ETO Design Task Force: **Optical Layout**

Key Modifications and Updates Post-2024 Design

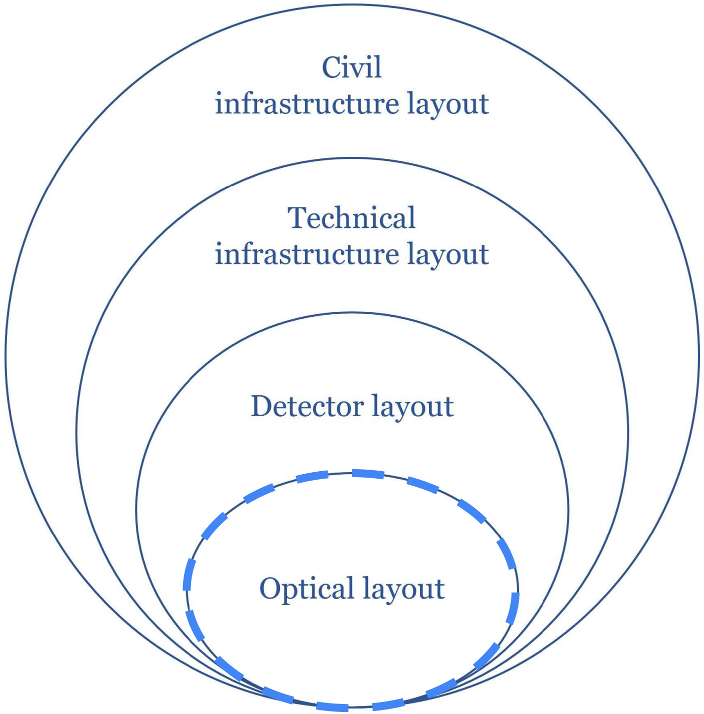
A.C. Green & A. Perreca on behalf of the Optical Layout Team

XV ET Symposium

Bologna, Italy (26-30 May 2025)

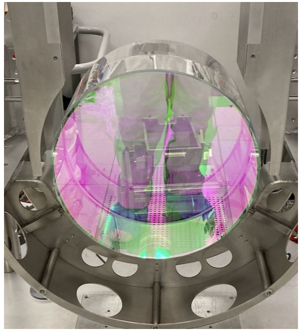
ET-0228A-25

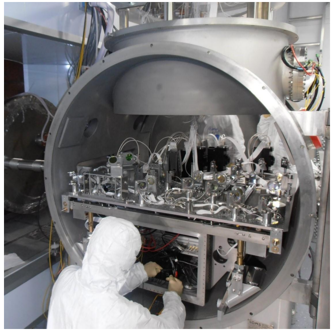
The Optical Layout



The core of the layout "onion" defining **positions**, **orientations** and/or **footprints**, plus select derived parameters, of (*only*) optical elements

- Core interferometer
- squeezed light
- input and output optics
- auxiliary systems

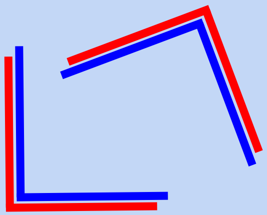




Recap of 2024 Optical Layout Baseline

Requirements we start with:

- Overall geometry: **L-shape, ~15km** arm length
- Just **2** interferometer arms **(HF+LF)** per 'side' of the detector



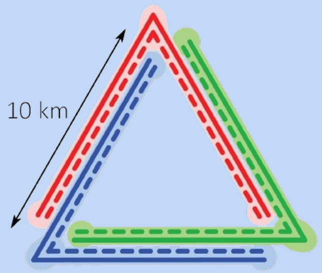
Xylophone concept: LF & HF

Basic Assumptions

- Minimise the number of optics as far as reasonably possible
  Optical losses, controls, noise
- HF is more tolerant to suspension/controls noises
  - Simplified suspension
  - Less strict number of optics
  - HF plane can sit above LF plane
- LF and HF sits on two parallel planes

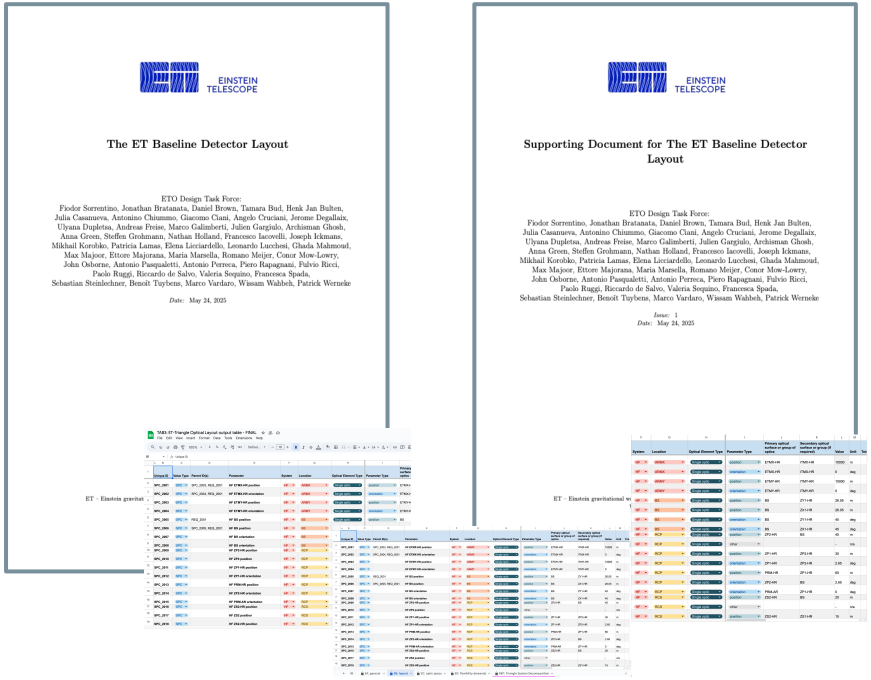
Requirements we start with:

- Overall geometry: **Triangle -shape, ~10km** arm length
- **4** interferometer arms **(HF+LF)** per 'side' of the detector



The Optical Layout:
ETO Design Task Force Goals

- Revise the layout to help optimize the cost of construction without degrading the detector performance
  - Exploit / clarify existing flexibilities
  - Make changes: technical challenges vs infrastructure costs
- Further complete aspects of the designs presented last year
- More integration with wider design team (detector, civil, etc)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The ET Baseline Detector Layout

ETO Design Task Force:
Fiodor Sorrentino, Jonathan Bratanata, Daniel Brown, Tamara Bud, Henk Jan Bulten, Julia Casanueva, Antonino Chiummo, Giacomo Ciani, Angelo Cruciani, Jerome Degallaix, Ulyana Dupletsa, Andreas Freise, Marco Galimberti, Julien Gargiulo, Archisman Ghosh, Anna Green, Steffen Grohmann, Nathan Holland, Francesco Iacovelli, Joseph Ickmans, Mikhail Korobko, Patricia Lamas, Elena Licciardello, Leonardo Lucchesi, Ghada Mahmoud, Max Majoor, Ettore Majorana, Maria Marsella, Romano Meijer, Conor Mow-Lowry, John Osborne, Antonio Pasqualetti, Antonio Perreca, Piero Rapagnani, Fulvio Ricci, Paolo Ruggi, Riccardo de Salvo, Valeria Sequino, Francesca Spada, Sebastian Steinlechner, Benoît Tuybens, Marco Vardaro, Wissam Wahbeh, Patrick Werneke

Date: May 24, 2025

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Supporting Document for The ET Baseline Detector Layout

