quantum noise due to the phase noise is defined by the corresponding sensitivity curve		
8	SYS_003	HFI	SPC	0304	SPC0304	REQ0301	HF_sens_quantum_XiFC		The designed contribution to quantum noise due to the coupling of FC length RMS to phase noise is defined by the corresponding sensitivity curve		
9	SYS_003	HFI	SPC	0305	SPC0305	REQ0301	HF_sens_quantum_XiSEC		The designed contribution to quantum noise due to the coupling of SEC length RMS to phase noise is defined by the corresponding sensitivity curve		
10	SYS_003	HFI	SPC	0306	SPC0306	REQ0301	HF_sens_quantum_MM		The designed contribution to quantum noise due to the mode mismatch is defined by the corresponding sensitivity curve		
11	SYS_003	HFI	SPC	0307	SPC0307	REQ0301	HF_sens_quantum_Arm		The designed contribution to quantum noise due to the optical loss in the arm cavities is defined by the corresponding sensitivity curve		
12	SYS_003	HFI	SPC	0308	SPC0308	REQ0301	HF_sens_quantum_SEC		The designed contribution to quantum noise due to the optical loss in the SEC is defined by the corresponding sensitivity curve		
13	SYS_003	HFI	SPC	0309	SPC0309	REQ0301	HF_sens_quantum_FilterCavity		The designed contribution to quantum noise due to the optical loss in the filter cavities is defined by the corresponding sensitivity curve		
14	SYS_003	HFI	SPC	0310	SPC0310	REQ0301	HF_sens_quantum_Injection		The designed contribution to quantum noise due to the optical loss upon injection path from squeezer to IFO is defined by the corresponding sensitivity		
15	SYS_003	HFI	SPC	0311	SPC0311	REQ0301	HF_sens_quantum_Readout		The designed contribution to quantum noise due to the optical loss upon readout path from IFO to the homodyne detector is defined by the correspond		
16	SYS_003	HFI	REQ	0302	REQ0302	REQ0300	HF_sens_seismic		The sum of noise contributions with a source in seismic domain shall remain equal to or below the reference Taskforce HF_sens_seismic curve		
17	SYS_003	HFI	SPC	0312	SPC0312	REQ0302	HF_sens_seismic_HR		The designed contribution to seismic noise due to horizontal coupling is defined by the corresponding sensitivity curve		
18	SYS_003	HFI	SPC	0313	SPC0313	REQ0302	HF_sens_seismic_HB				
19	SYS_003	HFI	SPC	0314	SPC0314	REQ0302	HF_sens_seismic_VR				
20	SYS_003	HFI	SPC	0315	SPC0315	REQ0302	HF_sens_seismic_VB				
21	SYS_003	HFI	SPC	0316	SPC0316	REQ0302	HF_sens_seismic_TR				
22	SYS_003	HFI	REQ	0303	REQ0303	REQ0300	HF_sens_newtonian				
23	SYS_003	HFI	SPC	0317	SPC0317	REQ0303	HF_sens_newtonian_BodyWave				
24	SYS_003	HFI	SPC	0318	SPC0318	REQ0303	HF_sens_newtonian_RayleighWave				
25	SYS_003	HFI	SPC	0319	SPC0319	REQ0303	HF_sens_newtonian_Cavern				
26	SYS_003	HFI	SPC	0320	SPC0320	REQ0303	HF_sens_newtonian_Atmospheric				
27	SYS_003	HFI	REQ	0304	REQ0304	REQ0300	HF_sens_coating				
28	SYS_003	HFI	SPC	0321	SPC0321	REQ0304	HF_sens_coating_Brownian				
29	SYS_003	HFI	SPC	0322	SPC0322	REQ0304	HF_sens_coating_ThermoOptic				
30	SYS_003	HFI	REQ	0305	REQ0305	REQ0300	HF_sens_substrate				
31	SYS_003	HFI	SPC	0323	SPC0323	REQ0305	HF_sens_substrate_Brownian				
32	SYS_003	HFI	SPC	0324	SPC0324	REQ0305	HF_sens_substrate_ThermoElastic				

Readme | Einstein Telescope | High-Frequency Interferometer | Low-Frequency Interferometer | REF: System Decomposition | draftLF | draftHF

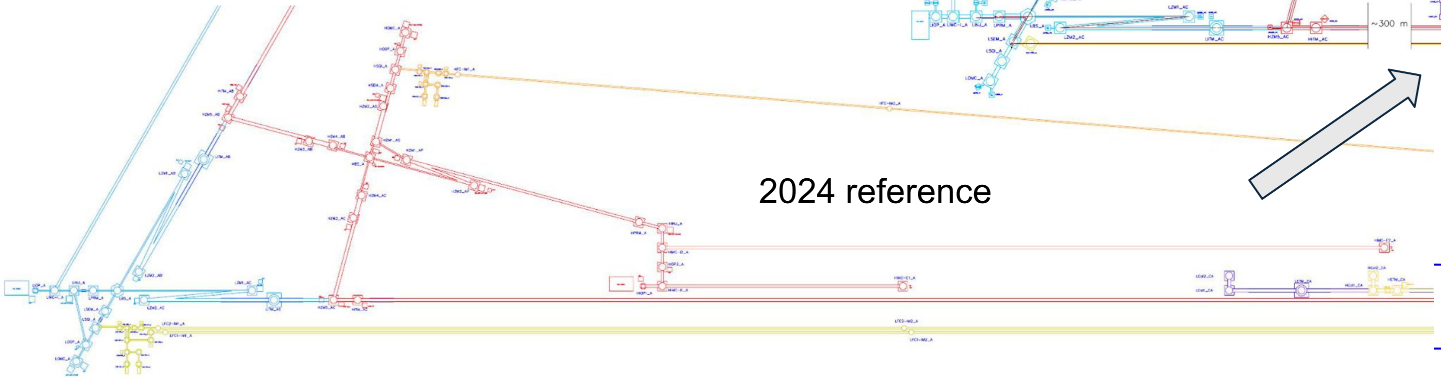
Optical layout update

- Main driver for civil infrastructure cost is from tunnels (arm + FC + IMC)
  - ~ 3200 m^3 in 2L (~80% of total volume)
  - ~ 2500 m^3 in Triangle (~70% of total volume)
- Main actions within Task Force
  - Move all filter cavities in main tunnels
  - Reduce length of input mode cleaners
  - Reduce number of nodes (towers) and connections (pipes) in vertex cavern

new baseline

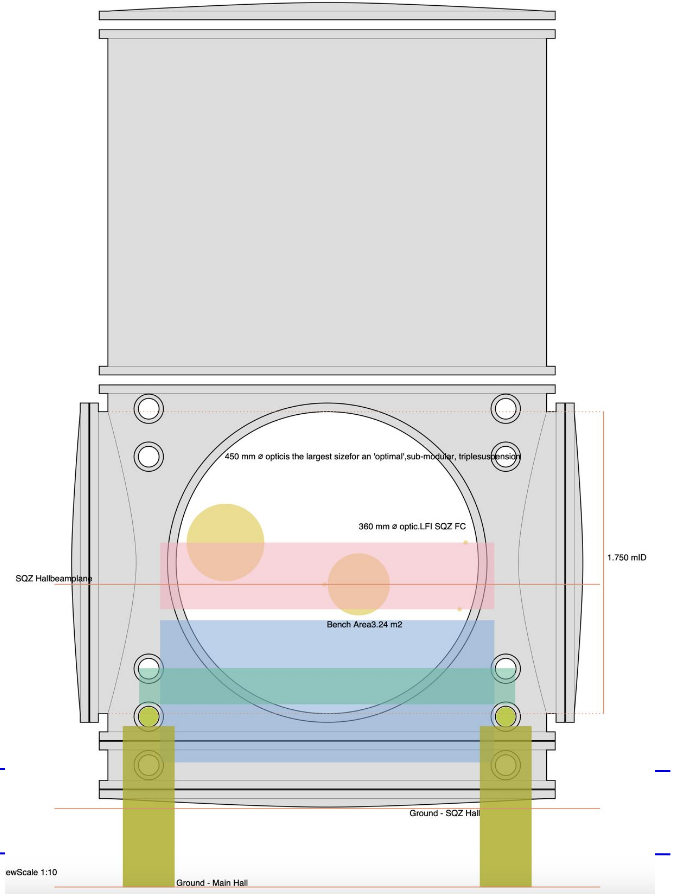


2024 reference



Integrated towers

- Identified main interfaces between design elements determining height and footprint of detector layout nodes
  - Seismic isolation and payload
  - Vacuum tank and access type
  - Cryostat and cryogenic payload for LF_TM
- Seismic isolation:
  - Improved categorisation
  - reduction of benches footprint and tower height wherever convenient
    - 29% reduction in overall caverns volume
- Tank access:
  - Identification of main constraints from optical layout, suspension design, cryogenic system
  - Identification of interface with technical infrastructure (clean rooms)
- Cryogenic systems:
  - Identification of available design options
  - Assessment of impact on detector layout and on civil infrastructure



Flexibility envelope & flexibility demands

- **Upgrade over 2024 reference optical layout**: extended flexibility **envelope** for **optical** layout, included basic **demands** from **optical** layout, introduced flexibility **envelope** for **detector** layout

