Development and Testing of Composite Vacuum Tubes for Einstein Telescope

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Vacuum Tubes for ET

- Total vacuum pipe requirement :
  - 3 detectors
  - 2 interferometers per detector
  - 2 arms per interferometer
  - Each arm is 10 km

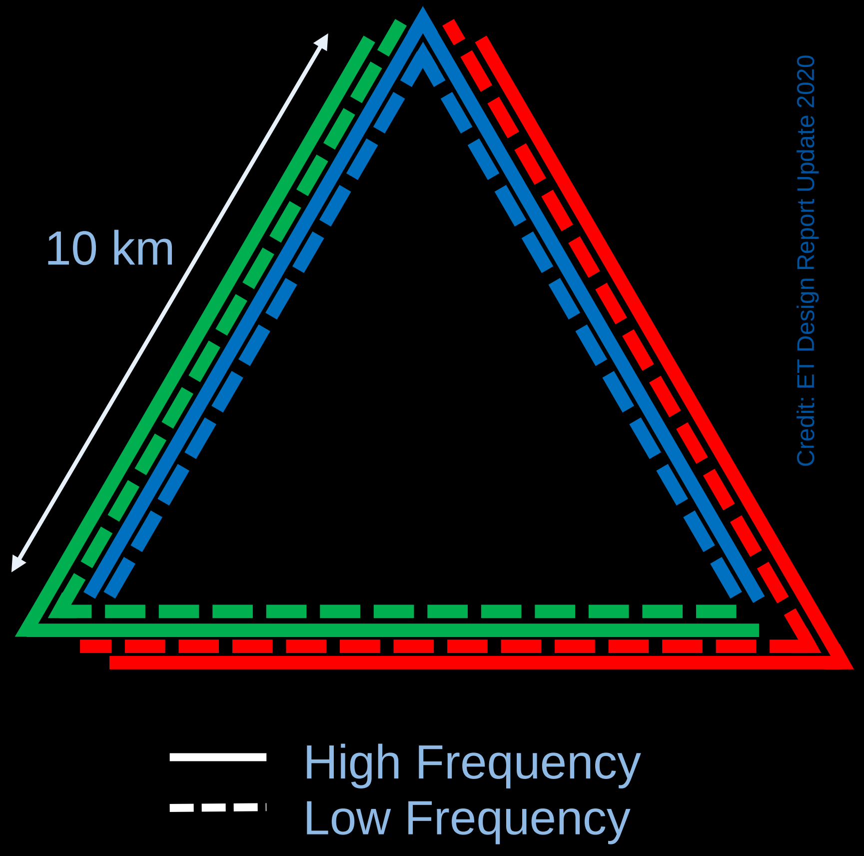
=> 3 x 2 x 2 x 10 km = 120 km

- Ultra High Vacuum (UHV) is required,

  - Reduce the noise due to excess gas density fluctuations along the beam path

  - Reduction of test mass motion and thermal isolation

  - Preserving cleanliness of optical elements



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Vacuum Tubes of Current Gravitational Wave Detectors

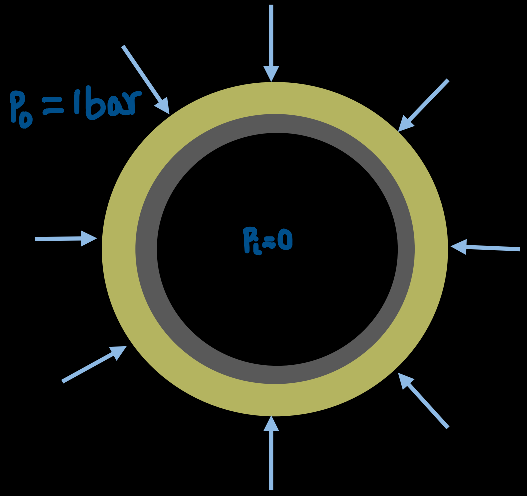
Credits: Caltech/MIT/LIGO Laboratory

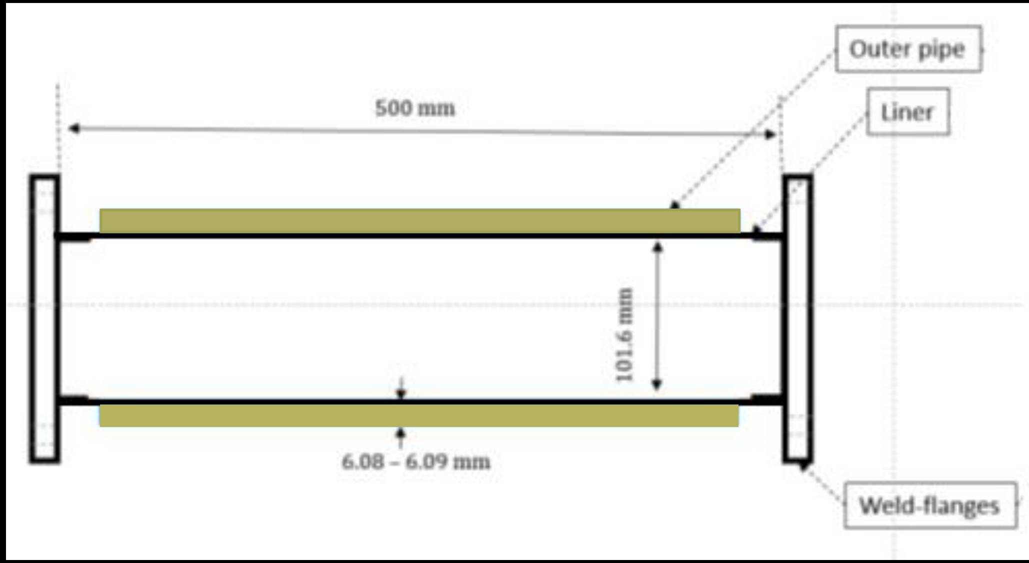
Credits: The Virgo Collaboration

- Stainless steel is the standard due to,
  - UHV compatibility and mechanical integrity
- With diameter up to 1 m and 120 km of vacuum pipes, Einstein Telescope requires,
  - Total volume ~ 100,000 m^3 (~ 10 times greater than LIGO)
  - Total surface area ~ 800,000 m^2
  - 4 mm thick stainless steel required ~ 100 kg/m (12000 tons in total)
- Decreasing of stainless steel would help in,
  - Reduction of vacuum firing cost (reduce H_2 outgassing)
  - Help in logistics of moving and assembly underground

Composite Vacuum Tube - First Prototype

- Composite Vacuum Tubes : metal liner + fiber composite have the potential of
  - Stainless steel reduction by a factor 10 (e.g., 4 to 0.4 mm)
  - Lighter tubes which help in logistics of moving and assembly underground
  - On-site production