ETO Design Task Force:
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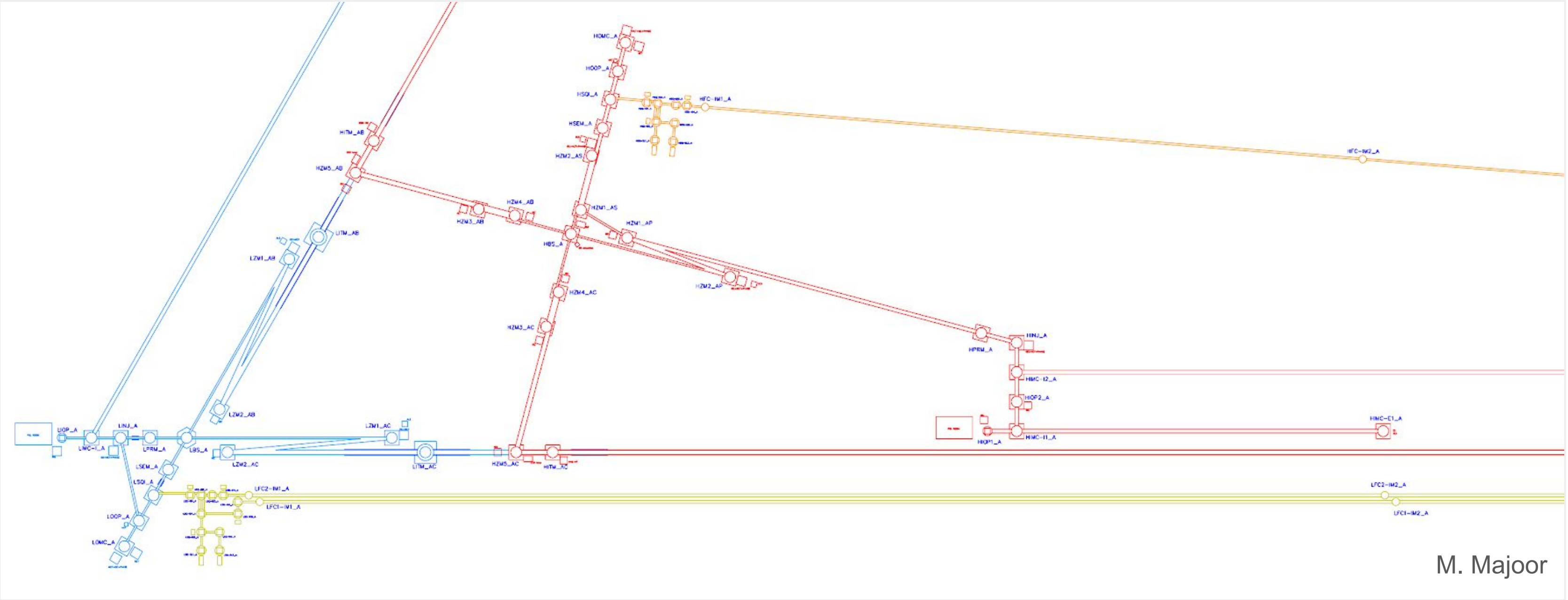
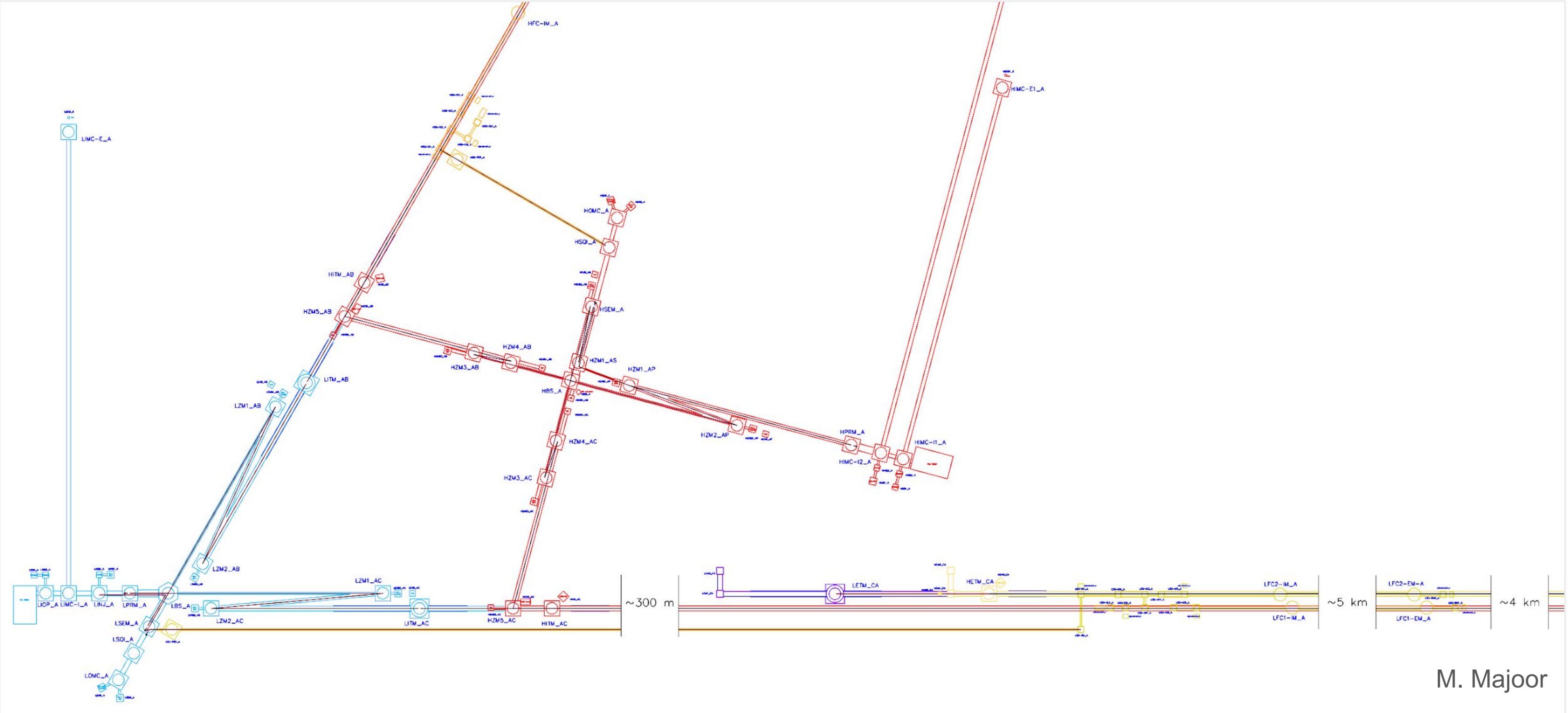
Issue: 1
Date: May 24, 2025