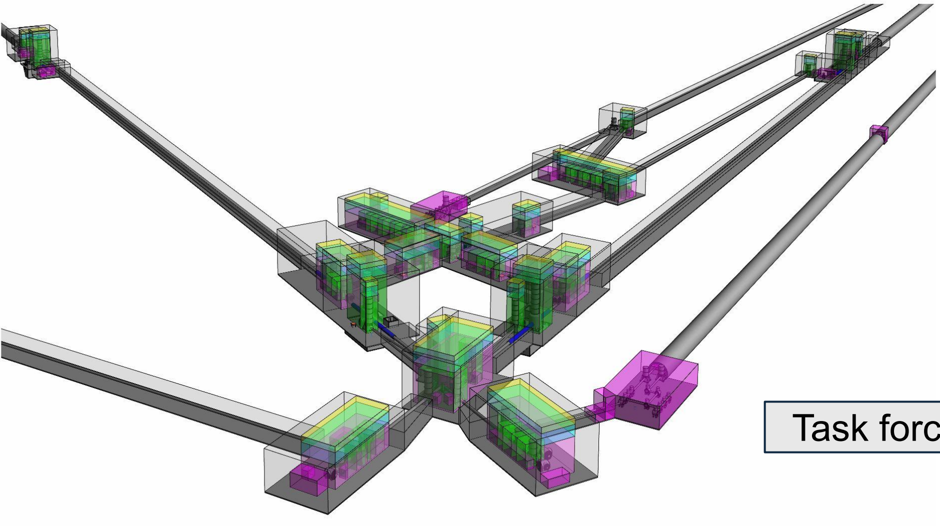
System	Location	Optical Element Type	OLD P	*Parameter (auto-generated)	Parameter Type	Primary optical surface or group of optics	Secondary optical surface or group (if required)	Value	unit	Tolerance	Readiness	Flexibility Envelope	OLD Specification/Requirement (by-hand)	*Sp
HF	ARMY	Single optic	HF-ET	HF ETMY-HR orientation	orientation	ETMY-HR	ITMY-HR	0	deg		experimental v...	none	HF-ETMY shall have a normal AOI with relation to HF-ITMY	HF 0 de
HF	RCY	Single optic	HF-ZY	HF ZY3-HR orientation	orientation	ZY3-HR	ZY2-HR	45	deg		analytical or n...	major redesign	The AOI at HF-ZY3 to HF-ZY2 shall be 45 degrees	HF . deg
HF	RCY	Single optic	HF-ZY	HF ZY1-HR orientation	orientation	ZY1-HR	ZY2-HR	2.5	deg		analytical or n...	major redesign	The AOI at HF-ZY2 to HF-ZY1 shall be 2.5 degrees	HF . 2.5
HF	ARMX	Single optic	HF-ET	HF ETMX-HR orientation	orientation	ETMX-HR	ITMX-HR	0	deg		experimental v...	none	HF-ETMX shall have a normal AOI with relation to HF-ITMX	HF 0 de
HF	RCX	Single optic	HF-ZX	HF ZX2-HR orientation	orientation	ZX2-HR	ZX3-HR	45	deg		analytical or n...	major redesign	The AOI from HF-ZX3 to HF-ZX2 shall be 45 degrees	HF . deg
HF	RCX	Single optic	HF-ZX	HF ZX1-HR orientation	orientation	ZX1-HR	ZX2-HR	2.5	deg		analytical or n...	major redesign	The AOI from HF-ZX2 to HF-ZX1 shall be 2.5 degrees	HF . 2.5
HF	RCS	Single optic	HF-ZS	HF ZS1-HR orientation	orientation	ZS1-HR	ZS2-HR	1.56	deg		analytical or n...	major redesign	The AOI from HF-ZS1 to HF-ZS2 shall be 1.56 degrees	HF . 1.5
HF	RCS	Single optic	HF-SE	HF SEM-HR orientation	orientation	SEM-HR	ZS1-HR	1.56	deg		analytical or n...	major redesign	The AOI from HF-SEM to HF-ZS1 shall be 1.56 degrees	HF 1.5
HF	RCP	Single optic	HF-ZP	HF ZP1-HR orientation	orientation	ZP1-HR	ZP2-HR	2.44	deg		analytical or n...	major redesign	The AOI from HF-ZP1 to HF-ZP2 shall be 2.44 degrees	HF . 2.44
HF	RCP	Single optic	HF-PR	HF PRM-HR orientation	orientation	PRM-HR	ZP1-HR	2.44	deg		analytical or n...	major redesign	The AOI from HF-PRM to HF-ZP1 shall be 2.44 degrees	HF 2.44
HF	global	Group of optics	HFI_c	HF unresolved - requires input	unresolved - r...				?		experimental v...	none	HFI X- and Y-cavities shall have symmetrical optical paths	?
HF	RCS	Single optic	HF-ZS	HF unresolved - requires input	unresolved - r...				?		analytical or n...	major redesign	HF-ZS2 shall be along the same axis as HF-BS and HF-ZY1	?
HF	RCP	Single optic	HF-ZP	HF unresolved - requires input	unresolved - r...				?		analytical or n...	major redesign	HF-ZP2 shall be along the same axis as HF-BS and HF-ZX1	?
HF	IN	Group of optics	HF-PS	HF PSL room footprint	footprint (shape)	PSL room		8x10	m		assumption	freedom on orientation	HF-PSL room surface area shall be at least 6x10m, with additional 2x10m along the side for hosting laser- & input/output electronic racks	The be 8
HF	OUT	Group of optics	HF-SC	HF unresolved - requires input	unresolved - r...				?		assumption		HF-SQI shall be in-line with HF-SEM and HF-ZS1	?
HF	ARMY	Single optic	HF-ET	HF ETMY-HR position	position	ETMY-HR	ITMY-HR	15000	m		analytical or n...	major redesign	The distance from HF-ETMY to HF-ITMY shall be 15000m	The be
													~~The distance along the optical path~~	

+ 3A: general | 3B: layout | 3C: optic specs | 3D: flexibility demands | old_HF-SQZ | old_LF-SQZ | REF: System Decomposition