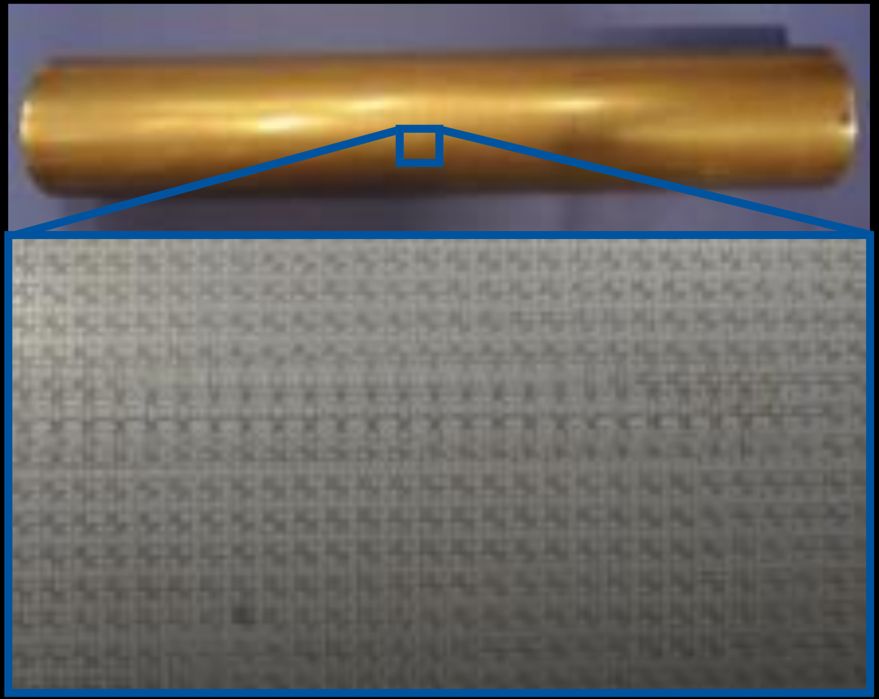


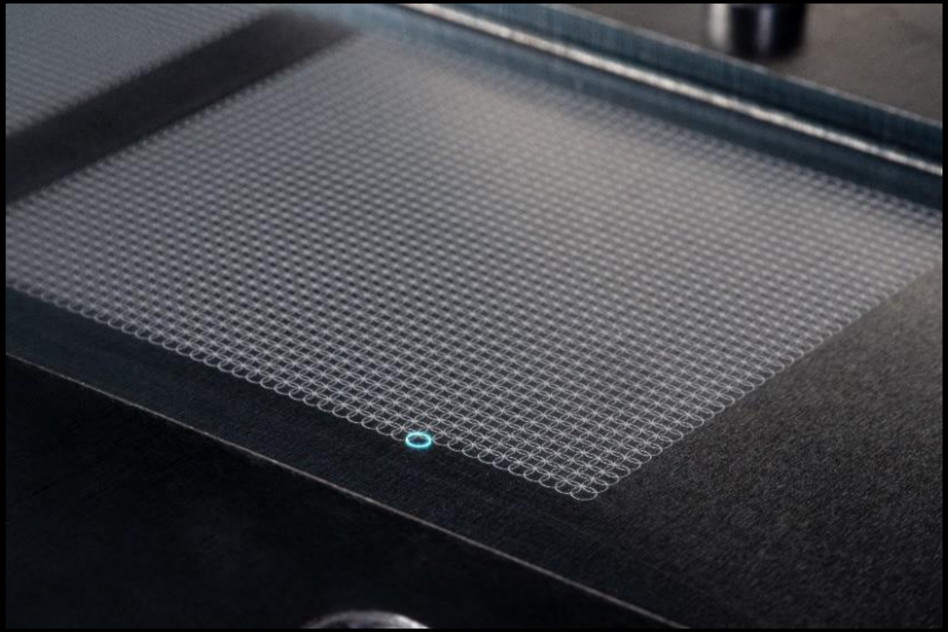


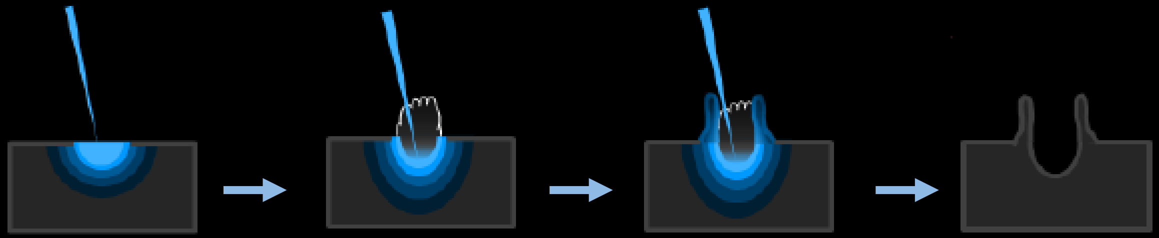
- Metal liner thickness - 0.8 mm
- Composite - 6 mm

Manufacturing of the First Prototype

- Stainless Steel Liner (304L, t = 0.8 mm)
  - Laser structuring of the liner : 20 µm deep groves
  - To improve the bonding between the liner and the composite material







