Beam Pipes for Gravitational Wave Telescopes
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# Leak Detection:
## component production to system installation


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# Outline

- Introduction
- Testing considerations & strategies
- Testing without flanges
- Cost (gu)estimates
- Summary

# Opening Remarks….

Good Leak Testing
(expensive, time consuming) — No → Good Leak Tightness

→ Doesn't leak, or…..does leak
☺ ☹ $$

Good Engineering Practice
(design, manufacture, assembly, commissioning, QC)
Vacuum engineer must be involved in all steps — Yes → Good Leak Tightness

Gravitation Wave Telescopes are a new adventure for us ……… so please guide us as much as possible !

# LHC Insulation Vacuum

- A few numbers.....

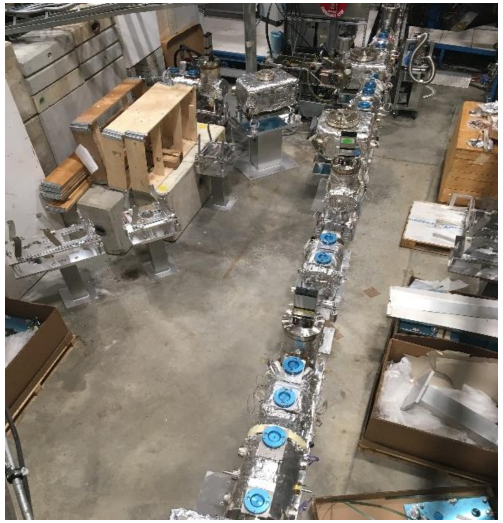
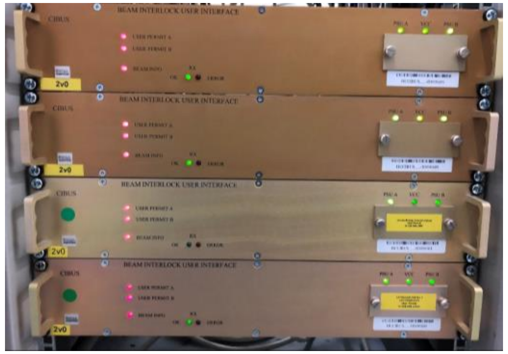
| Characteristic | Quantity for LHC machine & distribution line (QRL) |
|---|---|
| **Insulation vacuum system length** | **22,4 km & 25 km** |
| **Welds** | **~ 200 000 ( > 60 000 in-situ)** |
| **Weld length** | **~ 100 000 m** |
| **Elastomer joints** | **~ 18000** |
| **Elastomer joint length** | **~ 22 000 m** |
| **Multi-layer insulation** | **~ 9 000 000 $m^2$ or 200 $m^2$/m of cryostat** |
| **Vacuum subsectors** | **234** |
| **Vacuum subsector length** | **214 m (machine) & 428 m (QRL)** |
| **Vacuum subsector volume** | **~ 80 $m^3$** |
| **Fixed turbo pumps** | **178** |
| **Nominal turbo pumping speed** | **0,25 l/s/m of cryostat** |
| **Fixed vacuum gauges** | **974** |
| **Mobile turbo pumping groups** | **36** |
| **Mobile primary pumping groups** | **36** |

# Vacuum of CERN's accelerators

| Machine | Type | Year | Energy | Bakeout | Pressure [mbar] | Length |
|---|---|---|---|---|---|---|
| **Linacs, Booster, ISOLDE, PS, n-TOF and Antimater** | | | | | | **2.6 Km** |
| **Linac 4** | linac | 2018 | 160 MeV | ion pumps | $10^{-7}$ | 40 m |
| **ISOLDE** | electrostatic | 1992 | 60 keV | _ | $\mathbf{10^{-6}}$ | 150 m |
| **REX-HIE ISOLDE** | linac | 2001-2016 | 5.5 MeV/u | partly | $10^{-7}$-$10^{-12}$ | 50 m |
| **MEDICIS** | | 2017 | _ | _ | $10^{-6}$ | 10 m |
| **Linac 3** | linac | 1994 | 4.2 MeV/u | ion pumps | $10^{-8}$ | 30 m |
| **LEIR** | accumulator | 1982/2005 | 72 MeV/u | complete | $10^{-12}$ | 78 m |
| **PSB** | synchrotron | 1972-2020 | 1-2 MeV | ion pumps | $10^{-9}$ | 157 m |
| **PS** | synchrotron | 1959 | 26 GeV | ion pumps | $10^{-9}$-$10^{-10}$ | 628 m |
| **AD** | decelerator | 1999 | 100 MeV | complete | $10^{-10}$ | 182 m |
| **ELENA** | decelerator | 2016 | | complete | $\mathbf{10^{-12}}$ | 31 m |
| **PS to SPS TL** | transfer lines | 1976 | 26 GeV | _ | $10^{-8}$ | 1.3 km |
| **SPS complex** | | | | | | **15.7 Km** |
| **SPS** | synchrotron | 1976 | | extractions | $10^{-9}$ | 7 km |
| **SPS North Area** | | 1976 | | _ | $10^{-3}$-$10^{-8}$ | 1.2 km |
| **SPS HiRadMat** | transfer line | 2011 | 450 GeV | _ | $10^{-8}$ | 1.4 km |
| **SPS to LHC TL** | | 2004/06 | | _ | $10^{-8}$ | 2 x 2.7 km |
| **AWAKE** | wakefield acc | 2017 | | _ | $10^{-8}$ | 730 m |
| **LHC** | | | | | | **109 Km** |
| **LHC Arcs (Beam vacuum)** | | | | _ | $<10^{-8}$ | 50 km |
| **LHC Arcs (insulation vacuum)** | | | | _ | | 50 Km |
| **LSS RT separated beams** | collider | 2007 | 2 x 7 TeV | | | 2 x 3.2 km |
| **LSS RT recombination** | | | | complete | $<10^{-10}$ | 570 m |
| **Rxperimental areas** | | | | | | 180 m |
| **Beam dump lines TD62/68** | transfer lines | 2006 | 7 TeV | _ | $10^{-8}$ | 2 x 720 m |

| | |
|---|---|
| **High Vacuum** | **≈ 12** |
| **UHV-XHV** | **≈ 65** |
| **Insulation vacuum** | **≈ 50** |
| | **≈ 127 km** |




# Typical ET Build Sequence

| | |
|---|---|
| Arm Vacuum - System Total length (m) | 120000 |
| Arm Vacuum - System length (m) | 10000 |
| Arm Vacuum - Vacuum Sector length (m) | 5000 |
| Arm Vacuum - Pipe String length (m) | 312.5 |

- Components: Manufacture ‘Pipes’ & ‘Pumping Modules’
  - Inspect, clean, condition?, helium leak test, vacuum characteristation?, wrap?, ….
- Assemblies: Weld Pipes into x00 m ‘Strings’
  - Inspect, clean?, pump, helium leak test new welds, ….
- ‘Vacuum Sector’: Weld ‘Pumping Modules’ between ‘Strings’
  - Inspect, clean?, instrument, pump, helium leak test new welds & CF instr flanges, bake, global tests.