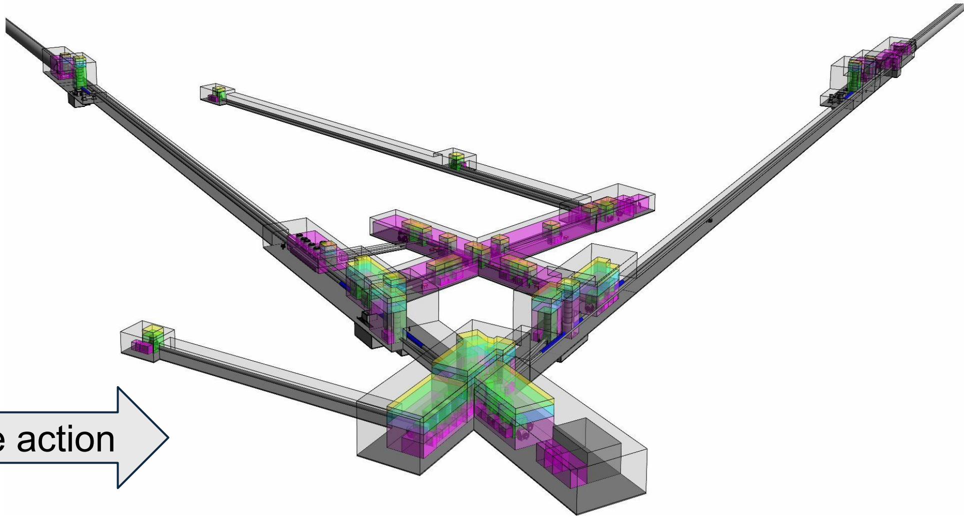
Detector layout - Triangle

2024 reference

new baseline design from Task Force:
~25% volume reduction



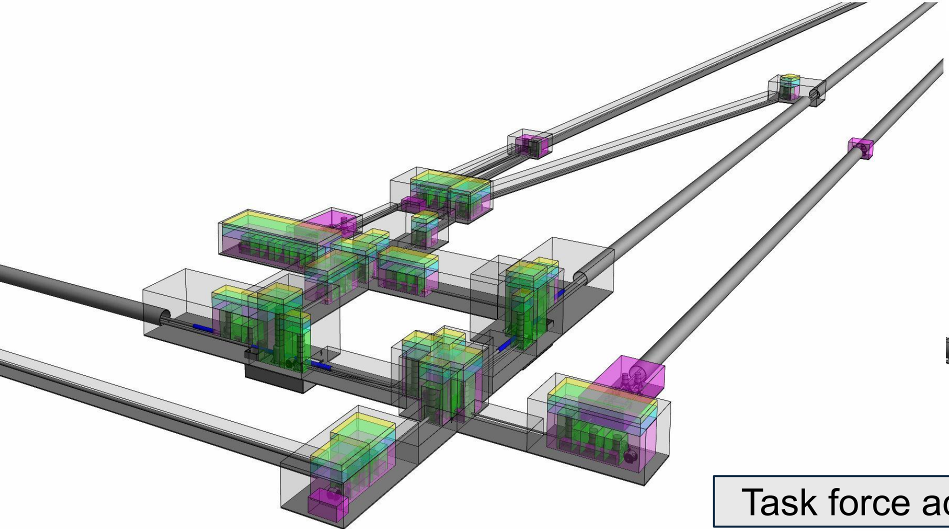
Task force action

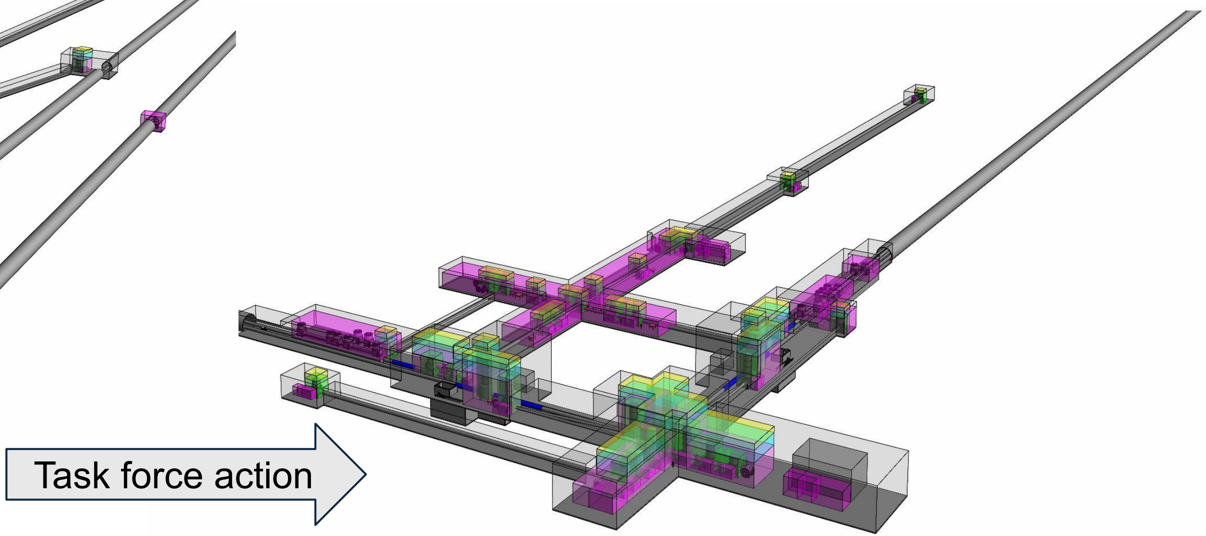


Detector layout - 2L

2024 reference

new baseline design from Task Force:
~28% volume reduction





Main outcomes from Task Force

- The ETO task force produced a new **baseline detector layout** for both triangle and 2L geometries
- Main features in comparison with 2024 reference detector layouts
  - Basic system decomposition - interfaces and requirements flow between instrument & infrastructure
  - Updated optical layouts
    - **Filter cavities in arm tunnels**, reduced length for IMC tunnels, simplified vertex design
    - Update of flexibility envelope, assessment of flexibility demands
  - Full classification of integrated towers, with reduction of benches footprint and tower height
  - Detector layout update
    - Better definition of technical infrastructure (cryogenics, clean rooms, noisy rooms)
    - Assessment of flexibility envelope
  - Interface with civil engineering
    - Identification of main cost drivers, estimate relative cost changes vs detector layout configuration
    - Identification of main engineering requirements on technical and civil infrastructure
  - Risk and flexibility analysis on design choices and alternative configurations
  - Noise budget, comparison with the official ET science case, scientific requirements on design parameters
  - Volume claims and infrastructure cost **reduced by ~25%** from 2024 reference layouts
- The new baseline detector layout corresponds to a **cost-effective** baseline design for the ET instrument
  - Further minor reduction of infrastructure cost may be achieved at the cost of substantial technical risk
  - Substantial reduction of infrastructure cost may only be achieved by descoping of the ET science case

Output documentation

Main document (74 pages): baseline detector layout

EINSTEIN TELESCOPE — The ET Baseline Detector Layout — date : May 24, 2025 page : 1 of 73

Contents

Extended supporting document (197 pages): details and study logic

EINSTEIN TELESCOPE — Supporting Document for The ET Baseline Detector Layout — issue : 1 date : May 24, 2025 page : 1 of 197

Contents

Technical annexes (33 additional files): tables, 2D&3D drawings, technical specifications

Name

- Technical Drawings for distribution
  - Triangle
    - Cross-sections arm cavity tunnel (triangle configuration).pdf
    - 2025-05-21 ET Triangle Optical Layout vector version.dwg
    - 2025-05-21 ET Triangle Optical Layout (vector version).pdf
    - 2025-05-21 ET Triangle Optical Layout (scale version).pdf
    - 2025-05-21 ET Triangle Detector Layout.pdf
    - 2025-05-21 ET Triangle Detector Layout.dwg
  - L
    - Cross-sections arm cavity tunnel (L configuration).pdf
    - 2025-05-21 ET L Optical Layout (vector version).pdf
    - 2025-05-21 ET L Optical Layout (vector version).dwg
    - 2025-05-21 ET L Optical Layout (scale version).pdf
    - 2025-05-21 ET L Detector Layout.pdf
    - 2025-05-21 ET L Detector Layout.dwg
- TD4 - Tower CAT mapping drawings
  - 2025-05-23 ET Triangle Tower CAT mapping.pdf
  - 2025-05-23 ET 2L CAT mapping.pdf
- Risk - TRL -DSM - PoC Technical Annexes
  - Volume and Cost Calculations - Penalty of Change.xlsx
  - Technology Readiness Level TRL Study.xlsx
  - Full Risk Study.xlsx
  - DSM - Rigidity Matrix.xlsx
- Output tables
  - Triangle (TAB1-6)
    - TAB6_ ET-Triangle Sensitivity and Noise Budget output table - FINAL.pdf
    - TAB5_ ET-Triangle Civil Functional Volumes output table - FINAL.pdf
    - TAB4_ ET-Triangle Detector Layout output table - FINAL.pdf
    - TAB3_ ET-Triangle Optical Layout output table - FINAL.pdf
    - TAB2_ ET-Triangle Integrated Towers output table - FINAL.pdf
    - TAB1_ ET-Triangle System Decomposition output table - FINAL.pdf
  - 2L (TAB7-12)
    - TAB12_ ET-2L Sensitivity and Noise Budget output table - FINAL.pdf
    - TAB11_ ET-2L Civil Functional Volumes output table - FINAL.pdf
    - TAB10_ ET-2L Detector Layout output table - FINAL.pdf
    - TAB9_ ET-2L Optical Layout output table - FINAL.pdf
    - TAB8_ ET-2L Integrated Towers output table - FINAL.pdf
    - TAB7_ ET-2L System Decomposition output table - FINAL.pdf
- 3D Detector Layout Model Links
  - 250523_Trimble_Connect_quick_guide.pdf
  - 2025 ET Baseline Triangle Detector Layout.url
  - 2025 ET Baseline L Detector Layout.url

Conclusions

- Civil & technical infrastructure are essential components of the ET project
  - instrument and infrastructure design are closely interconnected
- In 4.5 months the Task Force produced a first baseline layout of the ET detector accounting for interfaces with civil and technical infrastructure
  - civil infrastructure would be ~25% cheaper than with 2024 reference detecto layout
- Extraordinary effort by team members
  - final outcome is larger and better than my expectations
  - joint work of instrument scientists and engineers played a key role
- Material will be useful for engineering studies by local teams
- Methods can be useful for next steps to generate a full ET TDR
  - but emergency operation should **not** be taken as an example

Spare slides

Task Force composition - core team

Name	institution	main expertise
Anna Green	Nikhef	optics
Antonio Perreca	Trento University	optics
Marco Vardaro	Maastricht University	squeezing
Nathan Holland	Nikhef	Seismic isolation
Leonardo Lucchesi	INFN Pisa	Seismic isolation
Antonino Chiummo	EGO	Optics, injection
Francesca Spada	INFN PIsa	Seismic isolation, suspended benches
Paolo Ruggi	EGO	Seismic isolation
Julien Gargiulo	EGO	Vacuum, cryogenics
Henk Jan Bulten	Nikhef	Cryogenics, seismic isolation
Fulvio Ricci	Roma 1 University	Cryogenics
Angelo Cruciani	INFN Roma 1	Cryogenics
Jonathan Bratanata	Nikhef	Civil engineering
Max Majoor	Nikhef	Technical engineering
Mikhail Korobko	Hamburg University	Optics, squeezing, noise budget
Elena Licciardello	INFN-LNS	Civil engineering, TETI liaison
Romano Meijer	Nikhef	System engineering
Ghada Mahmoud	APC	Risk management
Benoit Tuybens	Nikhef	Organisation and documentation
Fiodor Sorrentino	INFN	Coordination
Ulyana Dupletsa	GSSI	OSB liaison
Francesco Iacovelli	Geneve University	OSB liaison
Patricia Lamas	Amberg Engineering	EMR liaison
Tamara Alice Bud	CERN	Civil engineering

NL
IT
other

science
optics
technologies
engineering
organisation

Task Force composition - consultants

Name	institution	main expertise
Tommaso Napolitano	INFN	ETO ED
Paolo Martella	INFN	TETI Liaison
Jan Vesely	EMR	EMR liaison
Tom Hundertmark	EMR	EMR liaison
Jerome Degallaix	IN2P3	optics
Daniel Brown	Adelaide University	optics
Giacomo Ciani	Trento University	squeezing, optics
Julia Casanueva	EGO	controls
Sebastian Steinlechner	Maastricht University	Optics, general
Conor Mow-Lowry	Nikhef	Seismic isolation
Antonio Pasqualetti	EGO	Vacuum, cryogenics
Steffen Grohman	KIT	Cryogenics

Name	institution	main expertise
Ettore Majorana	Roma 1 University	Cryogenics, payload
Piero Rapagnani	Roma 1 University	Cryogenics, payload
Wissam Wahbeh	Roma 1 University	Civil engineering
Maria Marsella	Roma 1 University	Civil engineering
Patrick Werneke	Nikhef	Technical engineering
Andreas Freise	Nikhef	Broad instrument expertise
Riccardo de Salvo	n.a.	Broad instrument expertise
Marco Galimberti	EGO	Optics, large infrastructures
Lucia Lilli	INFN Pisa	Organisation and documentation
Archisman Ghosh	Gent University	OSB liaison
Joseph Ickmans	EMR	EMR liaison
John Andrew Osborne	CERN	Civil engineering
Valeria Sequino	INFN	Optics, squeezing, noise budget

Configurations for Triangle and 2L

- New baseline: main changes from 2024 reference
  - LF Filter cavities in X arm with periscope
  - HF filter cavity in Y arm with periscope
  - 2-mirror FC -> reduced pipe diameter
  - Reduced length of LF IMC
  - Merging HF IMCs in same tunnel
  - Route BHD through BS
  - Other reshuffling in central area
  - Tower access constrained on LF_TM (bottom), SQZ (lateral), and few other
    - in flexibility envelope otherwise
  - Reduced LF TM susp. height to 13 m
  - Reduced tower height for other HFI optics
  - Reduce footprint of CAT1 benches

Alternative configurations

1. Double cavern
2. No periscope for LF_FC
3. Alternative routing for SQZ beam
4. Bow-tie IMC
5. Reduced tower height for HF TM
6. Reduced tower height for LFI optics
7. Reduced cryostat size