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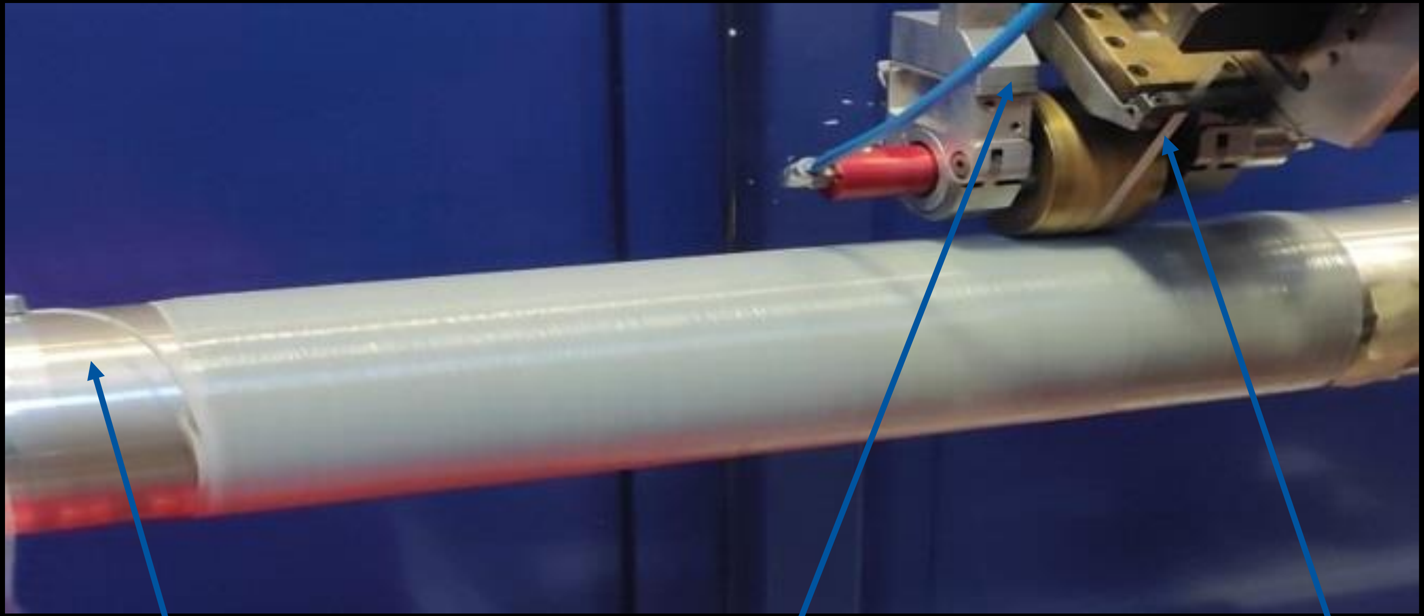
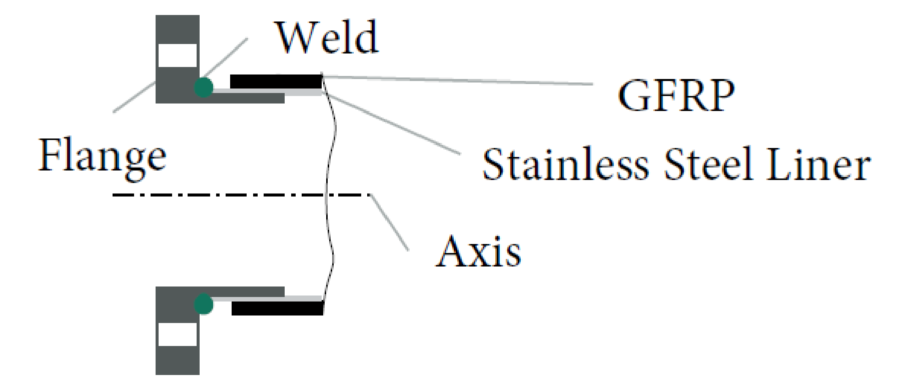
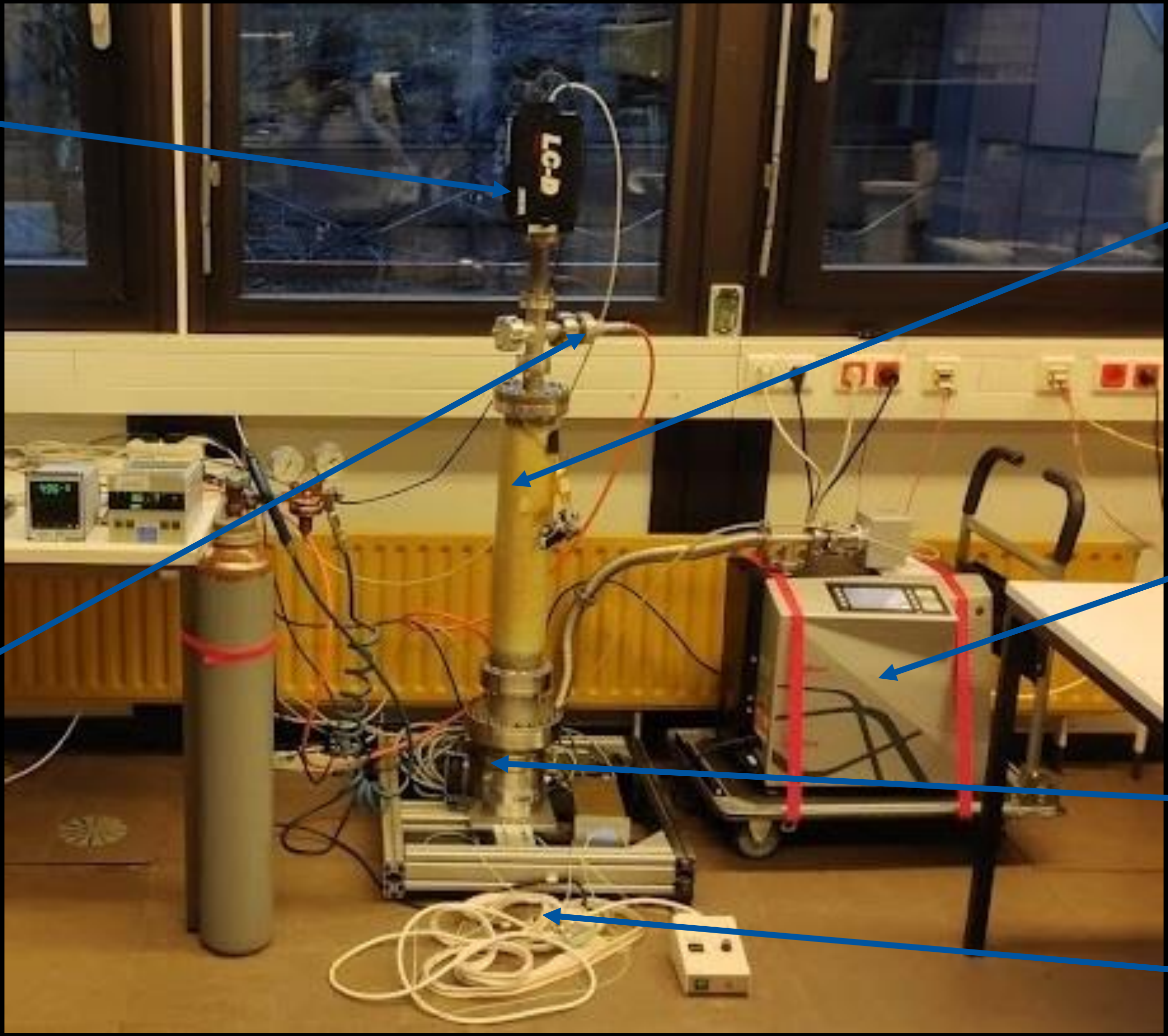
Manufacturing of the First Prototype

- Composite material - Glass Fiber Reinforced Plastic (GFRP)
  - Glass fiber with epoxy matrix (circumferential winding)
  - Curing Temperature : 120° C (limits the bake-out temp)





Vacuum System and Testing



The vacuum test :

- Helium leak test
- With turbo molecular pump after baking the system for 7 days at 100° C