What leak test delivery rates to achieve ? I’ve assumed a 2 yr build period, ~ 400 working days.

| **Vacuum System Item** | **Qty** | **Leak tests/day** | |
|---|---|---|---|
| | | **Factory** | **On-site** |
| Arm Pipe (15m unit length, Ø 1.2 m) | 8000 | 20/day | |
| Arm Pumping Module (1m unit /312.5m) | 385 | ~ 1/day | |
| Arm Pipe String (312.5m lengths) | 384 | | ~ 1/day |
| Arm Vacuum Sectors (5000 m length) | 24 | | ~1/month |

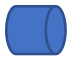
# Leak Testing: What could leak ?

- Ex-situ (components)
  - 15m Pipe
    - longitudinal weld (spiral or straight)
    - circumferential welds (if any)
    - material through-wall defects (porosity, inclusions, damage, weld arc errors, ..)
  - 1 m Pumping Module
    - welds, material defects, flange NC,…

Components:
under vacuum tests, external helium

20/day

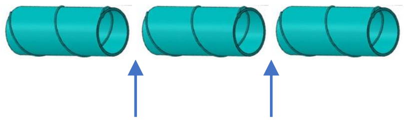
1/day



- In-situ ( x00 m Pipe Strings)
  - Pipe to Pipe circumferential welds
  - Degradation of validated components (transport, corrosion, etc)

Pipe Strings: Pipe to Pipe
(under vacuum tests, external helium)

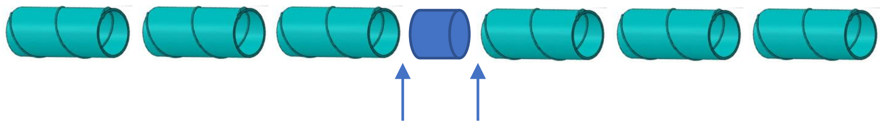
1/week



- In-situ (5 km Vacuum Sector)
  - Pipe to Pumping Module circumferential welds
  - Vacuum Instrumentation CF flange connections

Vacuum Sector: Pipe String to Pipe String

1/month



# Leak Testing Considerations

⇨ Assume manufacture/installation in 400 working days.
⇨ Use COTS vacuum equipment – mobile pumping groups, MSLD, etc.

Big infrastructure cost & space needs

$$\tau = \frac{V(liters)}{S_{eff}(liters/s)}$$

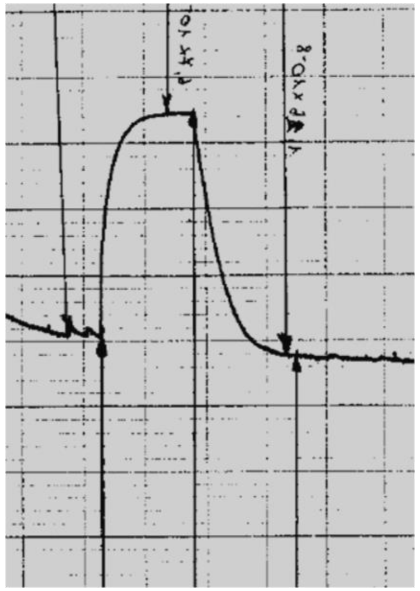
| Vacuum System Item | Qty | Leak tests/day | | Volume | Time constant (s) |
|---|---|---|---|---|---|
| | | Factory | On-site | (m3) | (with Seff 1000 l/s) |
| Arm Pipe (15m unit length, Ø 1.2 m) | 8000 | 20/day | | ~ 15 | ~ 15 |
| Arm Pumping Module (1m unit /312.5m) | 385 | ~ 1/day | | ~ 1 | ~ 1 |
| Arm Pipe String (312.5m lengths) | 384 | | ~ 1/day | ~ 312 | ~ 312 |
| Arm Vacuum Sectors (5000 m length) | 24 | | ~1/month | ~ 5000 | ~ 5000 |

$S_{eff}$ needs to be in ~ 10000 l/s range

Assume target tightness: $10^{-10}$ mbarl/s per component (yes?)

Signal rise time (& recovery time) needs to be considered

$$P_{He} = \frac{q}{S_{eff,He}}\left(1-e^{-\frac{t}{(V/S_{eff,He})}}\right)$$



$$P_{He} = \frac{q}{S_{eff,He}}\left(e^{-\frac{t}{(V/S_{eff,He})}}\right)$$

# Leak Testing: Strategy Options

| Leak Test Strategy | Fixed Costs (std tests) | Variable Costs (leaks) |
|---|---|---|
| ‘Max’ Testing Strategy<br>(classic, preventive approach) | Ex-situ: 100 % Component leak test ($$$),<br>In-situ: 100 % Subsector leak test($$),<br>In-situ: Vacuum Sector leak test ($), | NC localisation, repairs & retest ($)<br>NC localisation, repairs & retest ($)<br>NC localisation, repairs & retest ($) |
| ‘Mid’ Testing Strategy | In-situ: 100 % Subsector leak test($$),<br>In-situ: Vacuum Sector leak test ($), | NC localisation, repairs & retest ($$)<br>NC localisation, repairs & retest ($) |
| ‘Min’ Strategy<br>(corrective approach) | In-situ: Vacuum Sector test ($) | NC localisation, repairs & retest ($$$) |

## Max, Mid or Min approach ?

Leak Test Strategy will depend on:

⇨ How many leak we expect to get (past experience from similar projects),

⇨ Fixed cost of 100% component test vs Variable costs of leak repairs in-situ

⇨ Solutions for in-situ leak localization

⇨ Solutions for in-situ leak repairs

⇨ Other constraints eg all 8000 Pipes need individual insulation/bakeout/vacuum characterizated before installation ?

⇨ Approach can be changed/tailored during execution……

# How many leaks ?

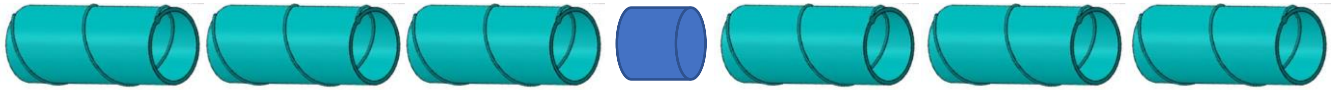
- LIGO experience on 20 m Pipes (report P990023-00-B)
  - Auto welding ⇨ visual inspection (plus x-ray or US ?) ⇨ manual weld repairs ⇨ leak test.
  - No leaks on ~ 1000 tube/components. Statistics on in-situ leaks to be gathered

- VIRGO experience
  - Statistics on component & in-situ leaks to be gathered

- LHC experience on insulation vacuum
  - Zero leaks on spiral weld of dipole cryostats (~ 1350 units)
  - Leaks of 1-5 ‰ welds in overall project ~ 200k welds (auto & manual)
    - 2d inclusions, Cu contamination, poor manual/auto execution, damage, etc.
  - Some leaks only appear during or after cold thermal cycle