Configuration changes for Triangle & 2L

Ratio of (cost-volume reduction in CI)/(risk & flexibility cost)
High
Medium
Low

- Optical layout
  - LF Filter cavities in X arm
    - with periscope
      - two alternative routings
    - without periscope
  - HF filter cavity in Y arm
  - 2-mirror FC -> reduced pipe diameter
  - Reduced length of LF IMC
  - Merging HF IMCs in same tunnel
  - Route BHD through BS
  - Other reshuffling in central area
  - Bow-tie IMC

- Integrated tower
  - Tower access constrained on LF_TM (bottom), SQZ (lateral), and few other
    - in flexibility envelope otherwise
  - Reduced LF TM susp. height to 12 m
  - Reduced tower height for HF TM
  - Reduced tower height for other HFI optics
  - Reduced tower height for LFI optics
  - Reduce footprint of CAT1 benches
  - Reduced cryostat size
- Detector layout
  - Double cavern

Analysis on configurations for Triangle & 2L

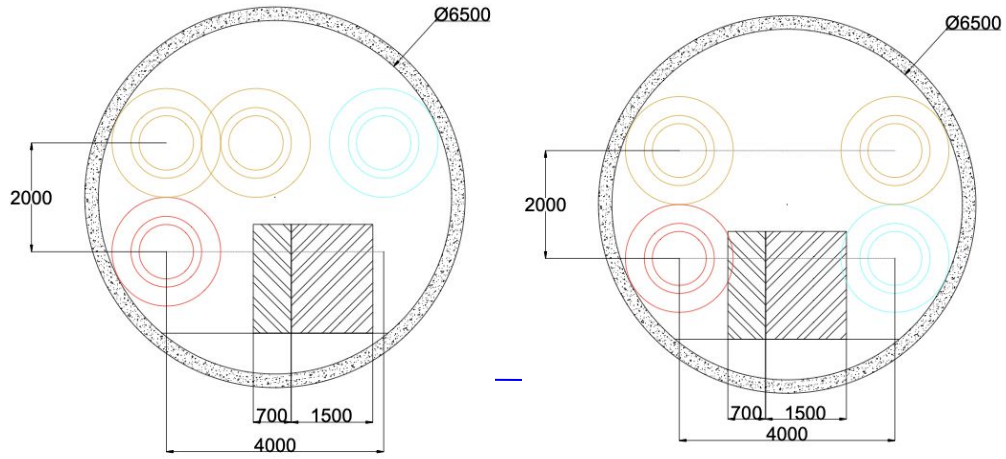
- Compare cost-volume reduction on CI and risk/flexibility cost of each option
- Validate preferred configuration in detail
  - combine all compatible green options
  - merge equivalent options into flexibility envelope
- Analysis on global configurations for main document
  - Compare 2024 reference with chosen configuration (new baseline)
    - separately for Triangle and 2L
  - consider an individual configuration for each considered change (green in the list)
  - for each configuration estimate change in
    - civil infrastructure cost
    - technical risk
    - Flexibility
- For extended document repeat on yellow and red configuration changes

Flexibility envelope & flexibility demands

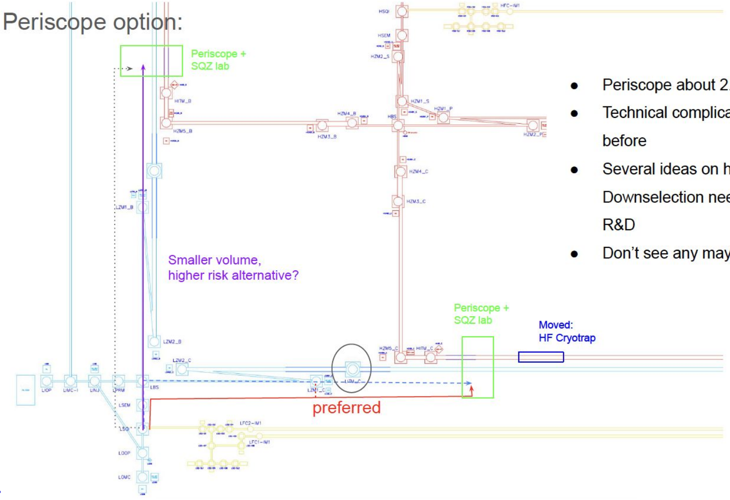
- **Requirement**: a required property of an element or a part of a subsystem
  - e.g. distance between 2 optical elements)
- **Tolerance**: the deviation that can be accepted for the element or subsystem to still fulfill its performance when constructed
  - e.g. deviation of the realised distance of the two optical elements compared to the design/nominal distance;
- **Flexibility Demand**: flexibility that is requested to be kept in the design at the current stage of the design process
  - e.g. we want to keep the possibility in the vacuum system / cavern design to be able to shift an optical element by e.g. 1 m sideways off the optical axis);
- **Flexibility envelope**: range of possible values that is given to the engineering team for optimisation
  - i.e. the optical design is based on a distance between two optical elements of e.g. 20 m (requirement) ±0.1 m (tolerance), but the optical design can be tuned to cope also if the distance is in the range from e.g. 15-25 m
- **Upgrade over 2024 reference optical layout**: extended flexibility **envelope** for **optical** layout, included basic **demands** from **optical** layout, introduced flexibility **envelope** for **detector** layout

Filter cavity positioning

- Configurations **for 2L geometry**
  - LF filter cavities in one arm tunnel (+ HF filter cavity in the other arm tunnel)
    - Possible options:
      - FCs on different plane from HFI and LFI
      - FCs on same plane as LFI, while HFI on different plane
    - Third option to separate LF FC into separate tunnels would increase vertex complexity without substantially reducing tunnel diameter



Periscope option:

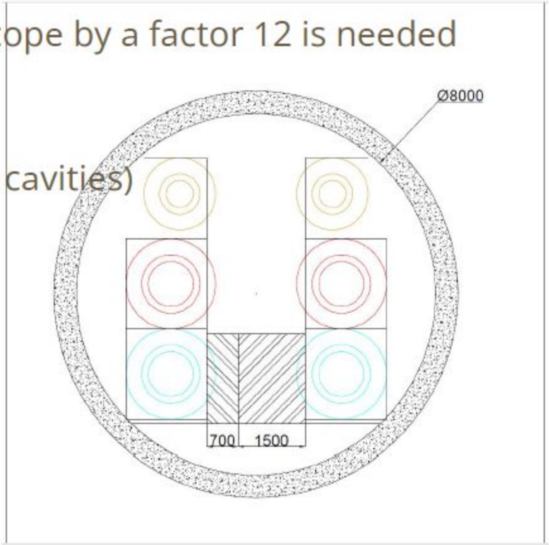


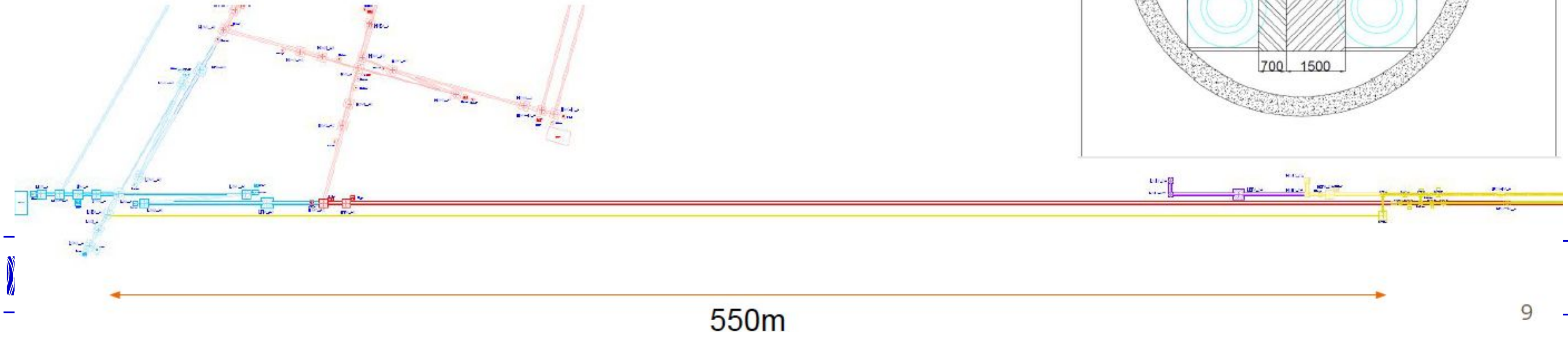
- Periscope about 2.5 meter tall
- Technical complication, not tested before
- Several ideas on how to implement it. Downselection needs further study and R&D
- Don't see any mayor showstopper

Filter cavity positioning - Triangle

In summary:

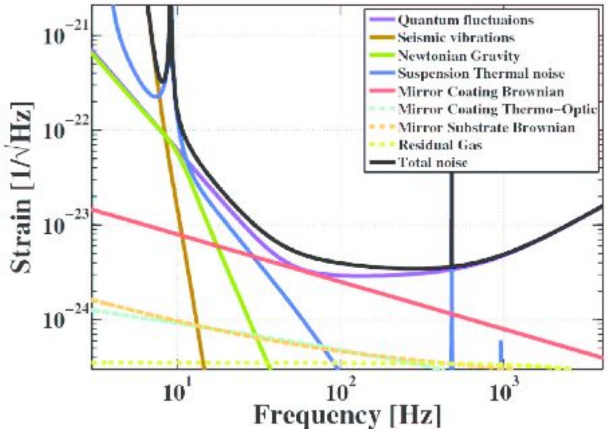
- 4.0m periscope
- 550m path from IFO to SQZ-lab
- Beam diameter should be around 4-5 cm thus beam reducing telescope by a factor 12 is needed between OFI and SEM vessels
- Flexibility on positioning of periscope (close to IFO or to SQZ-lab)
- 3.4m horizontal separation between cavities (3.8m for main ITF arm cavities)
- Preliminary tunnel layout results in 8.0m tunnel envelope diameter