$P = 7 \times 10^{-10}$ mbar

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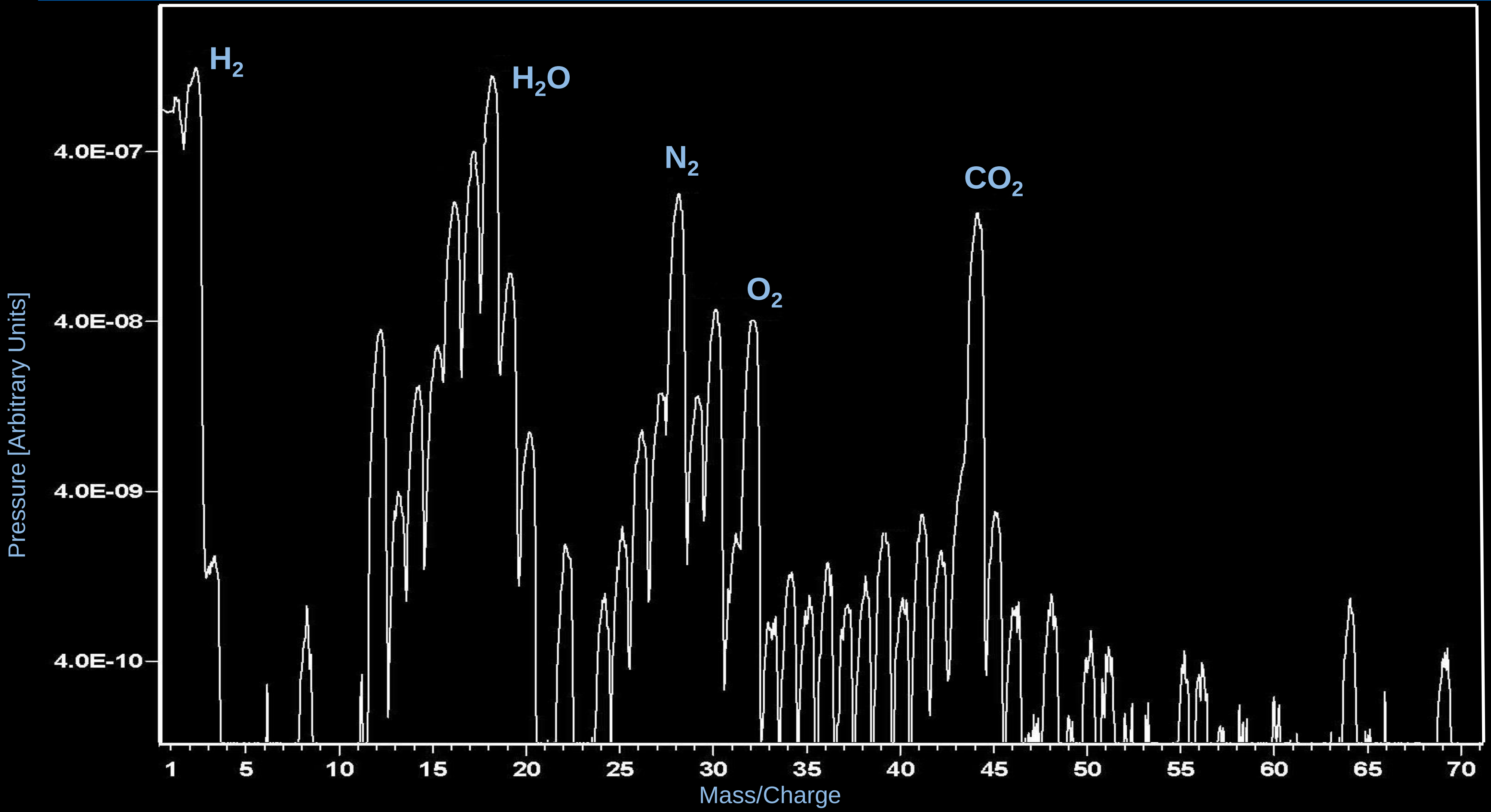
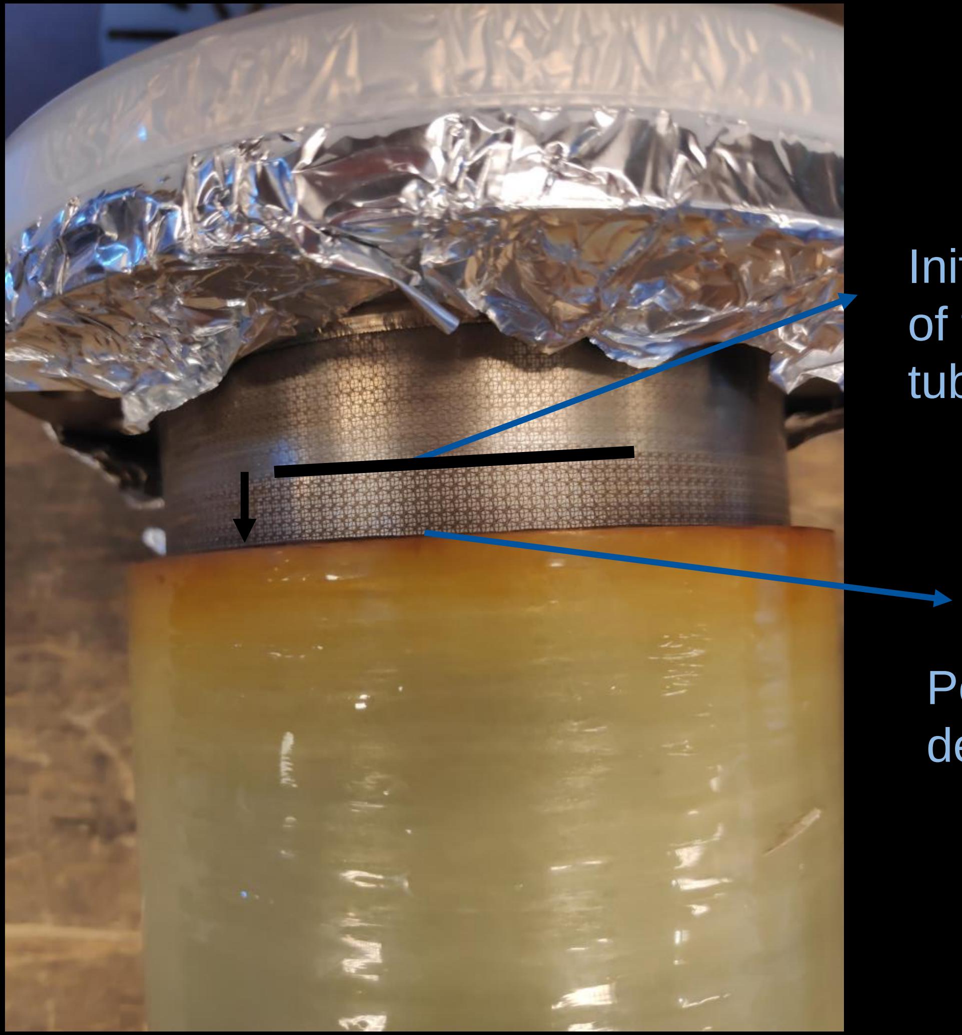
Residual Gas Spectrum



- H_2 and H_2O limited
- High CO_2 peak

Delamination of the First Prototype

- Operation for more than 6 months under vacuum and survived multiple bake-outs (100 °C)
- The liner got delaminated from fiber composite tube
- Partial destruction of laser structures while rolling the stainless-steel sheet into a tube