- Applying LHC experience to ET Arm Vacuum (120 km)
  - ~ 10000 ex-situ welds ⇨ qty of leaks: 10 – 50 range ( < 1 % of Pipes may leak)
  - ~ 10000 in-situ welds ⇨ qty of leaks: 10 - 50 range ( < 1 leak / km)

Ex-situ Component welds: 8000 Pipes 400 Pump Modules



In-situ Assembly welds: 8000 Pipe-Pipe 800 Pipe-Pump Modules 400 CF flanges

# Vacuum Vessel Testing: With/without flanges

ARIA Cryostats without flanges

LHC Cryostats with flanges

# Leak Testing without flanges - ARIA experience

(300m tall Ar distillation column)

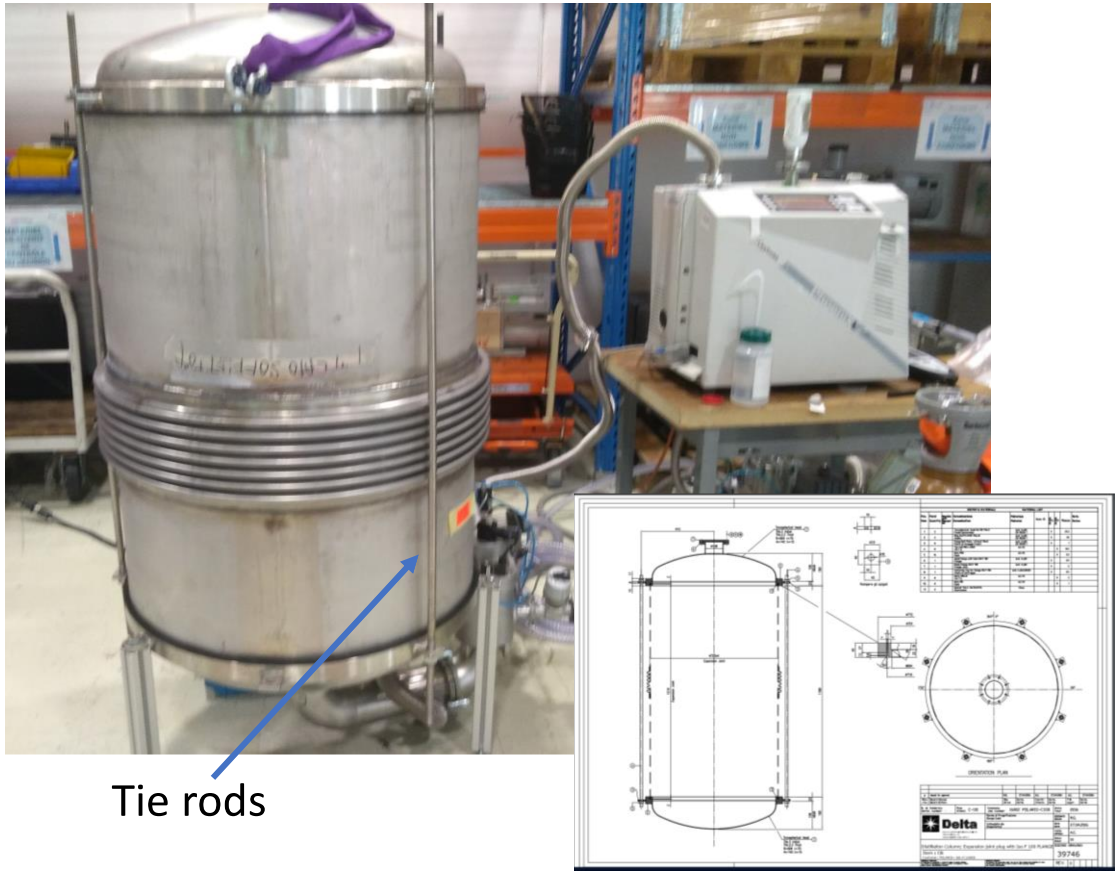