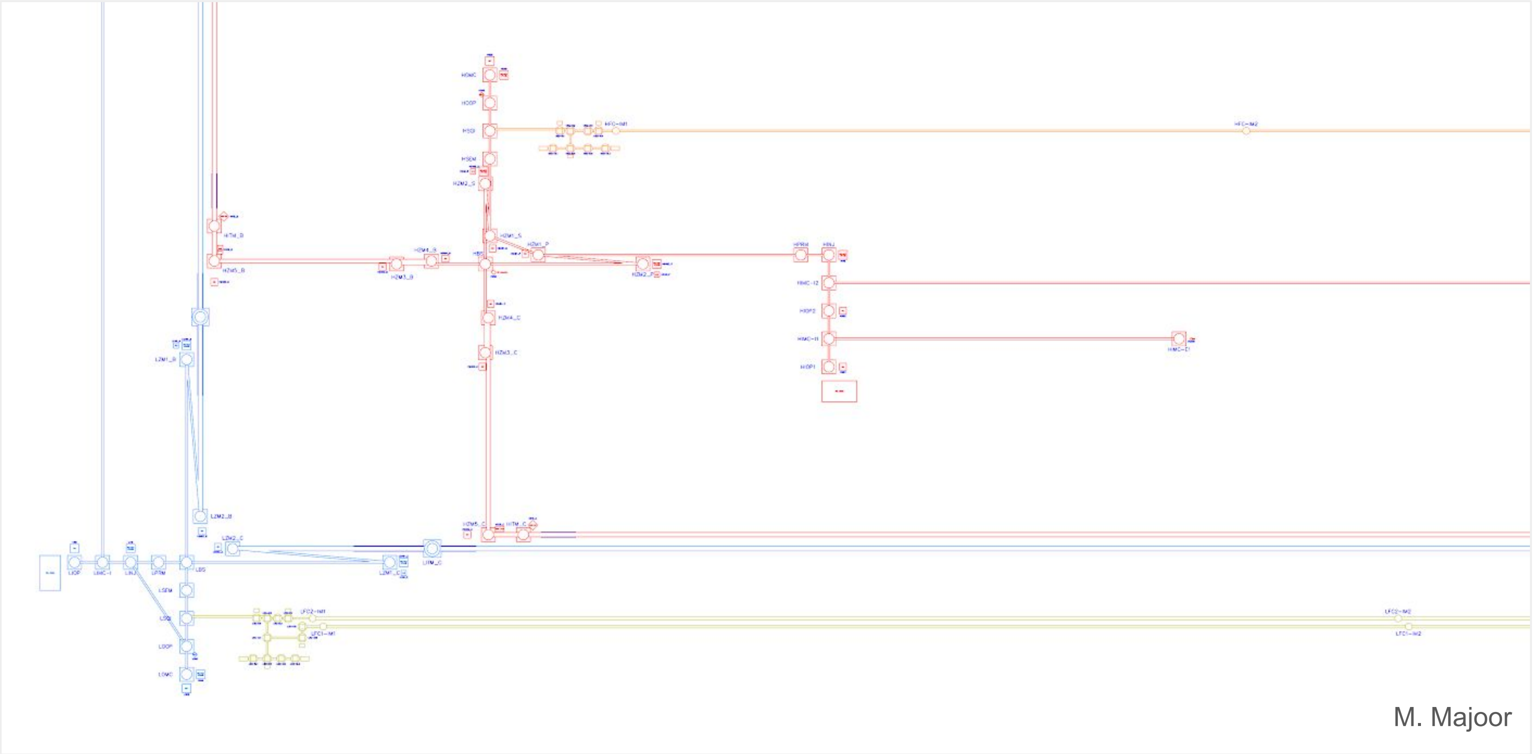
Triangle: 2024



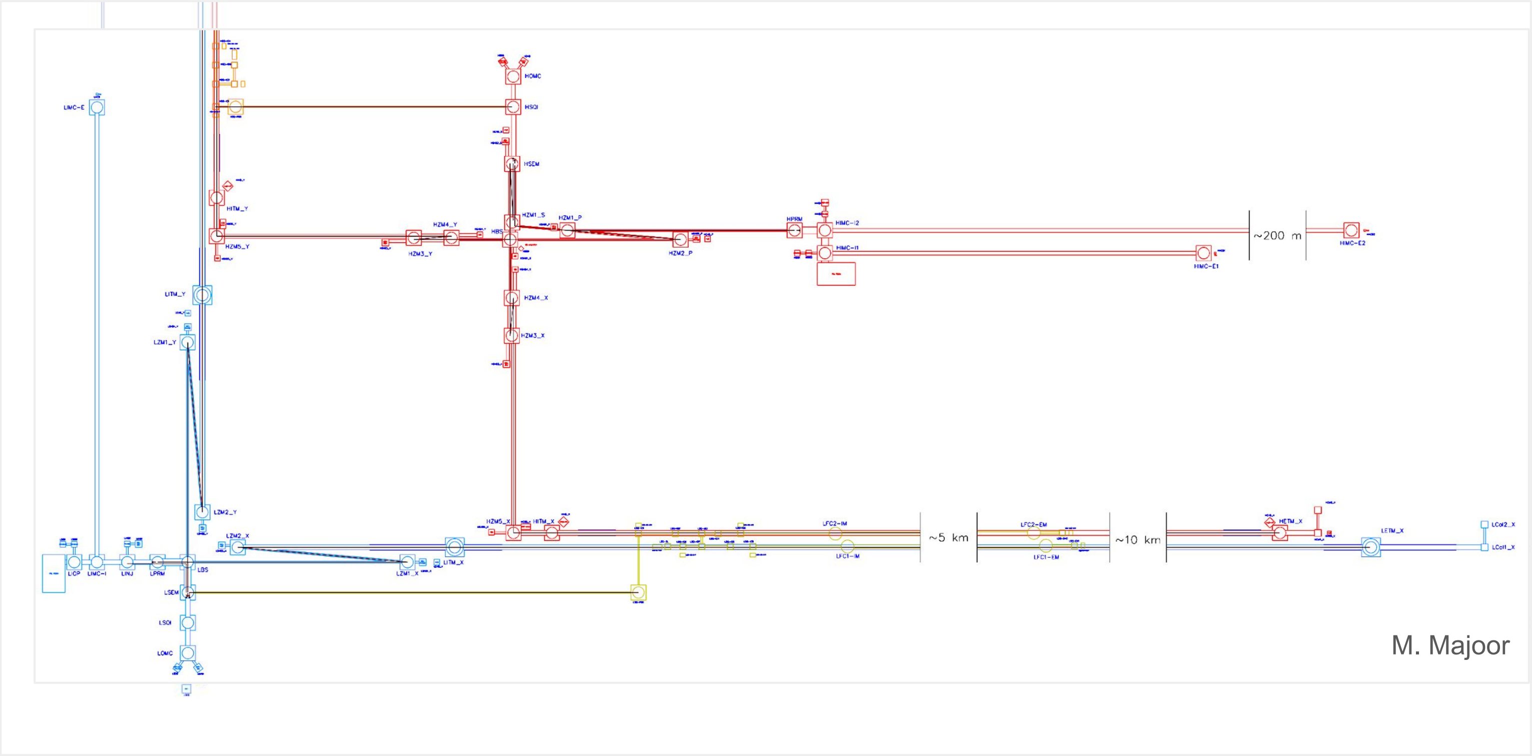
Triangle: → 2025



2L: 2024



2L: → 2025



HOMC
HSQI
HSEM
HITM_Y
HZM1_S
HZM1_P
HZM4_Y
HBS
HZM5_Y
HZM3_Y
HZM2_P
HPRM
HIMC-I2
HIMC-I1
~200 m
HIMC-E2
HIMC-E1
HZM4_X
HZM3_X
LIMC-E
LITM_Y
LZM1_Y
LZM2_Y
LZM2_X
LZM1_X
LITM_X
LICP
LIMC-I
LINJ
LPRM
LBS
LSEM
LSQI
LOMC
HZM5_X
HITM_X
LFC2-IM
LFC1-IM
~5 km
LFC2-EM
LFC1-EM
~10 km
HETM_X
LETM_X
LCol2_X
LCol1_X
M. Majoor

Overview of Task Force Driven Modifications

Task Force Mandate: "Review and optimize post-2024, focusing on cost-effectiveness, technical solutions, and risk assessment."

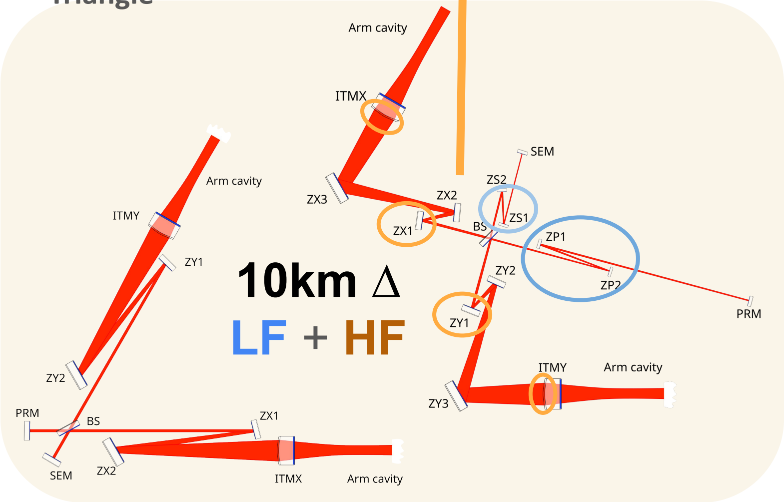
- Summary of 2024 update: main features in 2L and in triangle.
  - Optics merging in CITF
  - Filter cavities in main arms: available options for 2L and chosen configuration, reshuffling of SQZ lab
  - IMC updates for LF and HF
  - BHD routing
  - Flexibility envelope update
  - Flexibility demands

Recap of 2024 Optical Layout Baseline

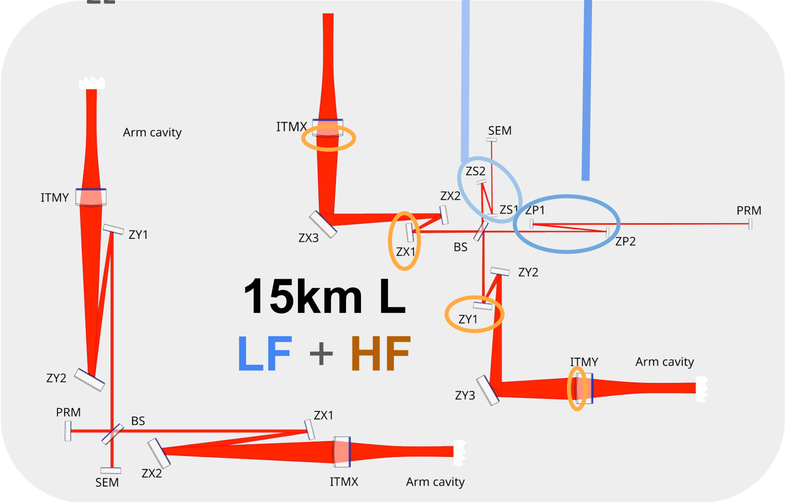
Beam collimation

- Gouy phase
- Beam size on PR/SR Mirror

Triangle



2L



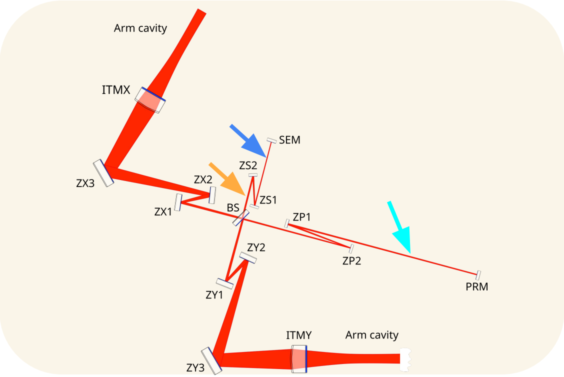
Central Interferometer Optimization

Optics Merging ("Tower Merging"):