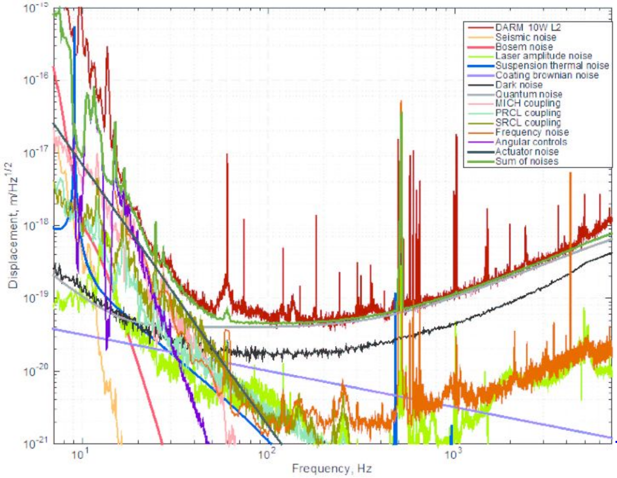


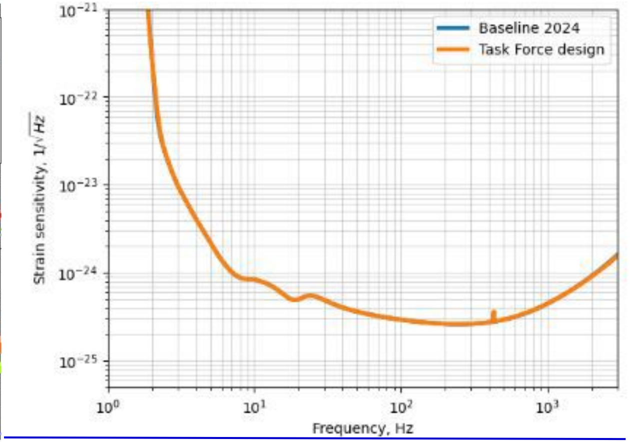


Integrated towers - seismic isolation

- aLIGO vs ET sensitivity:
  - 10x @30 Hz
  - 100x @10 Hz
  - ~10^6 @ 2÷3 Hz
- Direct transmission of seismic noise only relevant for ET_LF
- Control noise to be reduced by ~10÷100 in ET_HF, and by > 100 in ET LF

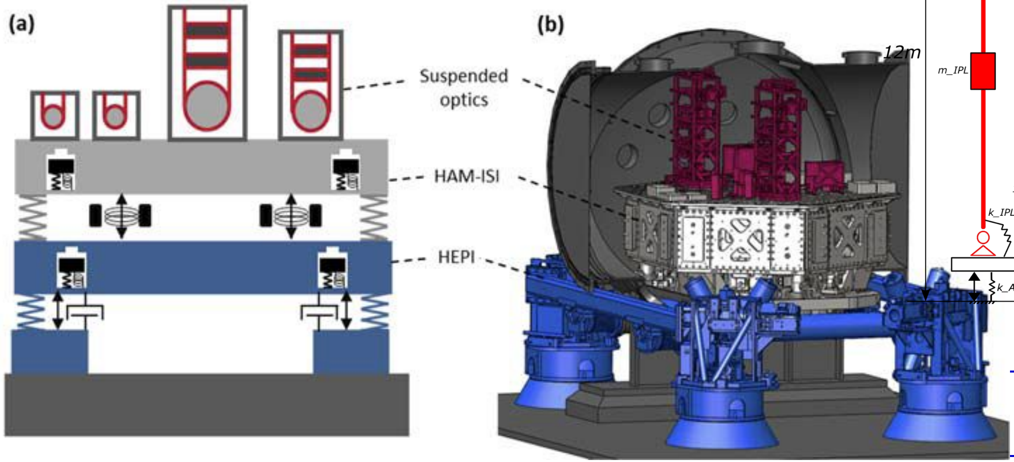


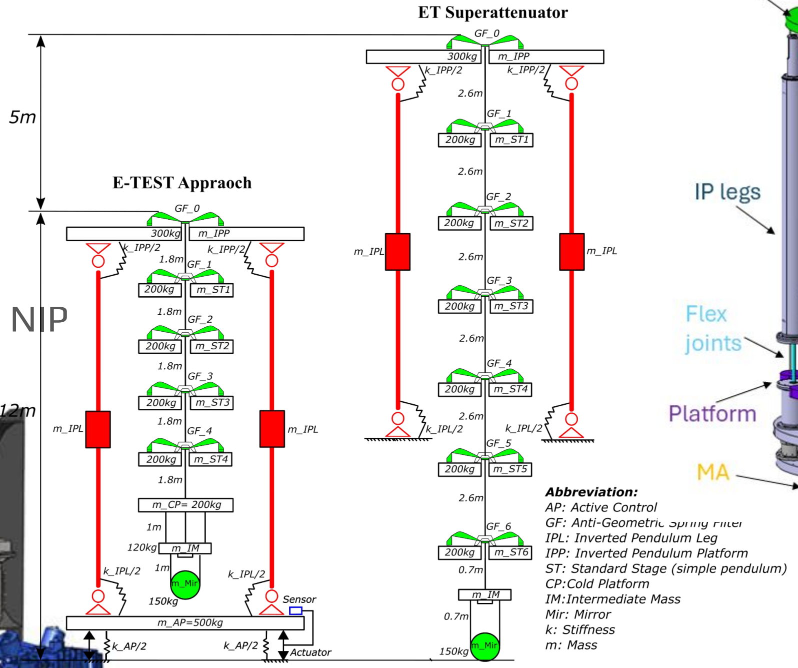


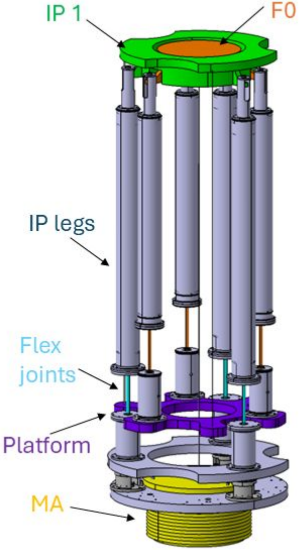


Integrated towers - seismic isolation

- Design concepts from existing detectors
- Soft suspension (Virgo)
  - highest filtering of direct seismic noise
  - Compatible with both access options
- Active platform (LIGO)
  - Compatible with co-located optics
  - Lateral access for top-loaded benches
  - Lower height
- Hybrid systems, e.g. E-TEST, or new concepts, e.g. NIP

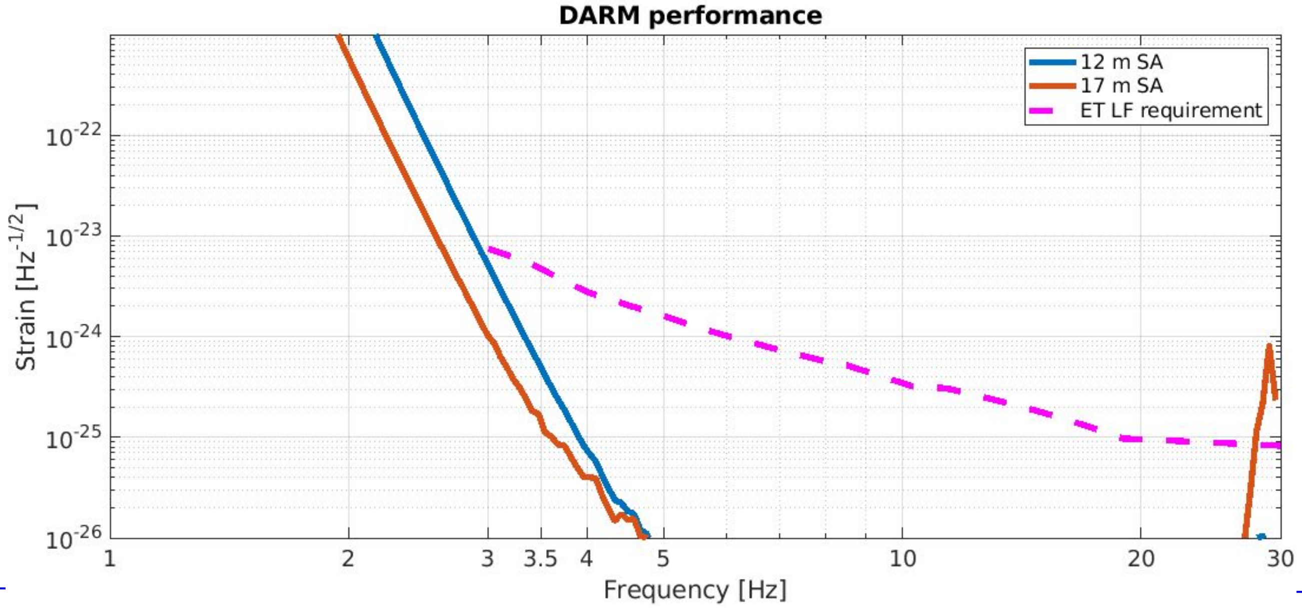






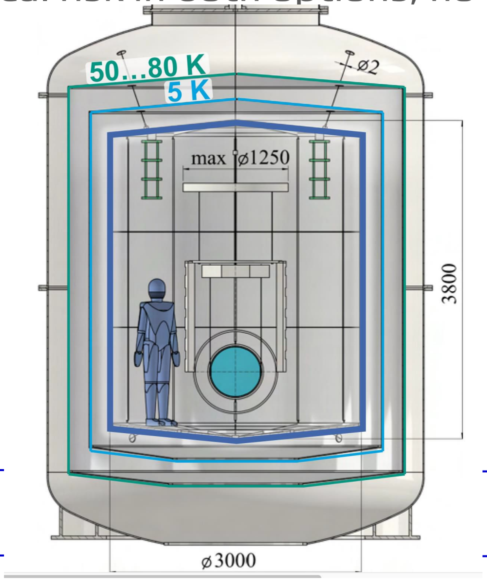
Integrated towers - seismic isolation

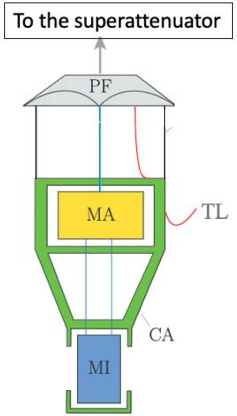
- For ET HF, new baseline has short suspensions (except TMs)
  - Compatible with moderate seismic noise requirements
- For ET LF, test mass tower reduction from 17 m to 12 m
  - compatible with science case