28 cryogenic pipe elements

29 bellows elements

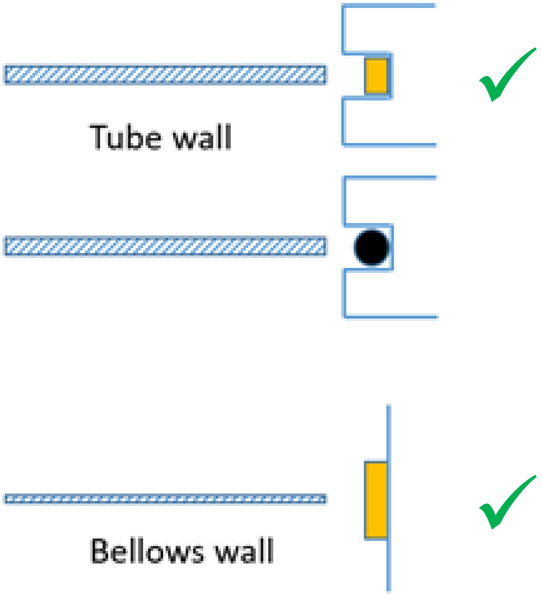
# End Sealing without flanges

DCM bellow – end flanges

ARIA bellow – Ø723 mm, no flanges, 4 mm wall

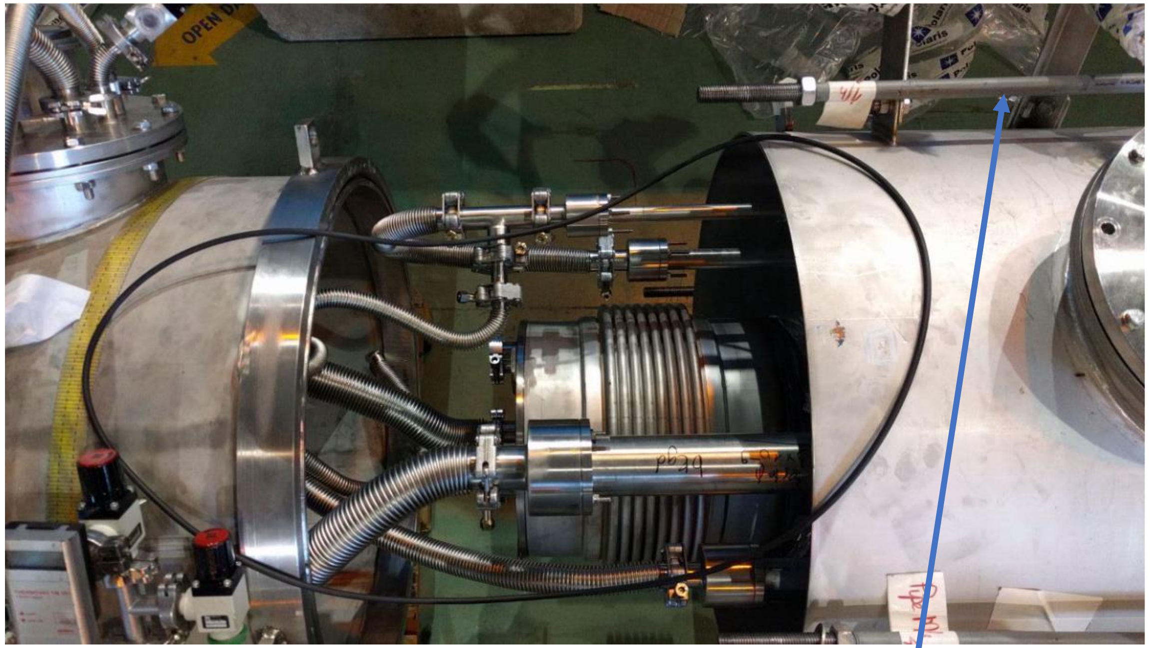


Tie rods

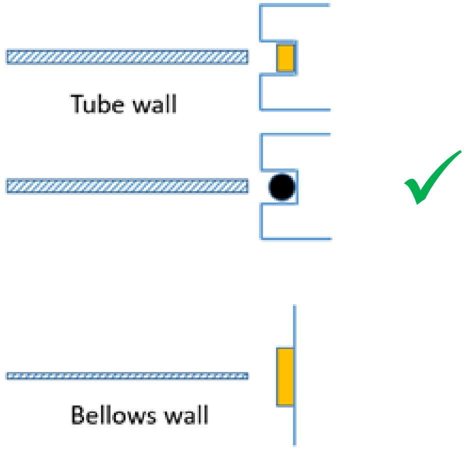


# End sealing without flanges

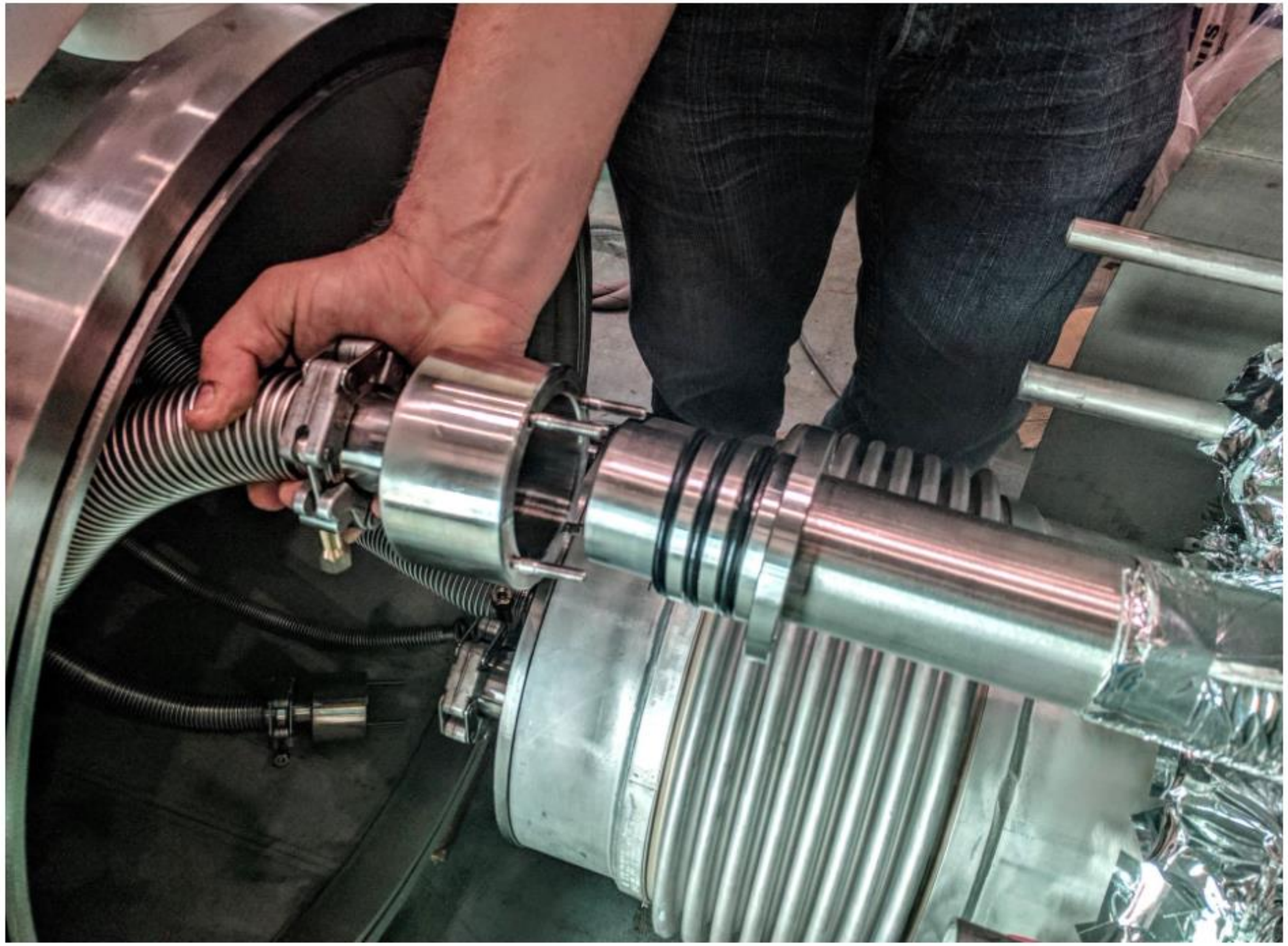
4 mm wall



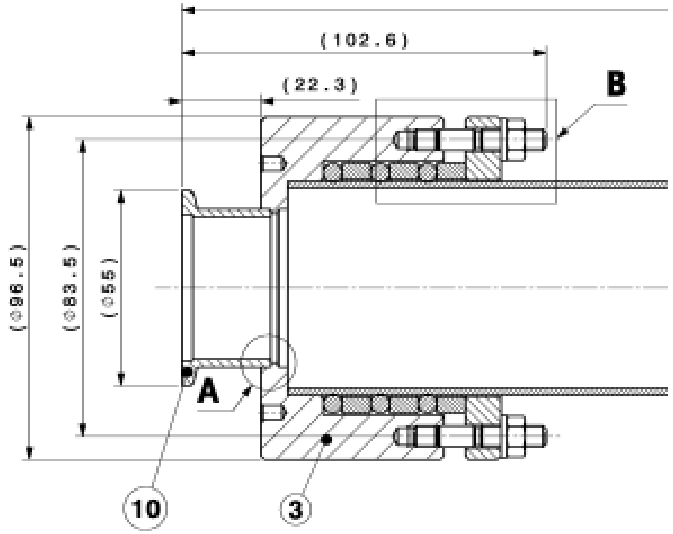
Tie rods



# End Sealing – no flanges

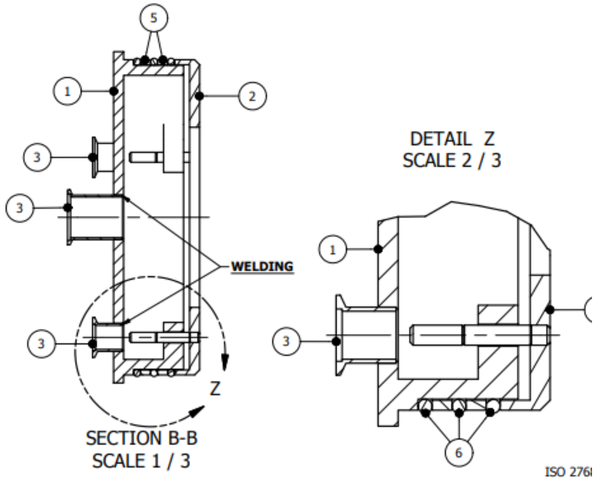


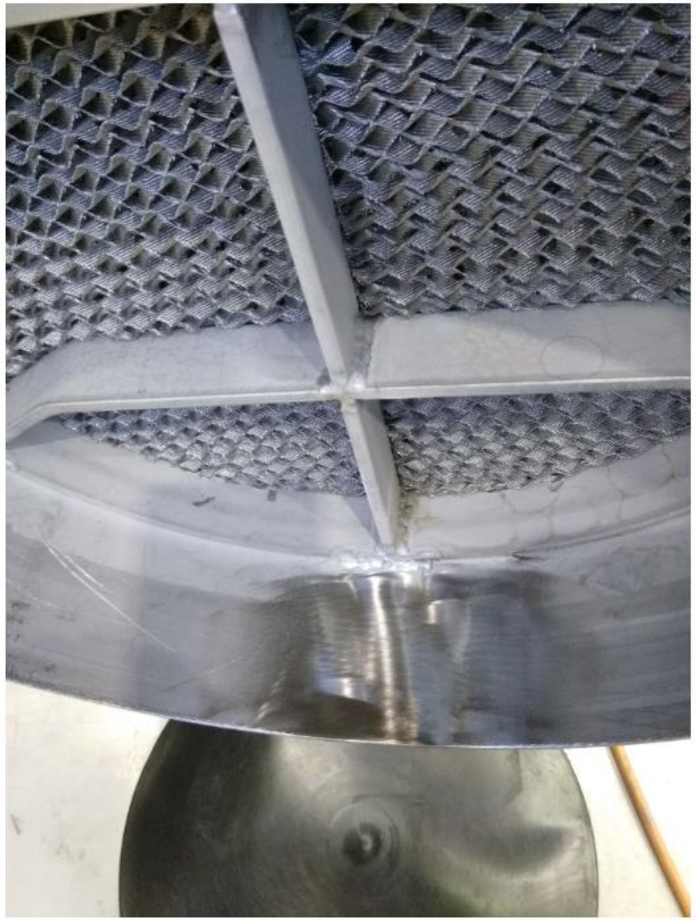
Triplet o-rings to prevent helium permeation