- Concept: Multiple major optics hosted in the same vacuum vessel.
- Focus: **Core optics** around the **HF-BS** (both 2L & Triangle). Impact:
    - **Triangular ET-HF:** SEC -10m, PRC -40m.
    - **2L ET-HF:** SEC -12m, PRC -15m.
- **ET-LF Core Optics**: Unchanged for both configurations.
- Benefit: More compact layout, cost reduction.
- Technical challenge: tighter tolerances

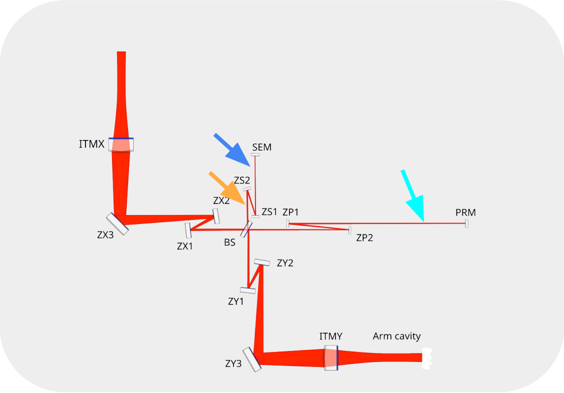
Distance names	Lengths [m]	Variations
Arms (identical for both arms)		
ETM to ITM:	10000	Not changed
Recycling cavities (Common path)		
TM's thickness	0.3	Not changed
ITM-AR to ZX(Y)3:	10	Not changed
ZX(Y)3 to ZX(Y)2:	45	Not changed
ZX(Y)2 to ZX(Y)1:	10	Not changed
ZX(Y)1 to BS:	26.05	Not changed
Distance name	**old → new [m]**	**Variation**
Signal Extraction Cavity path		
BS to ZS2:	22 → 20	2 m reduction
ZS2 to ZS1:	15 → 15	Not changed
ZS1 to SEM:	23 → 15	8 m reduction
Total length:	151.35 → 141.35	10 m reduction
Power Recycling Cavity path		
BS to ZP2:	45 → 45	Not changed
ZP2 to ZP1:	30 → 30	Not changed
ZP1 to PRM:	100 → 60	40 m reduction
Total length:	266.35 → 226.35	40 m reduction

Table 1: **Triangle** ET-HF: Arm and Recycling Cavities Lengths



Distance names	Lengths [m]	Variations
Arms (identical for both arms)		
ETM to ITM:	15000	Not changed
Recycling cavities (Common path)		
TM's thickness	0.3	Not changed
ITM-AR to ZX(Y)3:	10	Not changed
ZX(Y)3 to ZX(Y)2:	62	Not changed
ZX(Y)2 to ZX(Y)1:	10	Not changed
ZX(Y)1 to BS:	25.3	Not changed
Distance name	**old → new [m]**	**Variations**
Signal Extraction Cavity path		
BS to ZS2:	25 → 20	5 m reduction
ZS2 to ZS1:	15 → 15	Not changed
ZS1 to SEM:	22 → 15	7 m reduction
Total length:	169.6 → 157.6	12 m reduction
Power Recycling Cavity path		
BS to ZP2:	45 → 45	Not changed
ZP2 to ZP1:	30 → 30	Not changed
ZP1 to PRM:	75 → 60	15 m reduction
Total length:	257.6 → 242.6	15 m reduction

Table 3: **2L** ET-HF: Arm and Recycling Cavities Lengths

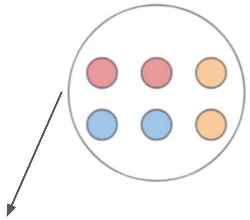


Squeezing

- General Task Force Decision:
  - FCs **into interferometer arm tunnels** (Most significant/impactful change to the layouts)
- Key design changes:
  - FCs hosted in the arm tunnels in a different optical plane respect to the interferometer (**above arm cavity beam tubes)**
    - **Vertical periscope** needed to connect FCs optical plane with ITF (4m for ET-LF Triangle, 2m for ET-LF 2L)
  - Reshuffling of **SQZ lab**
    - New position in front of the Filter Cavities in the arm tunnel (550 m from vertex ET-LF Triangle, 120 m ET-LF 2L)
    - Reduced number of benches, removal of 2nd source (less flexibility for future upgrades).
    - Layout to fit within main caverns.
  - **2-mirror** FC design (Simplified from 3-mirror coupled cavity configuration)
    - Benefits: Reduced beam spot, smaller pipes, increased effective length, simplified control.
    - Cons: Reduced tuning capability.

Squeezing

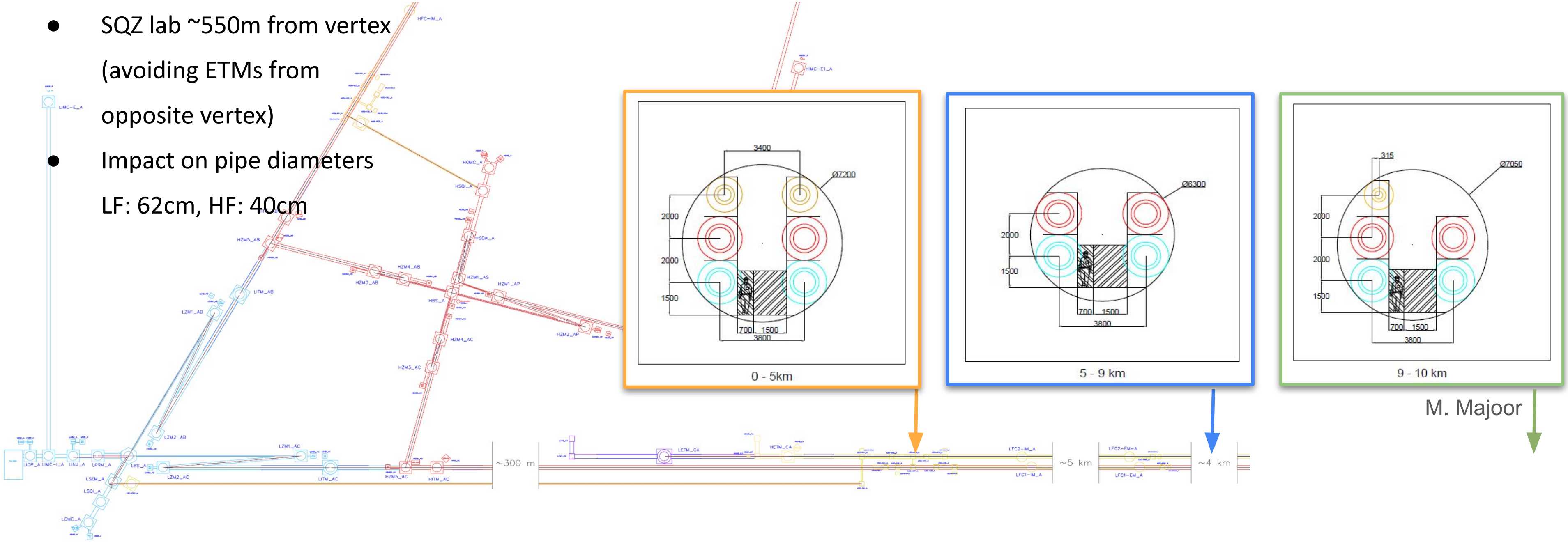
	2024 Reference	2025 Triangle	2025 2L
Position of FCs	Separate tunnel	ITF Arms Tunnel	ITF Arms Tunnel
Number of FC Mirrors	3	2	2
Diameter of FC Pipes	1 m (LF and HF)	62 cm LF, 40 cm HF	62 cm LF, 40 cm HF
FC Center-to-Center Distance	4.5 m (LF)	3.4 m (LF)	3.4 m (LF)
Length of Periscope	–	2.0 m (HF), 4.0 m (LF)	2.0 m (HF, LF)
Position of Periscope (HF)	–	Near SQZ Lab	Near SQZ Lab
Position of Periscope (LF)	–	Near the Vertex	Near SQZ Lab
SQZ Lab to Interferometer Distance	~50 m	~550 m	~120 m
# of Suspended Benches (SQZ Lab)	8 HF, 12 LF	6 HF, 11 LF	6 HF, 10 LF
Dimension of Suspended Benches	1.5 × 1.5 m	1.5 × 1.5 m	1.5 × 1.5 m