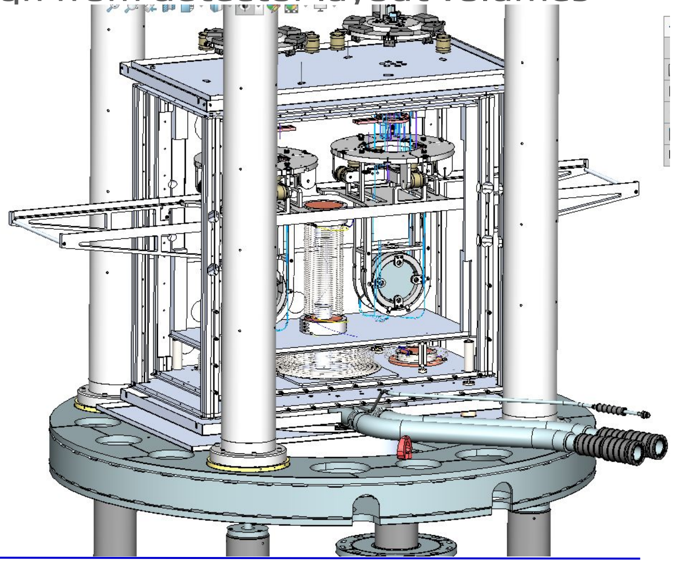


Integrated towers - cryogenic payload

- Baseline conceptual design from Instrument Science Board of ET collaboration
  - Bottom access, tank footprint diameter ~5 m
- Alternative concept from ET Pathfinder to reduce size of cryostat
  - lateral access, tank footprint diameter ~4÷5 m
  - inverted pendulum base underneath cryostat
- No impact on tunnel diameter for 2L, marginal impact for Triangle
- Large technical risk in both options, no need to constrain design from detector layout volumes

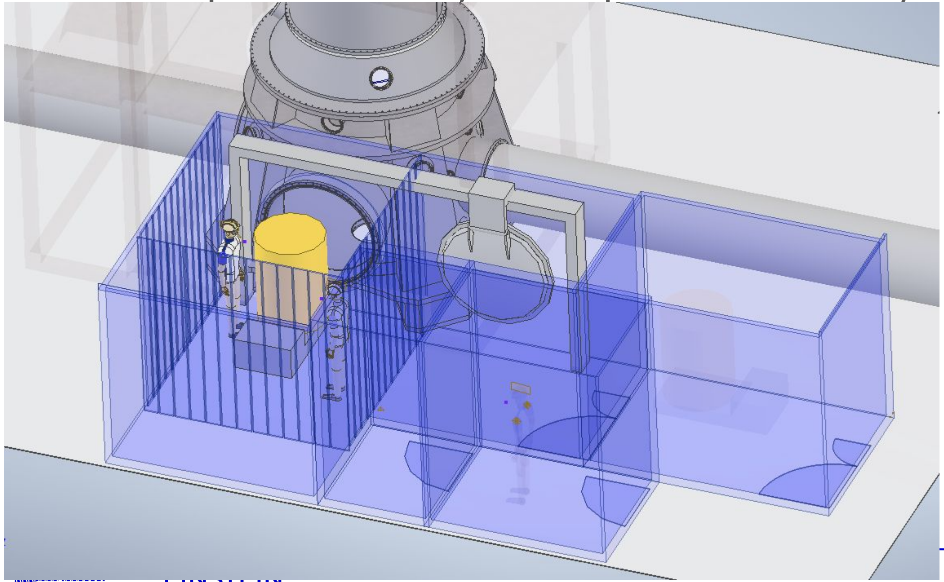


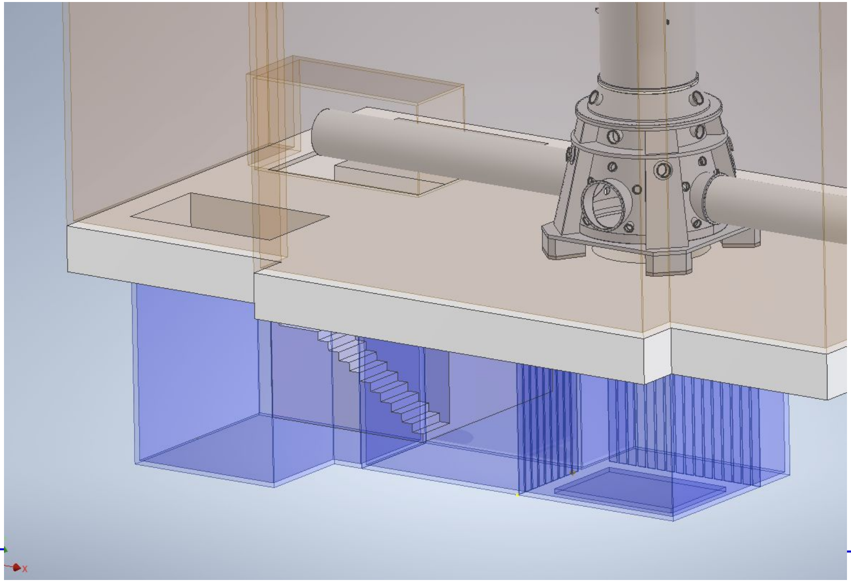




Integrated towers - tank access

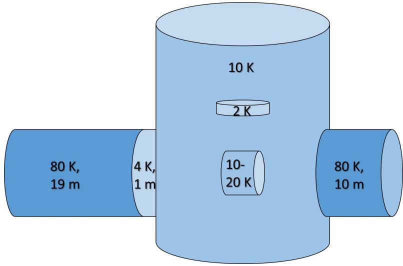
- Two types of access: lateral and bottom access
  - pros and cons of access options identified
- Assessment of sizes for different cleanroom classes from cleanliness requirements
- Assessment on constraints for tower access from optica/detector layout or from suspension design
  - input to flexibility envelope of detector layout

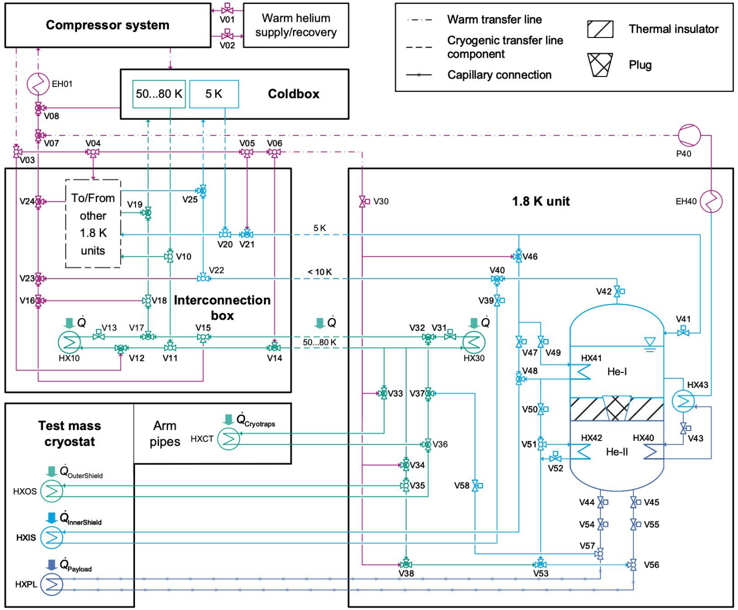


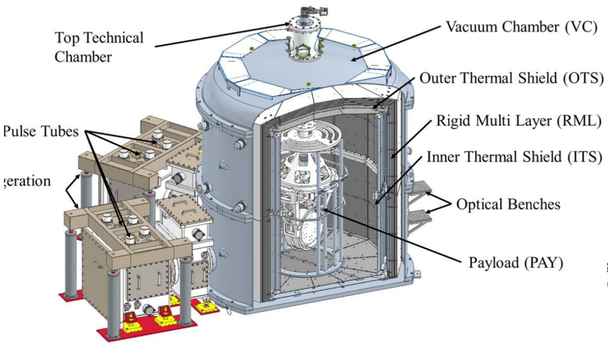


Detector layout - cryogenic system

- Three main tasks
  - 10 K cryogenic payload and surrounding cryostat for thermal noise mitigation on LF TM
  - cryotraps around LF TM for thermal shield
  - other cryotraps for UHV in both LFI and HFI
- Baseline design: liquid He distribution for all tasks (Instrument Scienc Board in ET collaboration)
- Alternative concepts:
  - battery of pulse tubes (KAGRA): issues with underground power dissipation, noise
  - liquid N + sorption coolers (ET Pathfinder): issues with safety, efficiency of sorption coolers







Y. Wu et al. / Cryogenics 84 (2017) 37–52

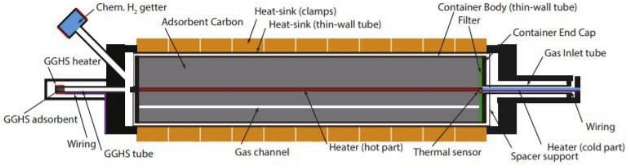


Fig. 4. Schematic of a sorption compressor cell operating with a gas-gap heat switch (GGHS).