# Sealing – no flanges

End plug sealing on internal tube surface



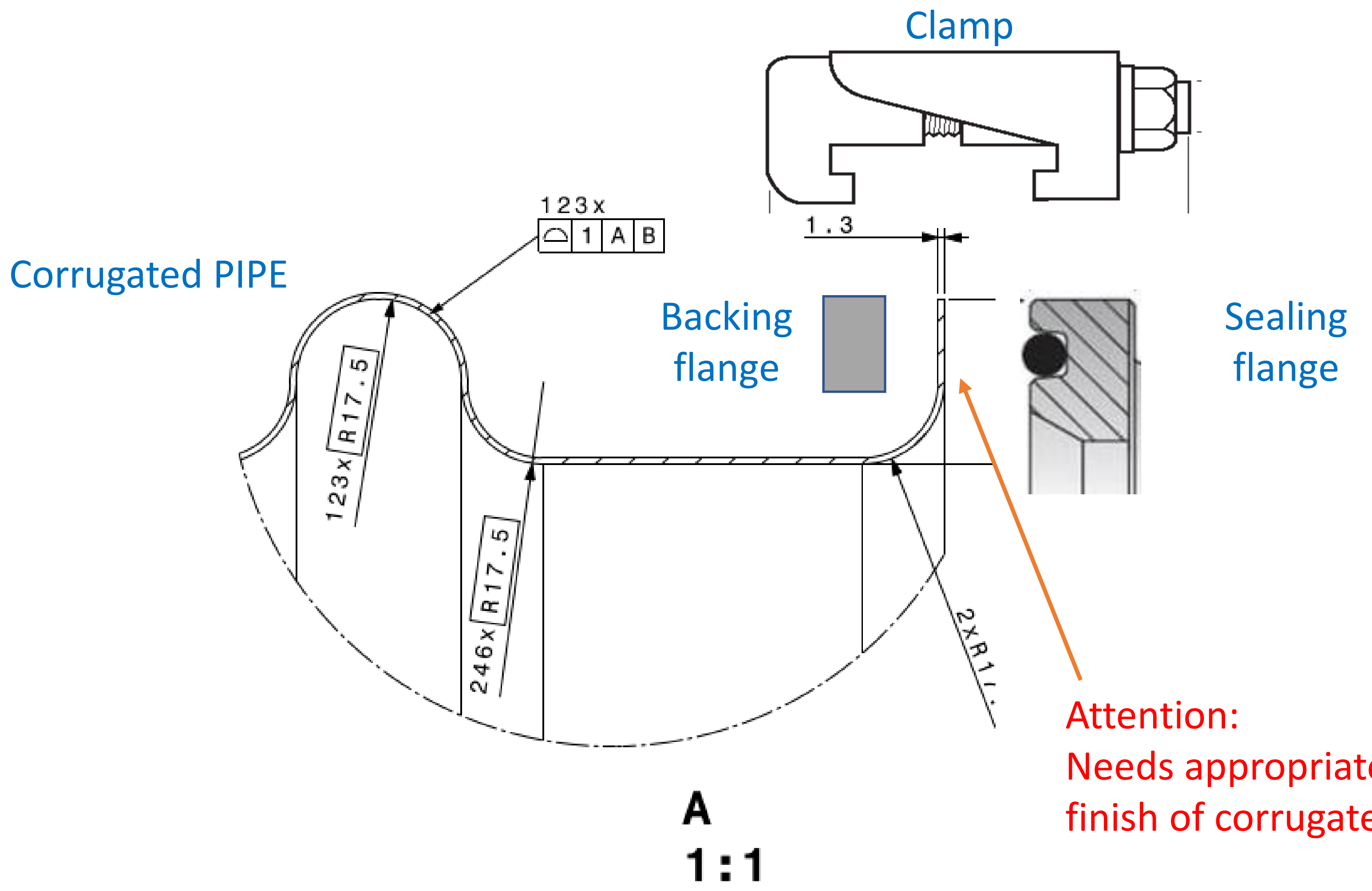



Smoothing of the longitudinal weld seam

# End Sealing – no flanges


Inflatable plug solution

# End Sealing – no flanges



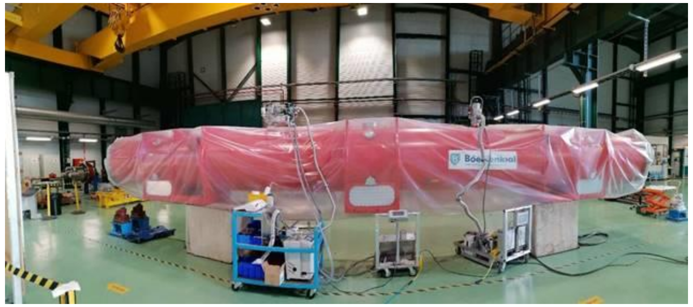

Attention:
Needs appropriate surface finish of corrugated extremity

# Helium delivery during ‘under vacuum’ testing ?

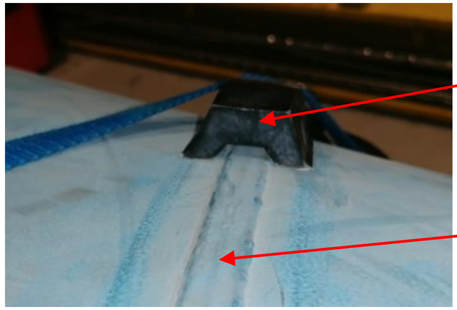
He delivery options:

⇨ Jet (not ideal for global test on large volumes)

⇨ Total immersion (ext pocket, ext secondary chamber)
- ⇨ Large helium cost
- ⇨ Rise in helium background in air
- ⇨ Complex tooling to recovery helium



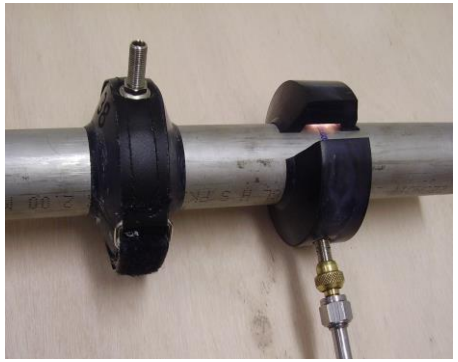

⇨ Local channel at weld to deliver external helium:
- ⇨ At longitudinal weld (spiral or straight)
- ⇨ At circumferential weld

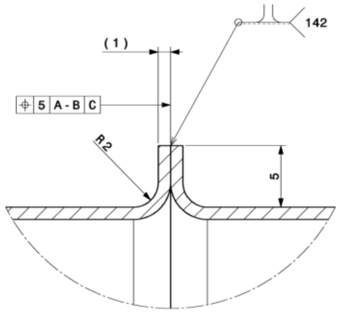


Temporary channel at the weld bead

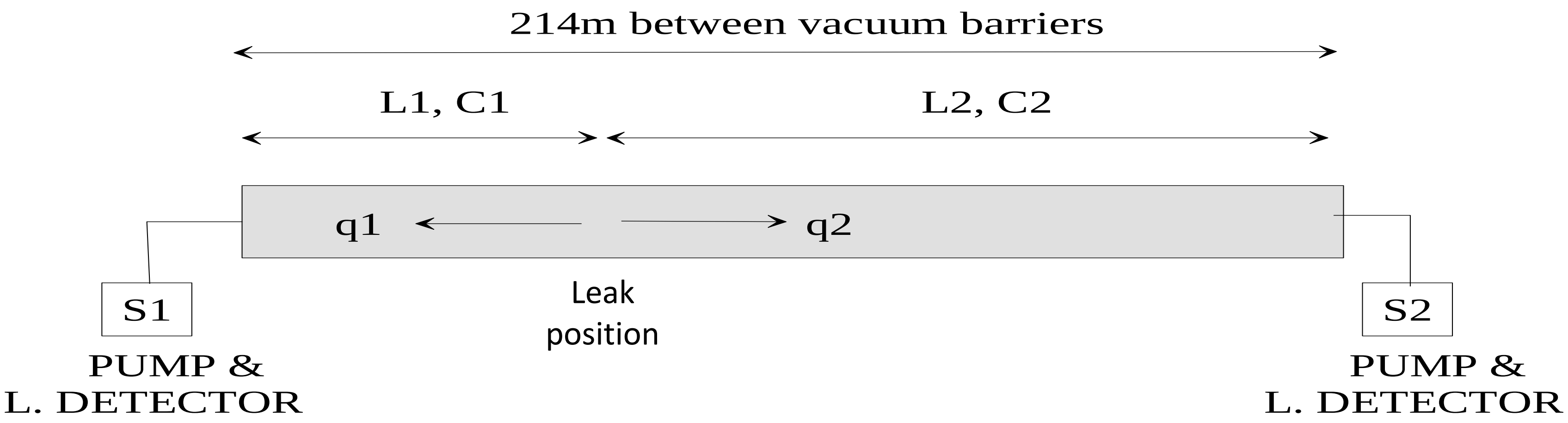
Spiral weld

⇨ External vacuum clamshell, internal helium
- ⇨ At Pumping Module circumferential welds
- ⇨ Helium (jet) delivery thro pumping port