- **FC analyzed flexibilities** (https://apps.et-gw.eu/tds/?r=19484)
  - Reduce beam pipe diameter and separation
  - Move FC in vertical on a different plane respect to the interferometer
  - Stack the filter cavities (requires big tunnel diameter and technically complicated optical and suspension)
  - Separate the LF FCs around the interferometer vertex (no advantage if we want host HF & LF FCs in arm tunnels)
  - Implement two coupled cavities instead two FCs in series (too stringent requirement in FC mirrors)

Filter Cavities Relocation: Triangle

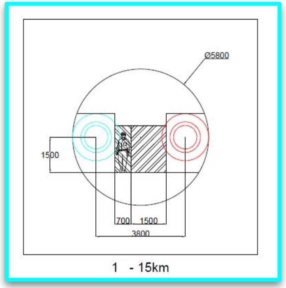
- 2m periscope for HF, 4m for LF
- SQZ lab ~550m from vertex (avoiding ETMs from opposite vertex)
- Impact on pipe diameters LF: 62cm, HF: 40cm

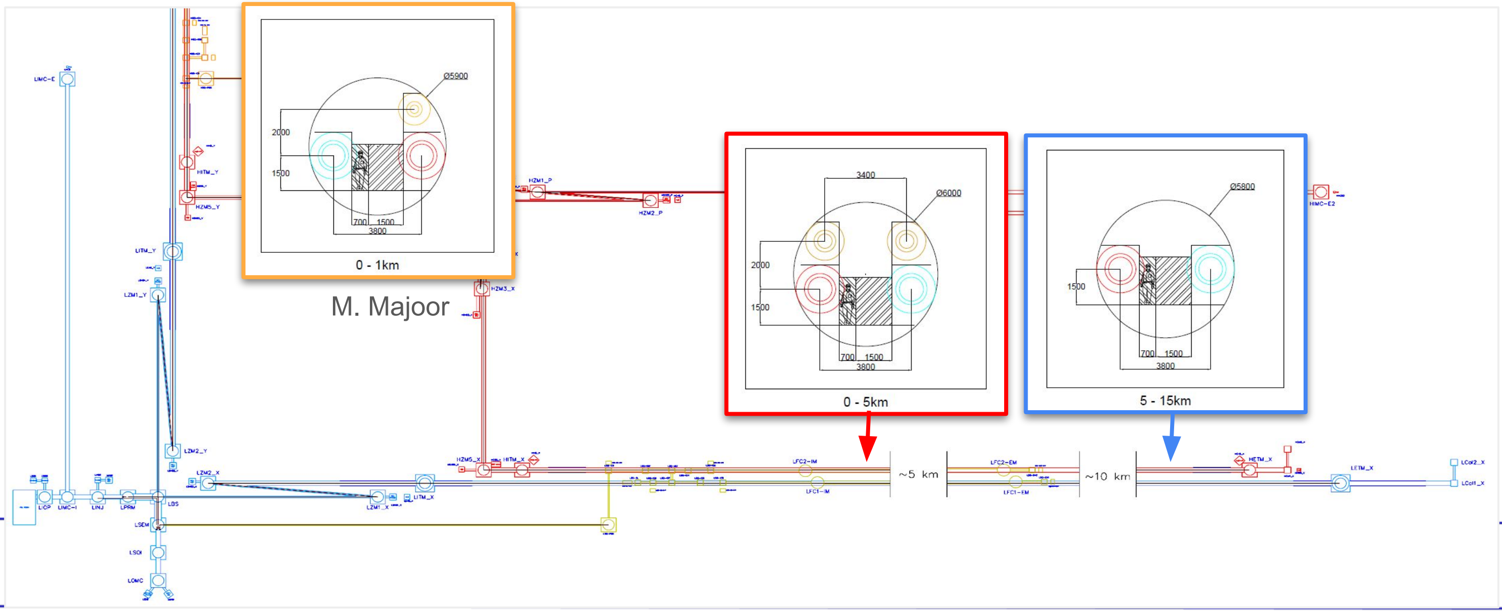


M. Majoor

Filter Cavities Relocation: 2L

- 2m periscope for LF *and* HF
- SQZ lab ~120m from vertex





Filter Cavities Relocated to Main Arms: Design & Rationale

- **Main technical risks and trade-offs:**
  - Two mirror FCs: less tunability to adapt linewidth to variation of ITF arm losses. Alternative tuning strategies: replace FC input mirror or Etalon effect on FC input mirror
  - Periscope:
    1. <u>Polarization mixing:</u> minimized with precise mechanical design and by optical coating that reflects both the polarizations equally
    2. <u>Alignment stability:</u> can add complexity in pre-alignment, once aligned can be optimized with control loops
    3. <u>Phase noise:</u> mitigated by reducing resonance in the mechanical structures in periscope design
    4. <u>Scattered light:</u> minimized with good design of periscope suspension and FC mirrors suspensions
    5. <u>Optical losses:</u> addition of two additional high quality mirrors does not increase drastically total losses
- **Overall SQZ Impact:** Significant cost reduction potential vs. new technical challenges (periscopes) & reduced flexibility.

Input and Output Optics

Here taken in the broadest sense. Major elements include:

- **Pre-Stabilised Laser** room
- **Input Mode Cleaner(s) (IMCs)**
- **Output Faraday Isolator** (used to inject squeezing)
- **Balanced Homodyne Detection (BHD)** optics
  (requires a Local Oscillator pick-off from the symmetric side of the interferometer [1])
- **Output Mode Cleaners**
- and large benches occupied by numerous smaller optics for **filtering**, **steering, shaping** and **controlling** the laser beam (e.g. Input Faraday Isolator, modulators, lenses, steering optics,...)

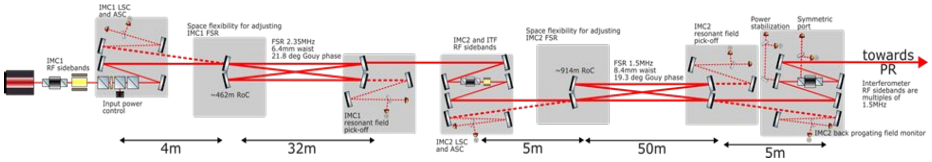
The design changes, applied symmetrically to both Triangle and 2L configurations, focused on **IMCs** and **BHD**

+ some redistribution of functions across optical benches, in collaboration with the tower integration team

1. Fritschel, Optics Express, 2014

A note on IMC geometry

Bow-tie IMC cavities were also considered for HF and LF (also noted in 2024).



early concept, M. Was

Benefits:

- Physical length from input to end mirror: bow-tie is ~factor 2 shorter than triangle for the same FSR
- Smaller angle of incidence at mirrors would potentially create less astigmatic thermal lenses (so it should be considered especially for HF)

But:

- more cumbersome to handle the separation between input and reflected beams & mode matching of larger beams → total physical length reduction is significantly less than the expected factor 2
- not yet demonstrated on long baselines (~100m)

→ **triangular** IMC is retained as baseline

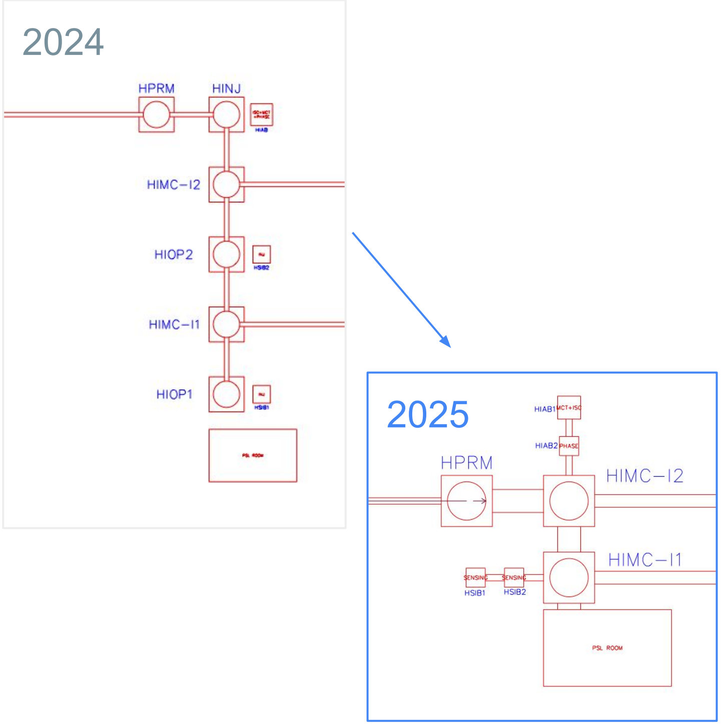
ET-HF updates

IMCs in a shared tunnel

- HF: 2 triangular IMCs, IMC1=100m, IMC2=300m
  - Require long (~100m) IMCs - demanding frequency noise requirements [1,2]
  - Longer arm (i.e. lower FSR): cannot use common arm length (CARM) as a reference for the control loop to suppress frequency noise
  - Second very long IMC could provide additional passive suppression for HF