Y. Wu et al. / Cryogenics 84 (2017) 37–52

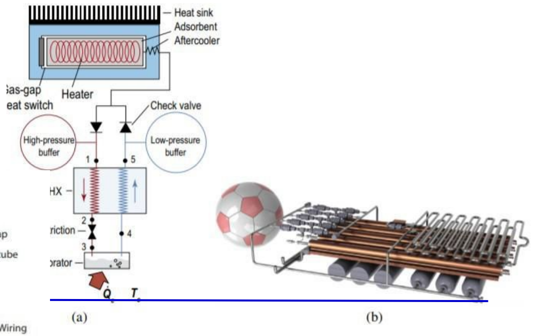
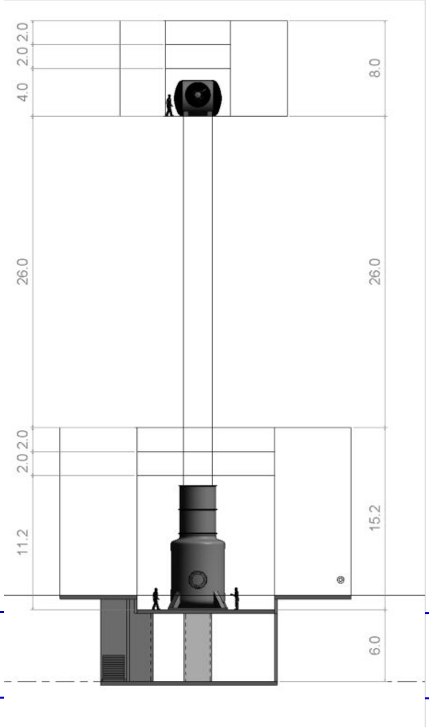
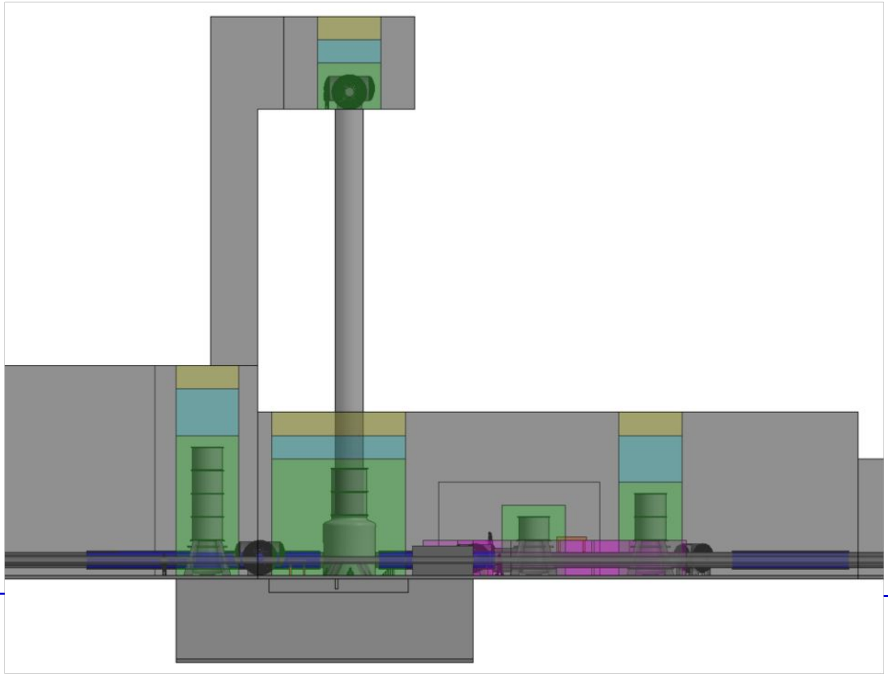


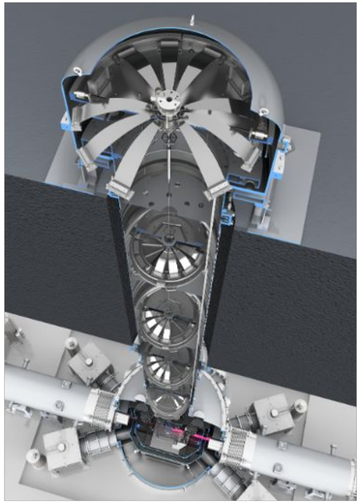
Fig. 1. (a) A schematic and (b) an artist impression of a sorption Joule-Thomson cooler.

Double cavern concept

- Advantage: risk mitigation by removing interface between cryostat and inverted pendulum
- Concept: reduce main cavern height, move inverted pendulum to upper cavern (like KAGRA), all mechanical filters outside of interconnecting shaft (unlike KAGRA)
- Definition of inter-cavern separation & access tunnels would require civil engineering studies



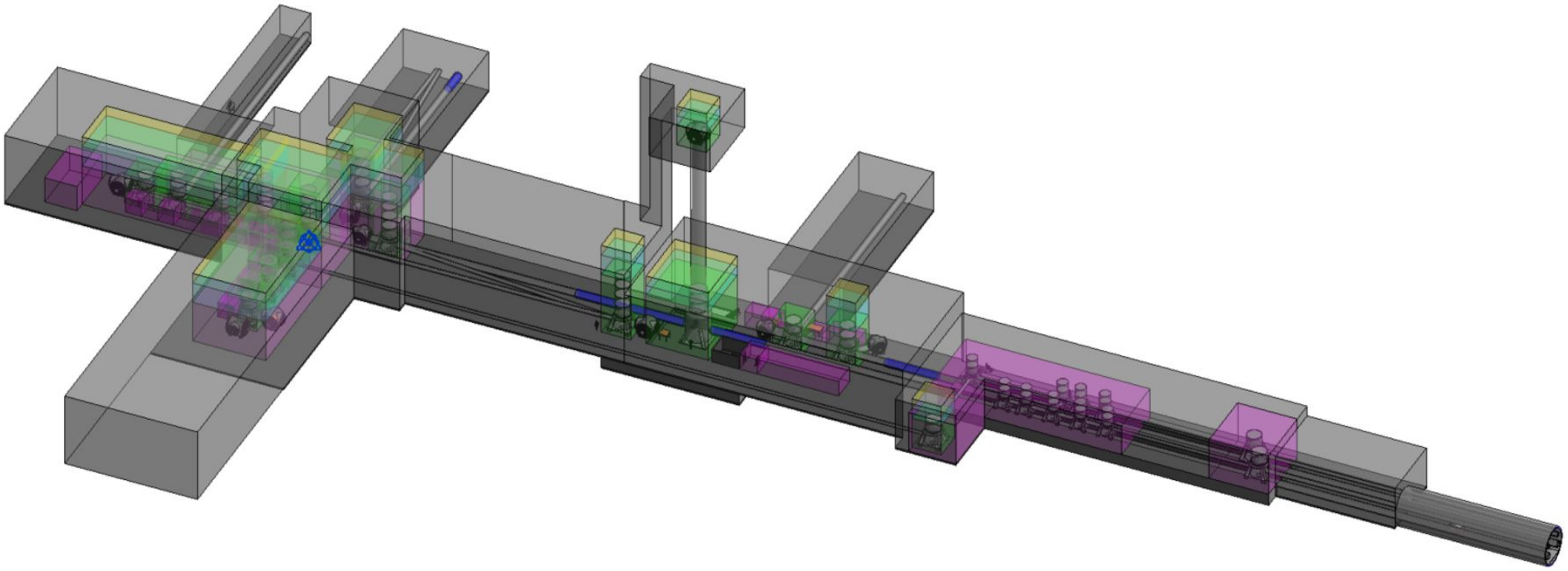




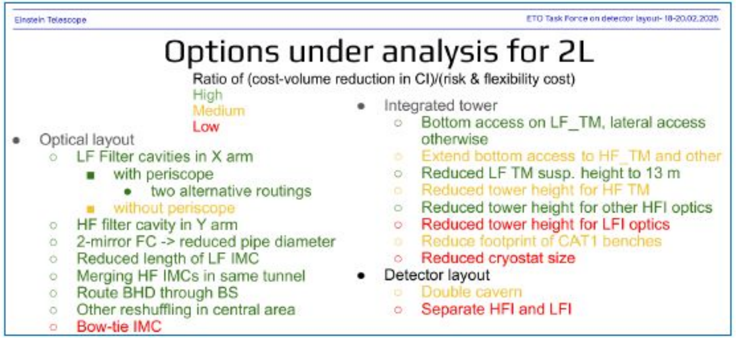
Double Cavern @KAGRA, source O. Miyakawa

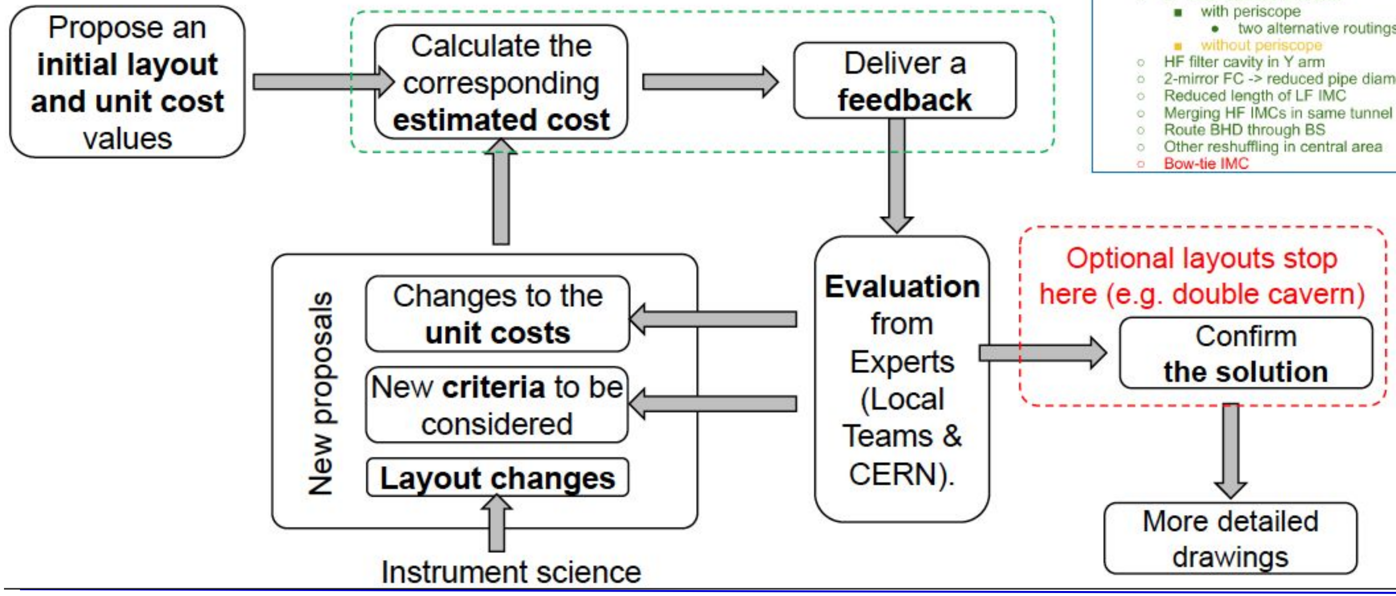
Double cavern concept

- Advantage: risk mitigation by removing interface between cryostat and inverted pendulum
- Concept: reduce main cavern height, move inverted pendulum to upper cavern (like KAGRA), all mechanical filters outside of interconnecting shaft (unlike KAGRA)
- Definition of inter-cavern separation & access tunnels would require civil engineering studies