# Leak localization in Pipe Strings




Method was used for leak localization in LHC internal helium circuits

'Under vacuum' leak test in molecular flow conditions:

- 2 identical turbo pumps at each extremity, plus leak detectors
- Helium as tracer gas.
- Measurements are made with system in equilibrium conditions.

Linear conductance of vacuum system, so $C \propto 1/L$

For S >> C1 or C2: $q1/q2 \propto C1/C2 \propto L2/L1$

Ratio of He signal arriving at each detector is inversely proportional to its distance from the leak

# Leak Testing Costs - Pipes

- Pipes (15m components)
  - Equipment costs for 2 leak test benches
    - 2 benches 60k, 2 pumping systems 100k, 2 leak detectors 40k = 200 kCHF
    - Dedicated facility of 150 $m^2$ @ 2 kCHF/$m^2$ = 300 kCHF

      (not including land purchase, in/out storage areas, handling, transport logistics, etc)
  - Manpower
    - 2 vacuum technicians producing 2 leak tests/day = 0.5 kCHF/test
    - 2 vacuum technicians localizing 1 leak, repair and retest = 1 kCHF/NC repair & retest

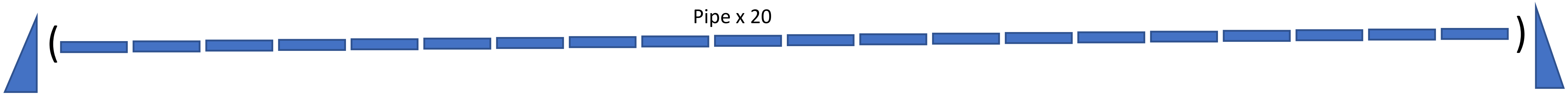
⇨ 8000 Pipes in 4000 days (2 benches): 500 kCHF & 4000 kCHF (+ NC repair & retest)