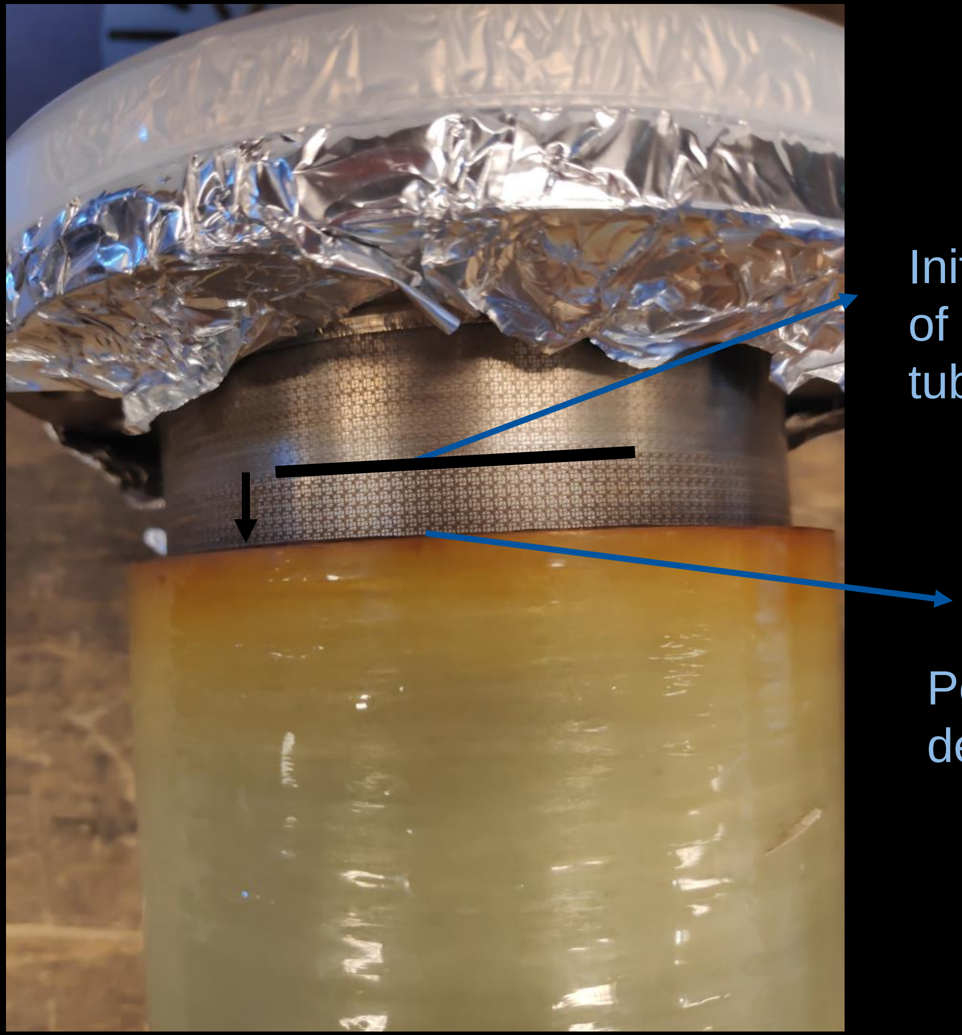
Initial position of the GFRP tube

Position after delamination

Possible Reasons for the Delamination

- Mismatch of coefficient of thermal expansion (CTE) of SS304L and fiber composite

Material	Typical CTE (µm / m °C)
SS304L	17.3
Fiber Composite	7.1 (along fibers) 31.3 (transverse to fibers)