- 2024: long chain of vessels IMC beam tubes in individual tunnels

- Task Force: **co-location** of IMC input mirrors and PRMs with other smaller optics + reviewing and using flexibilities
  → fewer vessels
  → IMCs share a tunnel



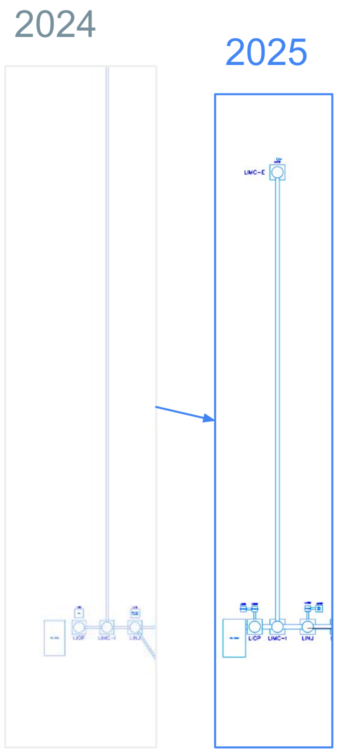
Shown for the L configuration

1. Cahillane, Optics Express, 2021; 2. Zhang, ET-0139A-22, 2022

ET-LF updates

1. IMC Length

- LF: single triangular IMC
- 2024: no dedicated study - upper limit of 300m, based on longest HF IMC
- Task Force: simple calculation → **120m** is sufficient:
  - Frequency noise requirements +
  - Granularity of choice for RF sideband frequencies used by ISC (longer = lower FSR)

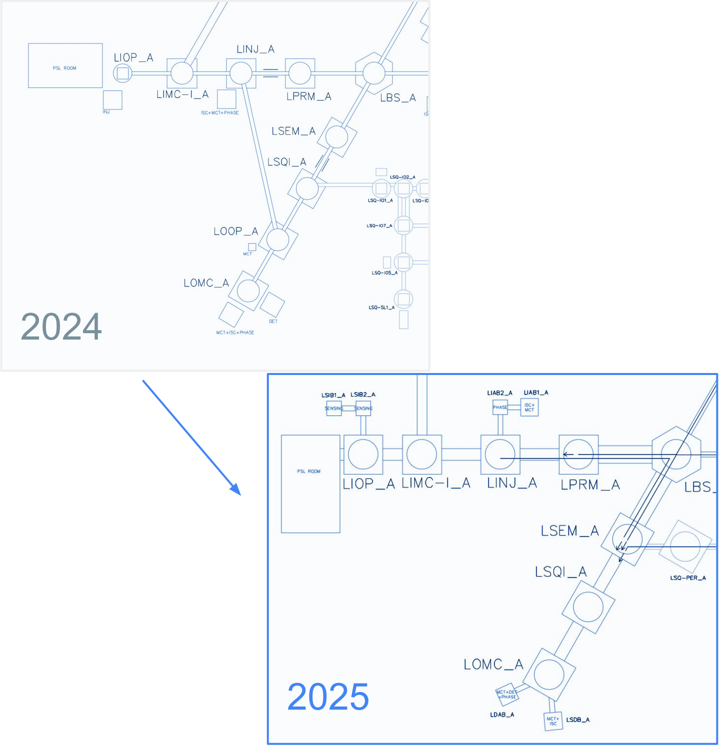


ET-LF updates

2. BHD path

- Local oscillator is picked off between IMC and PRM (no suitable pick-off inside PRC)
- 2024: assumed LF required BS to be suspended independently in a dedicated vessel
  → dedicated pipe - very challenging for access
- Task Force input from tower integration team: most optics can be suspended via benches, so vessels may house multiple optics
  → BHD path now travels via turning mirror co-located in BS vessel

The BHD path is unchanged for ET-HF: pick-off from ZM in PRM–BS path



Shown for the Triangle configuration

Auxiliary Optics

- A collection of additional optical subsystems - sensing, diagnostics, and (some) actuation - used to *control the interferometers:*

Wavefront Sensing and Control
Correct and maintain the shape of the laser beam

Includes both sensor and actuator considerations.
Assumes only HF will have 'hot defects' (thermal deformation)
- Phase cameras
- Mode converter telescopes
- Hartmann sensors
- Actuation in HF: *assumes Virgo-like system*
  - BS: CO_2 laser, CHRoCC and/or matrix mask
  - ITMs: CO_2 lasers

Global Sensing
longitudinal and angular mirror DOFs

Assumes RF demodulation, Ward technique.
PDs, steering/focusing optics

Calibration
E.g. photon/Newtonian calibrators

Local Controls
longitudinal and angular mirror DOFs

First stage of control
No footprint (inside/attached to existing tanks)

Auxiliary Laser System
Used during lock acquisition

Assumes KAGRA-like configuration
Additional laser source + PDs

*Matching Telescopes
Reduce large beam sizes and separate small AOI beams

for sensing on PDs
shared by multiple subsystems

- **2024:** identified locations of likely auxiliary optical benches, key functions and requirements, and *total* footprints → some very large area estimates, treated as requirements for single vessels

Auxiliary Optics

2025: Re-assessment in collaboration with tower integration and detector layout (Common to Triangle and L):

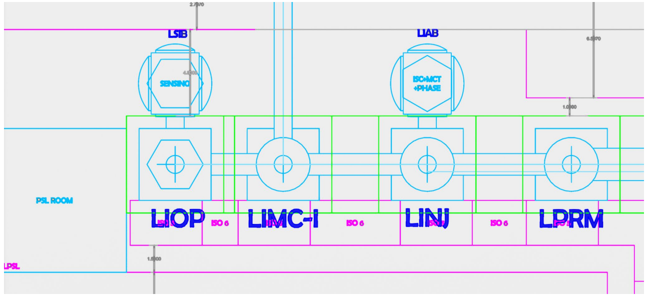
- We now provide *individual footprints* for all optical subsystems (ISC, ASC, TCS, CAL).
  - Combine several together into vessels, obeying subsystem positioning constraints
  - Vessels can be standardised sizes and types, of more accessible sizes
- Also identified and resolved:
  - some duplication (e.g. sensors in detection path)
  - some oversights (e.g. HWS vessels implemented in vacuum instead of in air)
  - some requirements clashes (e.g. CAL/WFS/ISC at ETMs)
  - some over-specified footprints (e.g. requiring large footprints rather than open space for matching telescopes)
  - Some sub-optimal sensor locations (e.g. MCTs in ET-HF moved to arm-side telescopes)
- Impact: Significantly streamlined space needed around primary optical systems

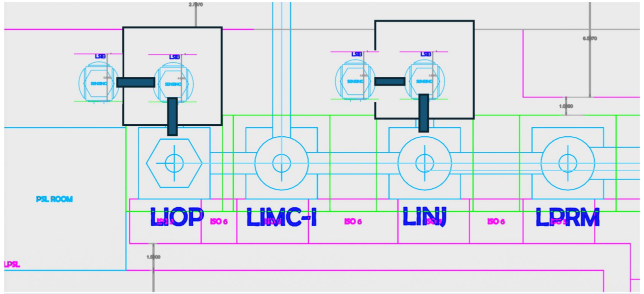
Example: IOO auxiliary vessels

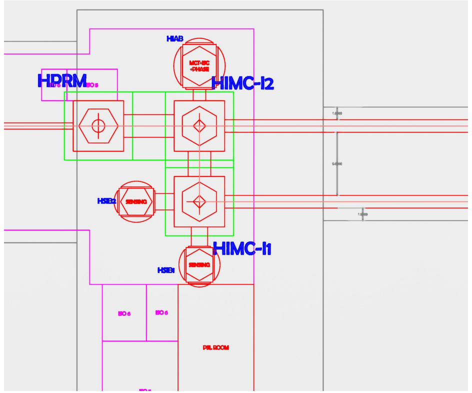
2024

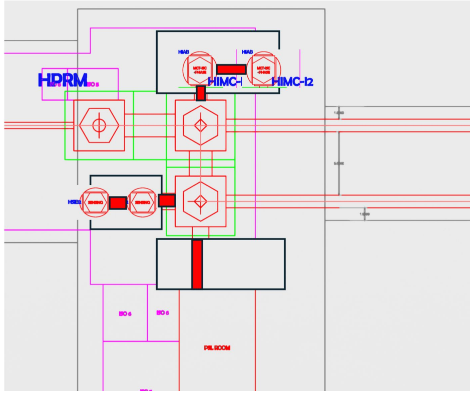
2025

M. Majoor / A. Chiummo









Shown for the L configuration

Flexibilities

We now consider **2 types** of flexibility in the optical layouts:

Flexibility Envelope:

Flexibilities given to detector layout (and ultimately local site teams) to optimize the design that is constructed.