⇨ 8000 Pipes in 400 days (20 benches x 0.5): 2500 kCHF & 2000 kCHF (+ NC repair & retest)

Effect of scaling & synergies

1 CHF = 1 Euro = 1 USD

# Leak Testing Costs: Pipe Strings




- Pipes Strings (312 m)
  - Equipment costs for 1 leak test setup:
    - 2 mobile end caps (20k) , 2 mobile fixed points (20k) = 40 kCHF
    - 1 mobile roughing (60k), 2 mobile 700 l/s turbos* (60k), 2 leak detectors (40k) = 160 kCHF
  - Manpower
    - 2 technicians producing 1 leak test/week = 5 kCHF/test
    - 4 technicians localizing 1 leak, repair & retest = 10 kCHF/NC repair & retest

⇨ 400 Pipes Strings, 400 wks: 200 kCHF & 2000 kCHF (+ NC repair & retests)

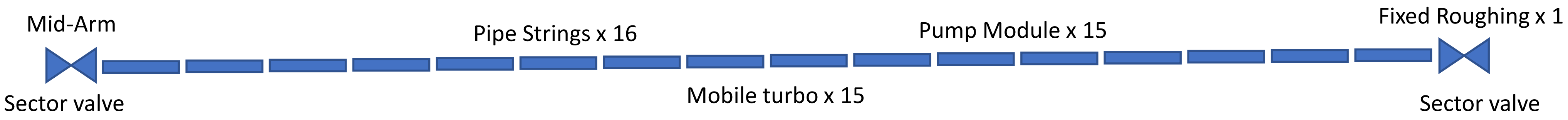
⇨ 400 Pipes Strings, 80 wks (5 setups x 0.5): 500 kCHF & 1000 kCHF (+ NC repair & retests)

Effect of scaling & synergies

*check any double counting

1 CHF = 1 Euro = 1 USD

# Leak Testing Costs – 5 km Vacuum Sectors




- Pipe Strings (312 m)
  - Equipment costs for 1 leak test setup
    - 1 fixed roughing unit (0 CHF)
    - 15 mobile 700 l/s turbos* (450 kCHF), 5 leak detectors (100 kCHF)
  - Manpower
    - 2 technicians producing 1 leak test/month = 20 kCHF/test
    - 4 technicians localizing 1 leak, repair & retest = 40 kCHF/NC repair & retest

⇨ 24 Vacuum Sectors in 24 months: 550 kCHF & 480 kCHF (+ NC repair & retests)

*check any double counting

# Leak Test Cost v Strategy v Leak Occurrence

| | | | Fixed Cost | | Test Strategy | | | | Variable Costs | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| To test | Leak test type | Qty weld | Equipment (kCHF) | Manpower (kCHF) | Max Pipe,String,Sector (kCHF) | Mid String,Sector (kCHF) | Min Sector (kCHF) | Cost 1 leak (kCHF) | 1 ‰ leak Qty | 1 ‰ leak Cost (kCHF) | 10 ‰ leak Qty | 10 ‰ leak Cost (kCHF) |
| 8000 Pipes | Ex-situ Pipe weld | 8000 | 2500 | 2000 | 4500 | | | 1 | 8 | 8 | 80 | 80 |
| 400 Strings | In-situ Pipe weld | 8000 | 0 | 1000 | | 1000 | | 10 | 8 | 80 | 80 | 800 |
| 400 Strings | In-situ Pipe-Pipe weld | 8000 | 500 | 1000 | 1500 | 1500 | | 10 | 8 | 80 | 80 | 800 |
| 24 Sectors | In-situ String-String & CF | 1200 | 550 | 240 | 790 | 790 | | 40 | 1.2 | 48 | 12 | 480 |
| 24 Sectors | In-situ Pipe weld | 8000 | 550 | 480 | | | 1030 | 40 | 8 | 320 | 80 | 3200 |
| 24 Sectors | In-situ Pipe-Pipe weld & CF | 8400 | 550 | 480 | | | 1030 | 40 | 8.4 | 336 | 84 | 3360 |
| | **Total fixed costs (no leaks)** | | | | **6790** | **3290** | **2060** | | | | | |
| | Variable cost 1‰ leak | | | | 136 | 208 | 656 | | | | | |
| | **Fixed + Variable 1 ‰ leak** | | | | **6926** | **3498** | **2716** | | | | | |
| | Variable cost 10 ‰ leak | | | | 1360 | 2080 | 6560 | | | | | |
| | **Fixed + Variable 10 ‰ leak** | | | | **8150** | **5370** | **8620** | | | | | |

# Leak Test Cost v Strategy v Leak Occurrence

Max Strategy:

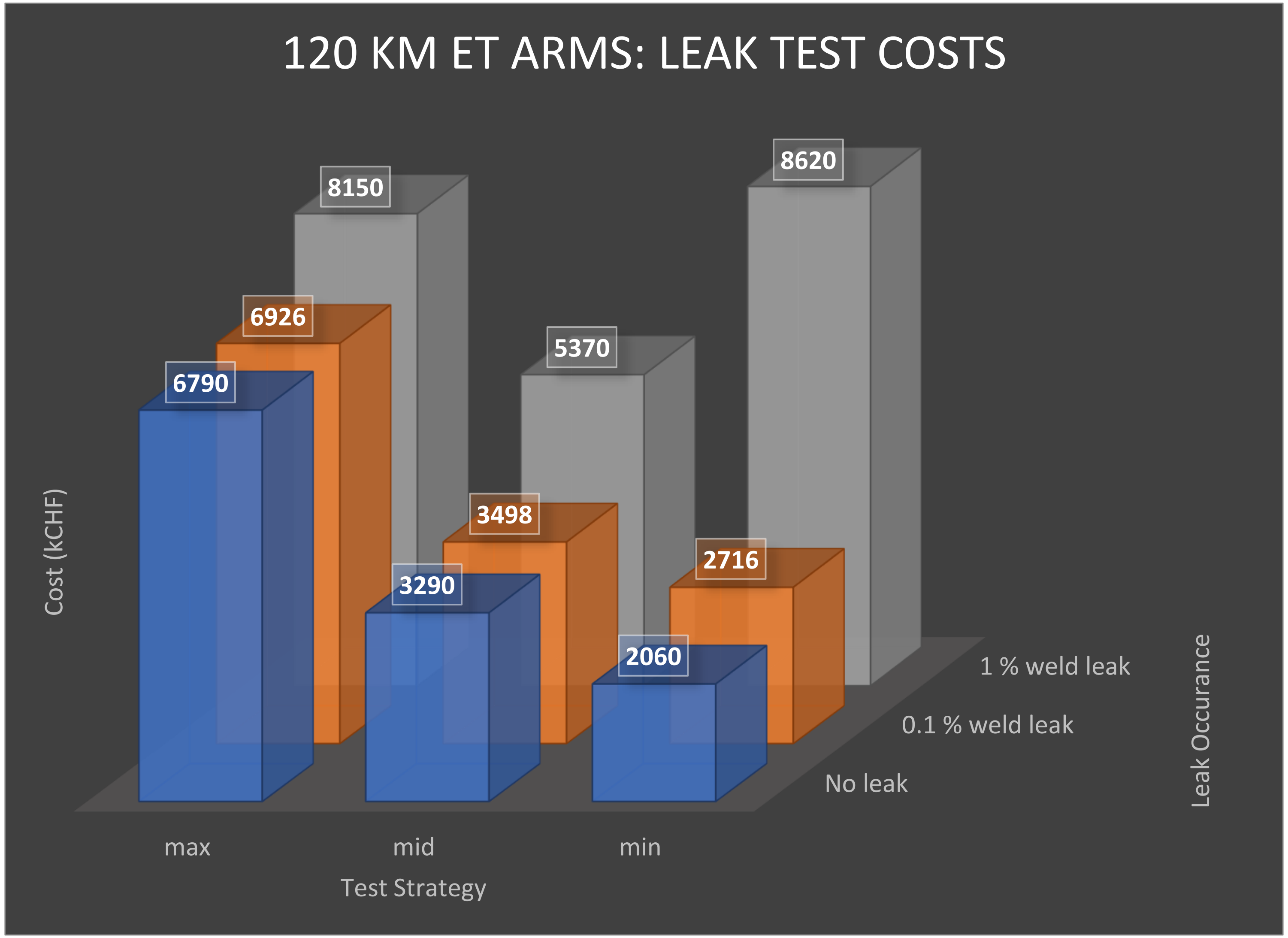
- Low risk
- Early warning of leak issues
- Dominated by component testing costs