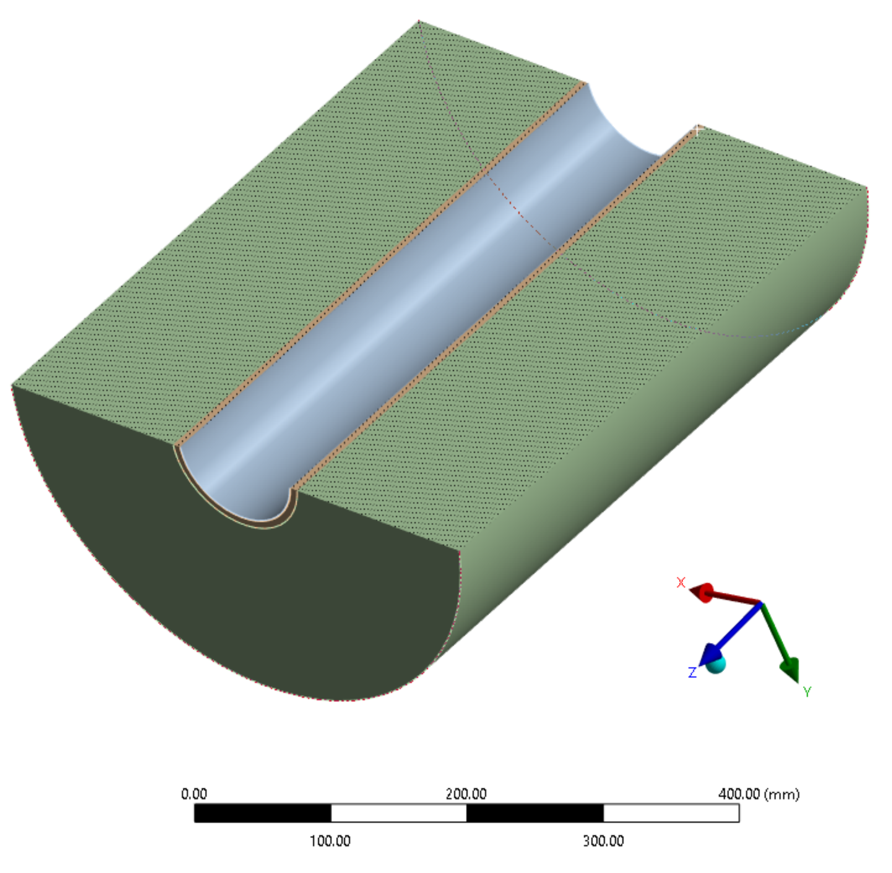


Initial position of the GFRP tube

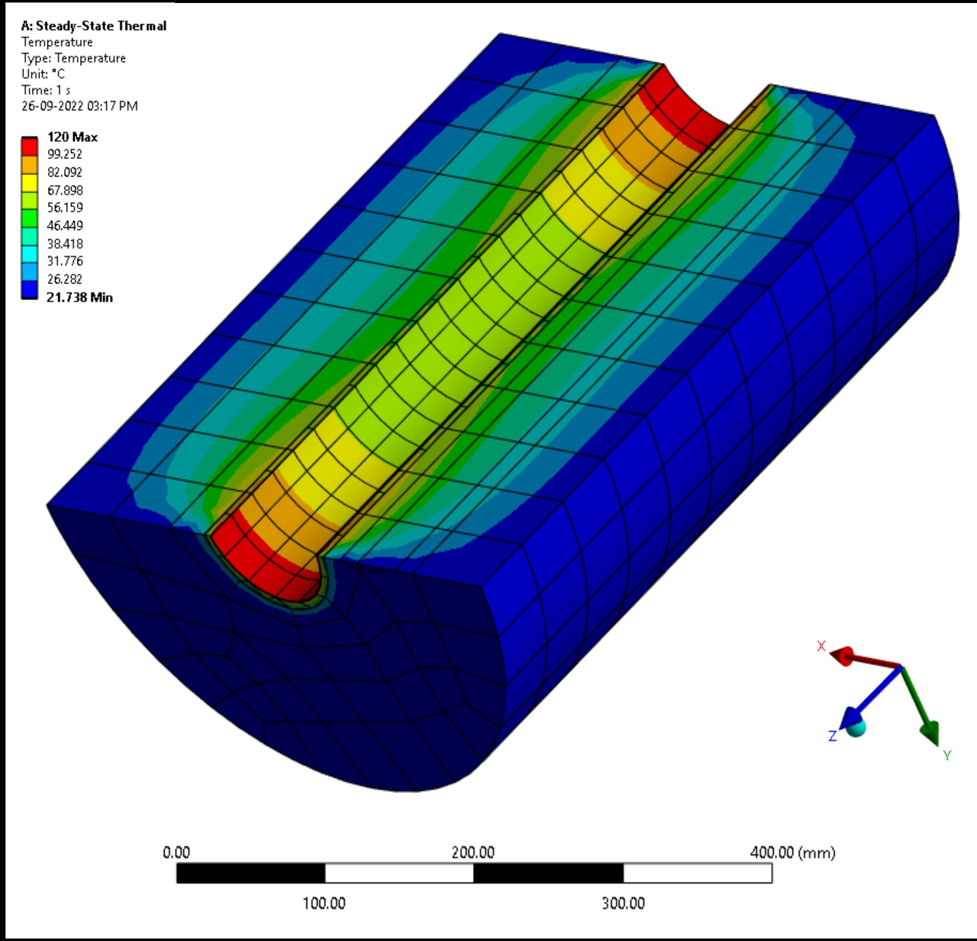
Position after delamination

Possible Reasons for the Delamination

- Differential thermal expansion due to temperature gradient along and across the composite vacuum tube

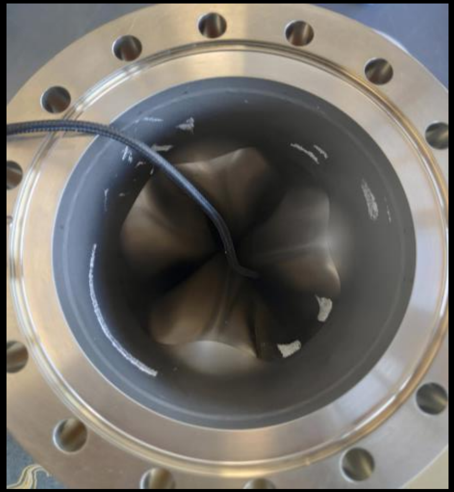


- Temperature of 120 °C at the stainless steel ends
- Insulation using mineral wool of 15 cm
- Convection boundary condition with coefficient of 5 Wm^{-2} $°C^{-1}$



Conclusions

- The first prototype was under vacuum for more than 6 months
- The fiber composite got delaminated from the stainless-steel liner
- Choice of composite :
  - Epoxy with randomly oriented fibers to make it isotropic and matching CTE with metal
- Simulation :
  - Minimize the material budget
  - Scaling of composite vacuum tube for ET dimensions
- Tests :
  - Shearing tests of chosen composites along with heat cycling test
  - UHV compatibility of composite tubes
  - Overpressure tests (safety margin)
- Design a heating strategy



Buckled Tube

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Thank You!

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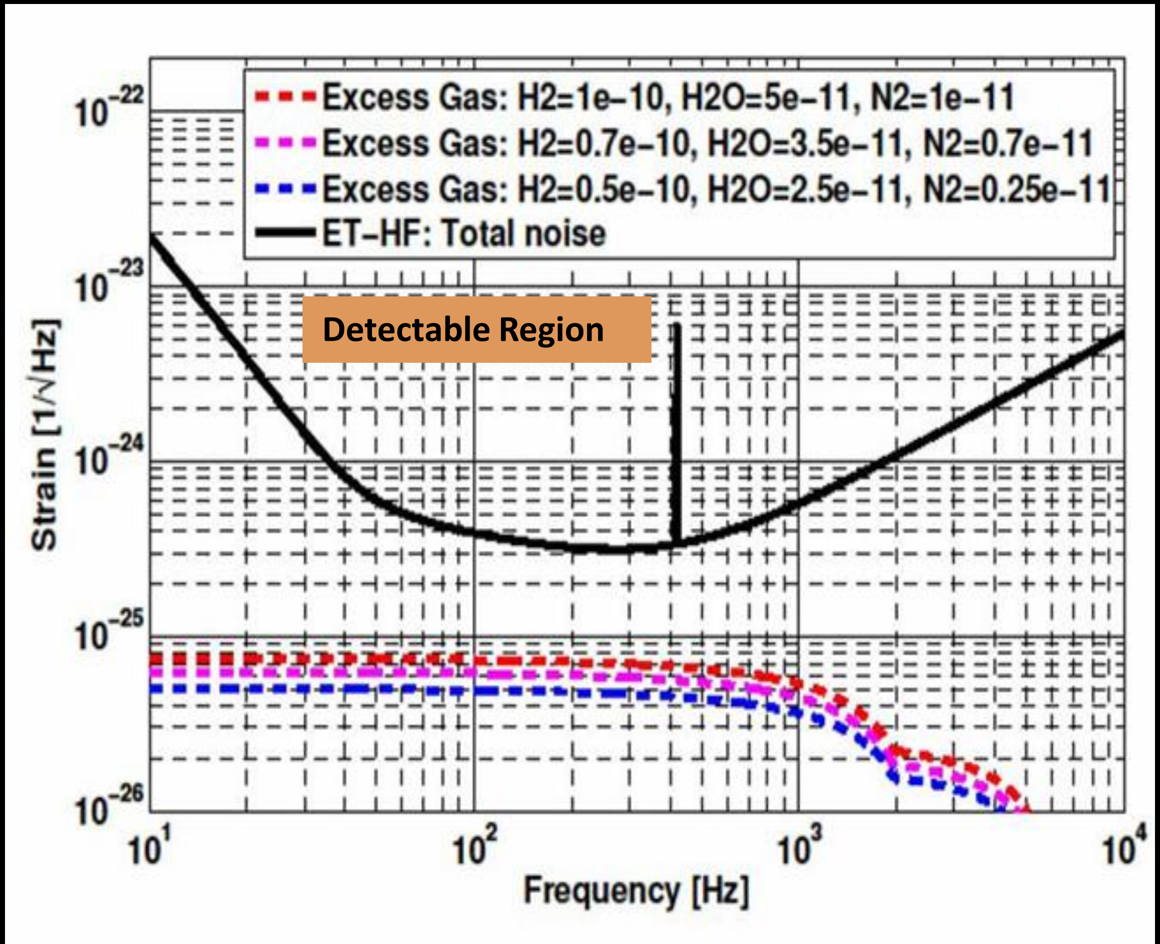
Appendix

Ultra High Vacuum(UHV) Requirement

- Reduce the noise due to excess gas density fluctuations along the laser beam path
- Reduction of test mass motion and thermal isolation
- Preserving cleanliness of optical elements
- Hydrogen (1 x 10^{-10} mbar) :
  - From the bulk during stainless steel production
- Water (< 5 x 10^{-11} mbar) :
  - Moisture from air
  - Removed using heating/bake-out
- Hydrocarbons (< 10^{-14} mbar) :
  - Deposited on the surface e.g., oil during machining
  - Careful cleaning using detergents and assembly



Credit: ET Design Report Update 2020

1 order sensitivity increase requires 1 order improvement in vacuum

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Vacuum Tubes of Current Gravitational Wave Detectors

LIGO, USA

Credits: Caltech/MIT/LIGO Laboratory

- Material : Stainless Steel 304L
- Diameter : 1.2 m
- Arm length : 4 km each
- Achieved pressure : 2 x 10^{-9} mbar