Interface with civil infrastructure



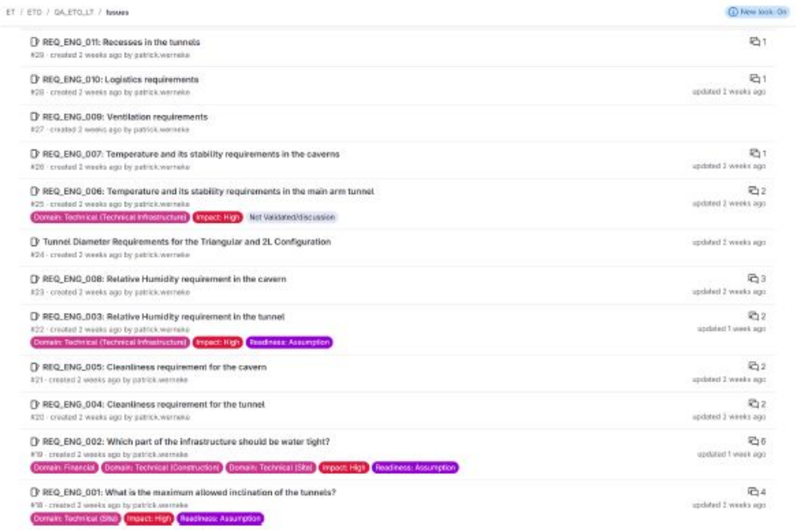


Engineering requirements

- Technical infrastructure has several critical interfaces with instrument
  - deserves coordinated technical design
- Task Force identified most critical requirements with impact on infrastructure cost, and provided a preliminary assessment

Requirement #	reqirement name	units	value/range	explanation	source	status
REQ_ENG_001	arm tunnel center inclination	mrad	<1.5	H/V coupling on TM, same order as minimum inclination from Earth curvature	SUSP, PAY (thermal noise)	initial guess
REQ_ENG_002	water tightness	m	>250	distance from TM: all caverns and part of arm cavity tunnel	Newtonian Noise	initial guess
REQ_ENG_003	humidity in tunnel	%	40÷60	lifetime of equipment	VAC, electronics, ENV sensors	initial guess
REQ_ENG_004	tunnel cleanliness	ISO	ISO 9	lifetime of equipment	VAC, electronics, ENV sensors	initial guess
REQ_ENG_005	cavern cleanliness	ISO	ISO 9 in general, ISO 7 and better in cleanrooms as specified in detector layout	vacuum contamination, stray light from dust, monolithic suspension failure from dust	VAC + SLC + PAY	initial guess
REQ_ENG_006	temperature stability in tunnels	deg	natural undeground stability is sufficient		VAC, electronics, ENV sensors	initial guess
REQ_ENG_007	temperature stability in caverns	deg	0.1/hr, 0.2/day, 0.3/month	actuation range for suspensions, misalignment of in-air optical systems, and many other	SUSP + OPT + INJ + other	initial guess
REQ_ENG_008	humidity stability in caverns	%	+/-5 within 40÷60	in-air optics, maybe other equipment	Virgo experience	initial guess
REQ_ENG_009	ventilation	TBD	TBD	seismic noise, acoustic noise, NN	SUSP, NN	initial guess
REQ_ENG_010	logistics	m	as specified in detector layout	main building blocks, i.e. cryostat and pipe sections	CRYO, VAC	initial guess
REQ_ENG_011	recesses in tunnels	#, m^3, m^2	TBD	safety/escape routes, gate valves	CE, VAC	initial guess
REQ_ENG_0	expected lifetime	year	>50	infrastructure lifetime of at least 50 years		
REQ_ENG_0	allowable main arm tunnel deformation	mm, mm/yr	TBD	Maintaining optical axis alignment.		
REQ_ENG_0	allowable differential deformation	mm	TBD; per 20m beampipe segment	To limit stress on welding lips (a few mm of differential motion per 15m segment is the limit for Virgo)	VAC, Virgo experience	

- Besides the space demands, technical requirements from detector may largely affect the cost of underground infrastructure
- The civil engineering working group in task force collected a list of relevant requirements
  - to be possibly attached to the baseline detector layout
  - to allow for a technical feasibility study on the ET infrastructure.



Noise budget and science case

- Use python code from ET scientific collaboration (Py-GWINC) to generate noise budget for different configurations
- Analyse sensitivity curves against ET science case with a set of figures of merit
  - Compare 2024 reference with new baseline layout from Task Force
  - Derive scientific requirements on critical design parameters

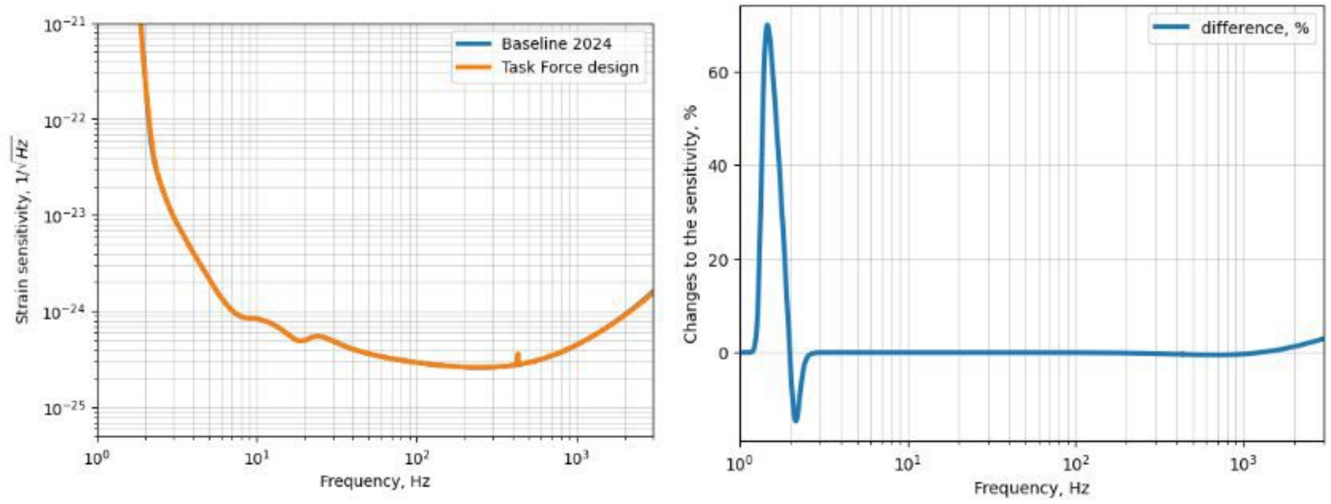


Figure 6: Comparison between the baseline sensitivity and the task force result (left) and the difference between the old and new sensitivities, expressed in % (right). Positive represents better sensitivity in the task force design. The difference at very low frequency comes from the new suspension design, and the difference at the very high frequency from slightly reduced HF signal extraction cavity length.

Background information

- Terms of Reference of External Review Committee (shared);
- ETO Task Force mandate (shared);
- Optical layout 2024 document for Triangle (pdf);
- Optical layout 2024 document for 2L (pdf);
- 2D drawing of optical layout 2024 for Triangle (pdf);
- 2D drawing of optical layout 2024 for 2L (pdf);
- Detector layout 2024 document for the Triangle (pdf);
- Detector layout 2024 document for the 2L (pdf);
- 3D model of 2024 detector layout (trimble connect) for the Triangle;
- 3D model of 2024 detector layout (trimble connect) for the 2L;
- Trimble guideline;
- ESFRI proposal: 2020 CDR;
- Tunnel diameter requirements (pdf);
- Reference document for cryogenic system (pdf);
- LF TM suspension document (draft pdf);
- Suspension system classification (pdf) - completely changed in ETO Task Force work, highlight relevant sections;
- Science case: COBA paper (pdf);
- ET noise budget: sensitivity curve update (pdf);
- Reference on Civil Engineering (TBD);
- Guideline how to read the documents.

International review committee

- Following the mandate by ET Coordinators, ETO directorate set up an international review committee
  - composition: 8 members from LIGO Lab, LSC, KAGRA, PSI, CERN
  - terms of reference: review will focus on
    - Mandate Compliance & Infrastructure Feasibility
    - Clarity, Consistency & Supporting Information
    - Scientific & Design Justification
    - Risk, Flexibility & Decision Support
- Output documents by task force were delivered to review committee on 23/05
- Draft documents shared with ETC since 12/05 - periodically updated until delivery
- Review outcome expected in ~2 weeks
- Task force to provide final version after review by **end of June**
- ETC EB is organising an independent review