Flexibility Demands:

Flexibilities we want to retain for adjusting and/or upgrading the optical design over the facility lifetime.

Note: We take a strictly *optical* perspective - these flexibilities are another input for detector layout and beyond, for further development into the overall facility design.

Flexibility Envelope

This information is collected together with each primary layout parameter* (positions, lengths, and footprints).

Included in 2024 layout outputs, but now *standardised* into a ‘traffic light’ system with clearer definitions:

- **Free** - unconstrained
- **Minor redesign** - likely possible
  Some moderate impact on local optical layout
- **Major redesign** - some limited flexibility
  Significant impact on the global optical layout
- **None** - completely constrained
  Only to be altered by the optical layout team - completely constrained by other parameters/requirements

Tolerances are further provided on many parameters, giving further insight into the likely degree of flexibility that can be exploited.

*Changes to those values will have a corresponding impact on derived optical parameters (e.g. radius of curvature), indicated by the classifications above.

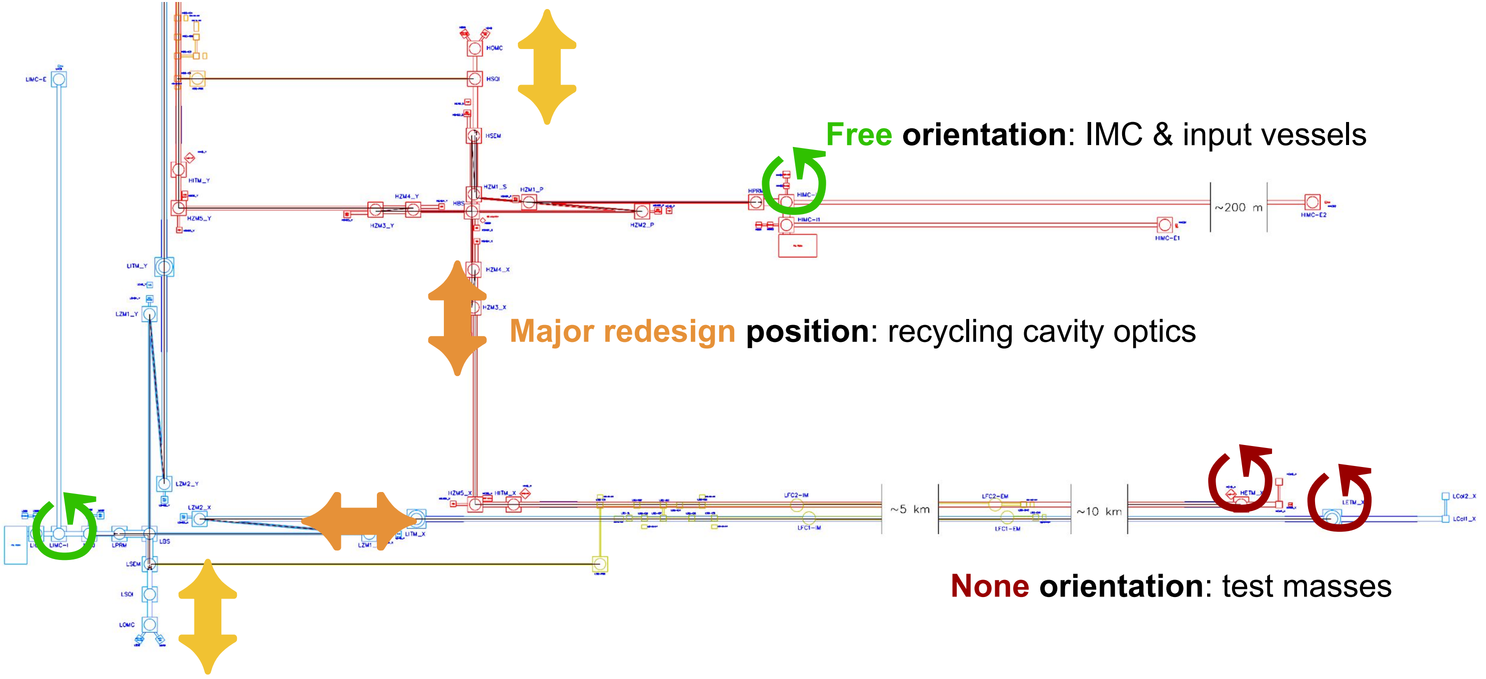
Flexibility Envelope: some examples

Minor redesign **position**: input and output vessels

Free **orientation**: IMC & input vessels

Major redesign **position**: recycling cavity optics

None **orientation**: test masses



Flexibility *Demands*

A big challenge of ET: building underground means defining the available volumes **at the point of construction**.

Design revisions that require changes in footprint are already challenging at ground-level

We must therefore try to **anticipate the evolution of ET** over its full intended lifetime.

- A challenging but essential task for long-term viability and performance of ET
- Very nebulous, largely not addressed in 2024 documents
- A first effort: this should be an ongoing activity to be (re-)expanded to the wider instrumentation community

Flexibility *Demands*

Our approach:

1. Gather **experience** from current detectors (LIGO, Virgo, KAGRA)
   General consensus: ‘you will use any and all flexibility available to you’

2. Collect design alterations that either:
   - Mitigate potential **risks** / technical challenges, or
   - Allocate volume for likely **future upgrades**

3. Group alterations by **physical scale** for consideration by detector/civil layout teams
   → Scope: separation between:
   - flexibility demands – which we want to be *incorporated into the baseline* concept that is to be built.
   - Complete facility redesigns – design changes that might be wanted or indeed needed, but significantly alter the concept of ET, so would likely require a *revision* of the baseline.

Flexibility Demands: examples

Large impact

E.g. moving or adding recycling cavity optics
Extending or adjusting RC paths by up to tens of meters , changing the number of telescopes, allowing space for a LIGO-style LF

Medium impact

E.g. BHD path rerouting (or alternate readout schemes) e.g. return of dedicated pipe in ET-LF