Virgo, Italy

Credits: The Virgo Collaboration

- Material : Stainless Steel 304L
- Diameter : 1.2 m
- Arm length : 3 km each
- Achieved pressure : 1 x 10^{-9} mbar

KAGRA, Japan

Credits: KAGRA Observatory, ICRR, The University of Tokyo

- Material : Stainless Steel 304L
- Diameter : 0.8 m
- Arm length : 3 km each
- Achieved pressure : 1 x 10^{-7} mbar

History of Composite Vacuum Tubes at CERN

New material development for transparent vacuum chambers – Structural composite

Case of an external thin leak tight aluminium envelop with internal C/C reinforcement


Internal C/C tube

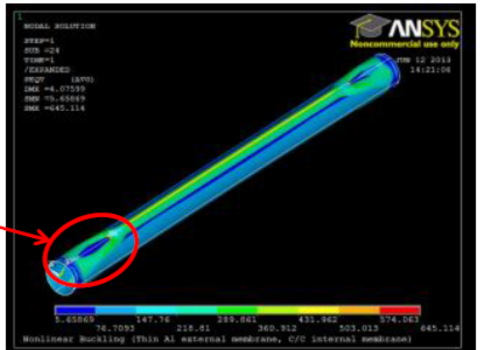
☺ Good vacuum performance:
- Outgassing rate ~ 10-12 mbar.l.s-1.cm-2 after bakeout
- Compatible with NEG coating

	Activation 200 ◦C for 24h	Activation 250 ◦C for 6h
H_2 Pumping Speed [l/s]	310	530
Sticking probability [-]	$5.9*10^{-3}$	$1*10^{-2}$

Pumping speed with NEG coating

☹ Issue with the mechanical behaviour:
- Differential thermal expansion → buckling of the thin aluminium envelop

Strain concentration

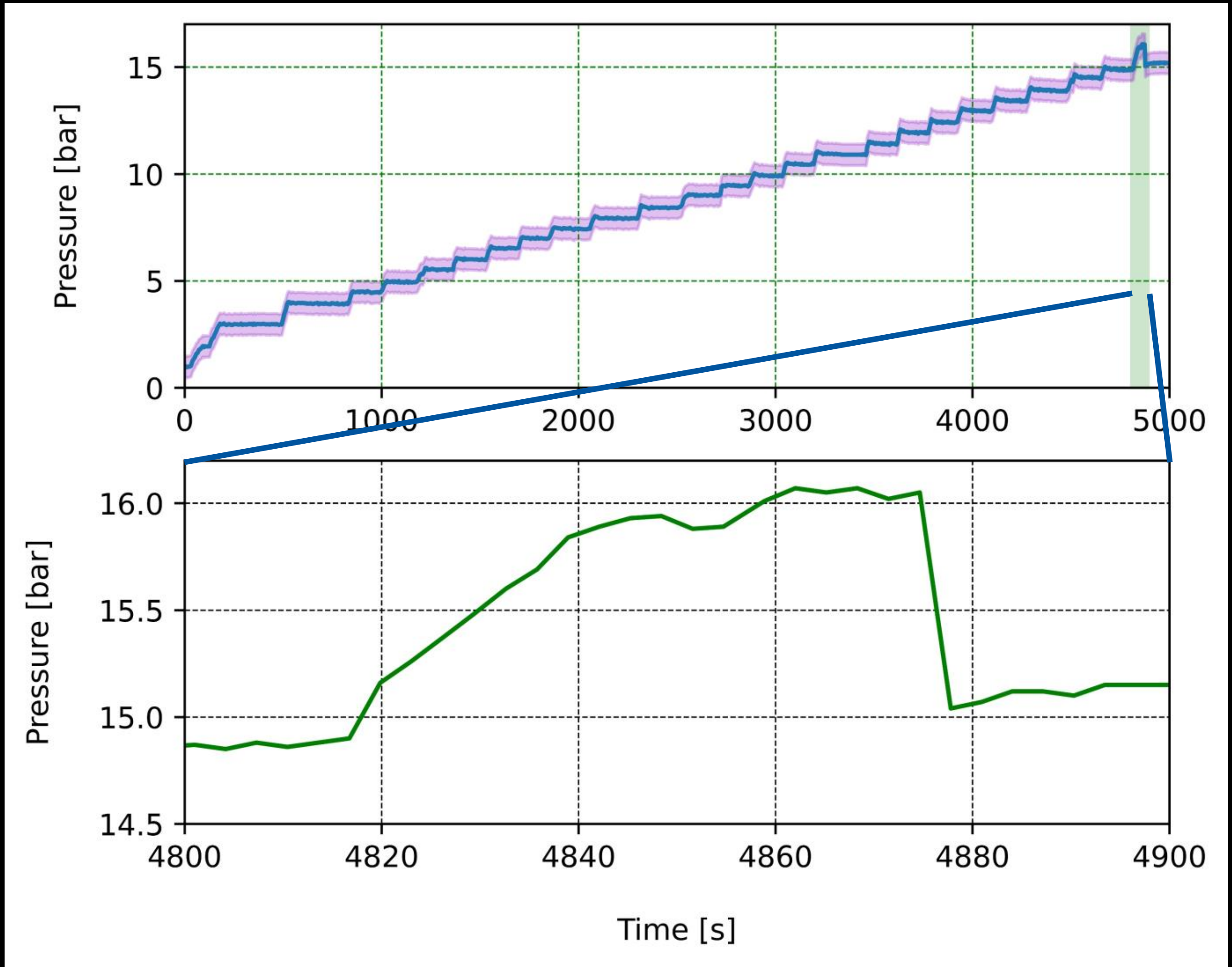


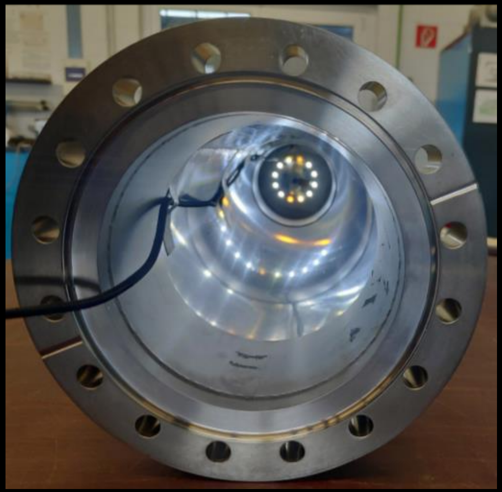
Buckling mode of long tube

→ Need to have significant envelop thickness
→ Either not reliable or not interesting

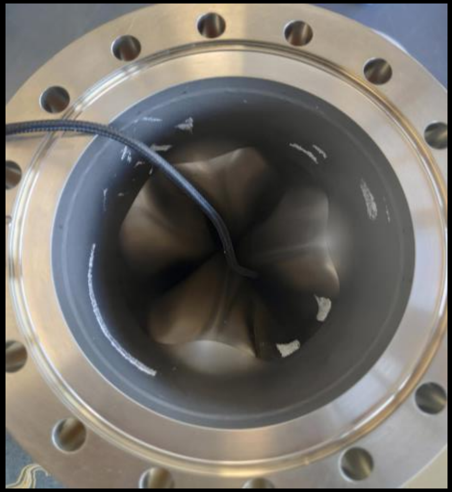
(Source :https://indico.cern.ch/event/278903/contributions/631198/)

Critical Buckling Pressure (16.0 ± 0.5 bar)



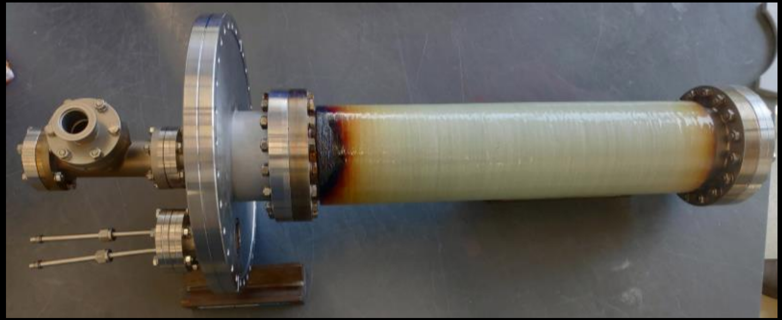


Original Tube

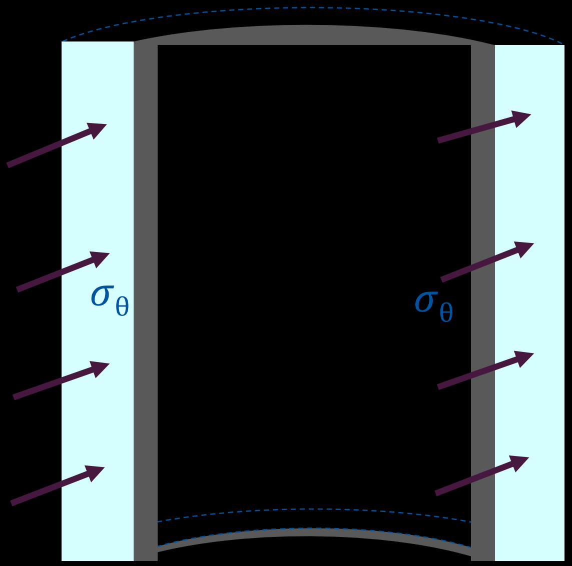


Buckled Tube

- Only the SS304 liner bucked and the GFRP tube stayed intact

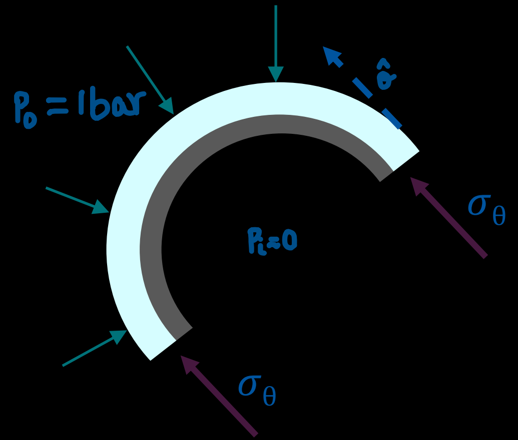


Hoop/Circumferential Stress in a Cylinder



- Hoop/Tangential stress : $\sigma_\theta(r) = \frac{p_0 r_0^2}{r_0^2 - ri^2}\left(\frac{r_i^2}{r^2} + 1\right)$ as d/t <20 (thick tube)

- Yield Stress = 205 MPa



Design	Thickness (mm)	Hoop Stress max at atmospheric pressure (MPa)
Prototype 1.0	0.8 + 6.08	- 0.88

- As the hoop stresses are compressive, epoxy matrix should support the load and prevent the E-glass fibers from buckling

- Longitudinal Compressive strength of E-glass Epoxy (V_f = 0.6) = 620 MPa

- Typical Compressive strength of an unmodified epoxy = 70 MPa

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Overpressure Test

- Overpressure test was performed in order to

  - Verify/set a baseline for the simulation results

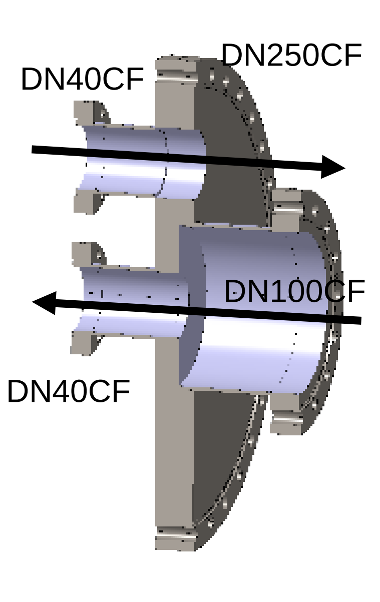
  - Effect of the delamination

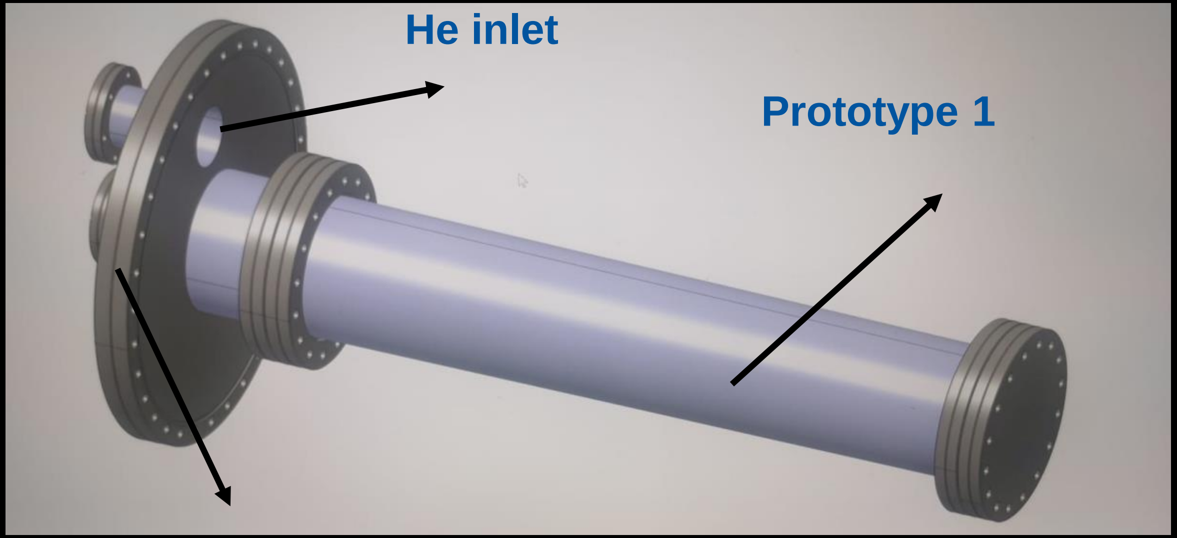
1300 mm

Thickness 2 mm

He 0-16 bar

Leak chaser





DN250CF outer flange