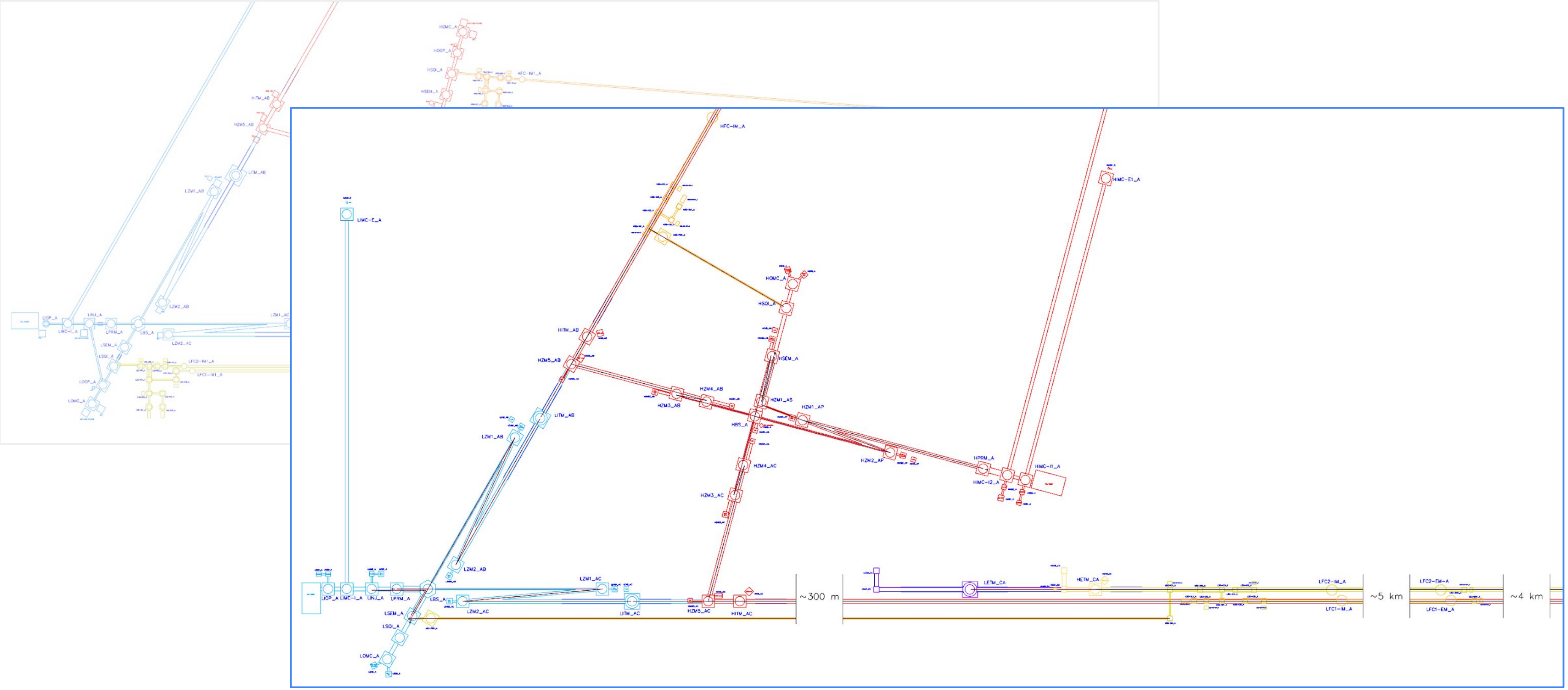
Small impact

E.g. Changes in optic curvatures or positions (up to tens of cm) within vessels

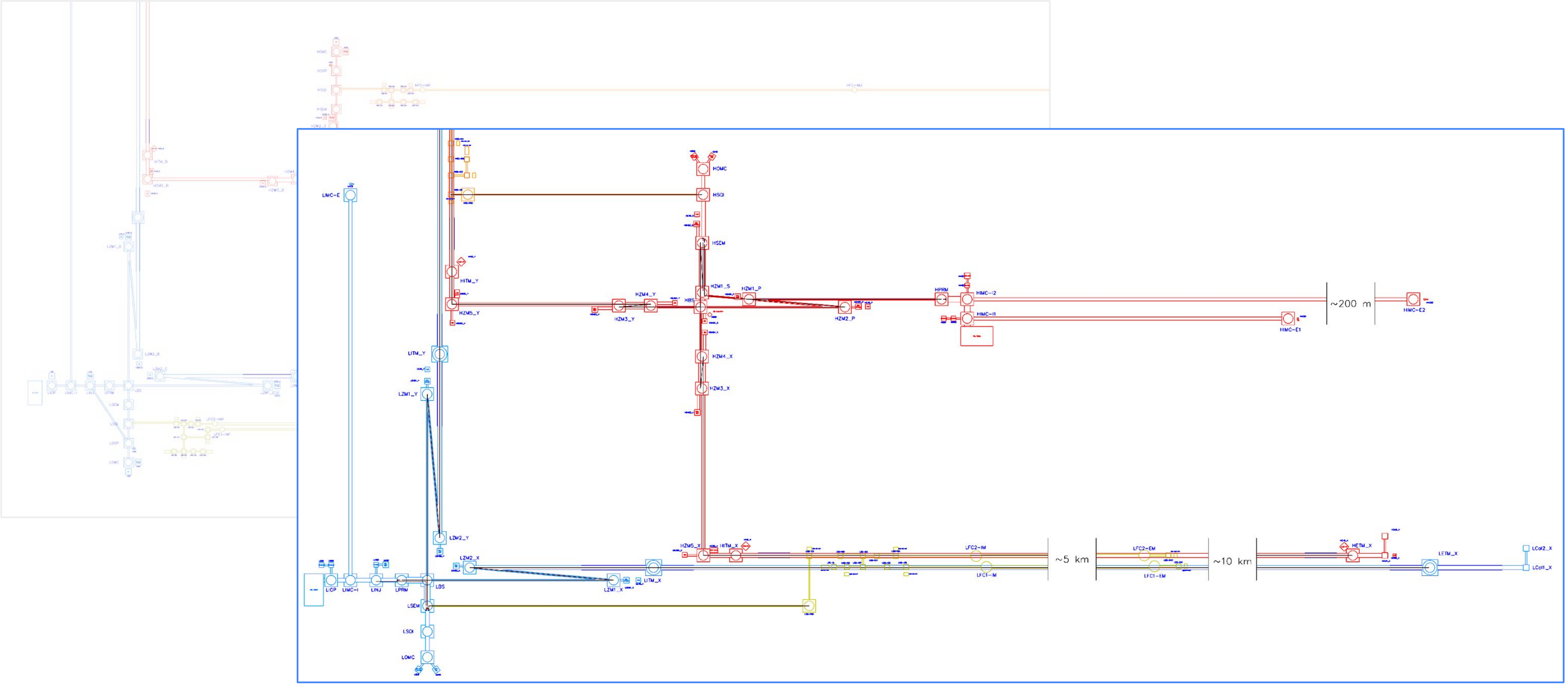
Several of these have already been incorporated into the Detector and Civil layouts.

Further discussion of the trade-offs will be necessary.

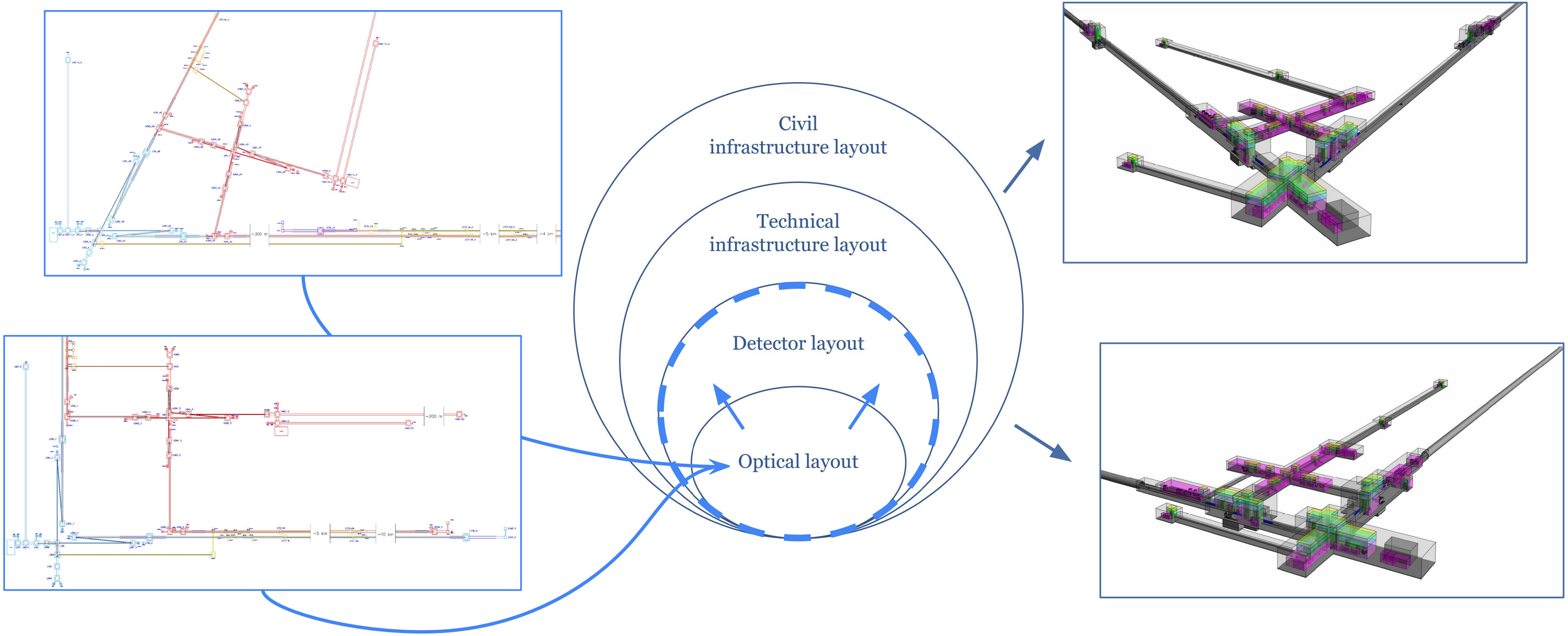
Triangle: 2024→ 2025



L: ⟶ 2025


HOMC
HSQI
HSEM
HITM_Y
HZM5_Y
HZM4_Y
HZM3_Y
HBS
HZM1_S
HZM1_P
HZM2_P
HPRM
HIMC-I2
HIMC-I1
~200 m
HIMC-E2
HIMC-E1
HZM4_X
HZM3_X
LIMC-E
LITM_Y
LZM1_Y
LZM2_Y
LZM2_X
HZM5_X
HITM_X
LFC2-IM
LFC1-IM
~5 km
LFC2-EM
LFC1-EM
~10 km
HETM_X
LETM_X
LCol2_X
LCol1_X
LICP
LIMC-I
LINJ
LPRM
LBS
LZM1_X
LITM_X
LSEM
LSQI
LOMC

Thank you


Civil
infrastructure layout
Technical
infrastructure layout
Detector layout
Optical layout