Min Strategy:

- High risk (high confidence)
- Dependent on low leak occurance
- Potential minimum cost

Mid Strategy

- Medium risk
- Higher leak occurance can be tolerated wrt cost.
- Can review strategy dependent on field results.



# ET Leak Test Strategy – brainstorming !

⇨ assume leaks in low ‰ range by stringent control on material & welding quality
⇨ adopt 'Mid' strategy, but with some targeted checking of Pipes as components

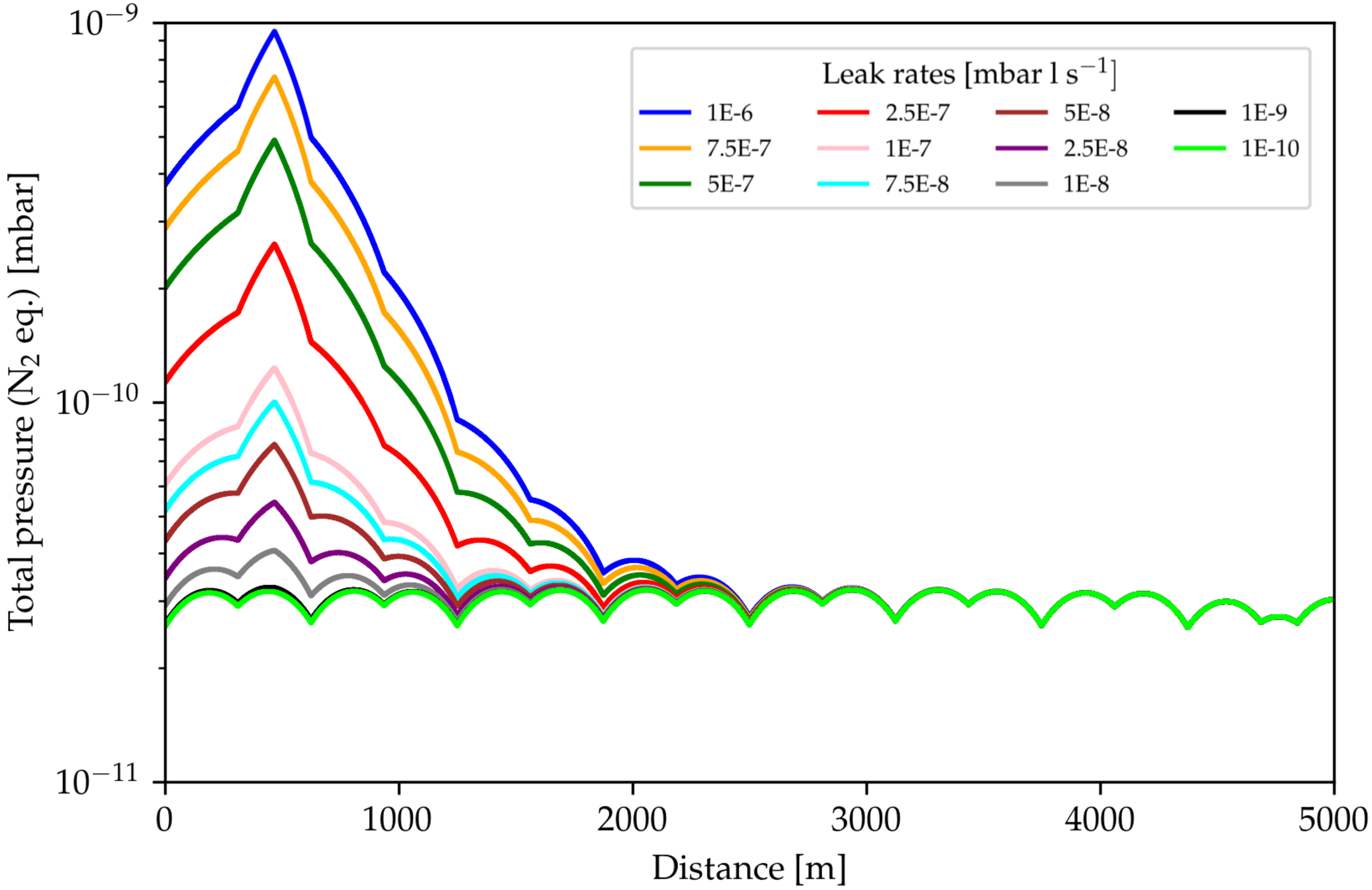
- Step 1 – Components, ex-situ
  - Leak test first 100 Pipes (eliminate systematics) — 100 tests
  - Leak test every 20th Pipe (avoid production deviations, cleanliness check, etc) — ~ 400 tests
  - (first 100 Pipes + every 20th Pipe: 6 % Pipes)
  - Leak test every Pump Module — ~ 400 tests
- Step 2a - 312 m Pipe Strings, in-situ — ~ 400 tests
  - Pump & leak test longitudinal & circumferential Pipe welds
- Step 2b - 5000 m Vacuum Sector, in-situ — 24 tests
  - Clamshell test Pipe to Pumping Module welds
  - Pump & leak test fully equipped Sector prior to bakeout

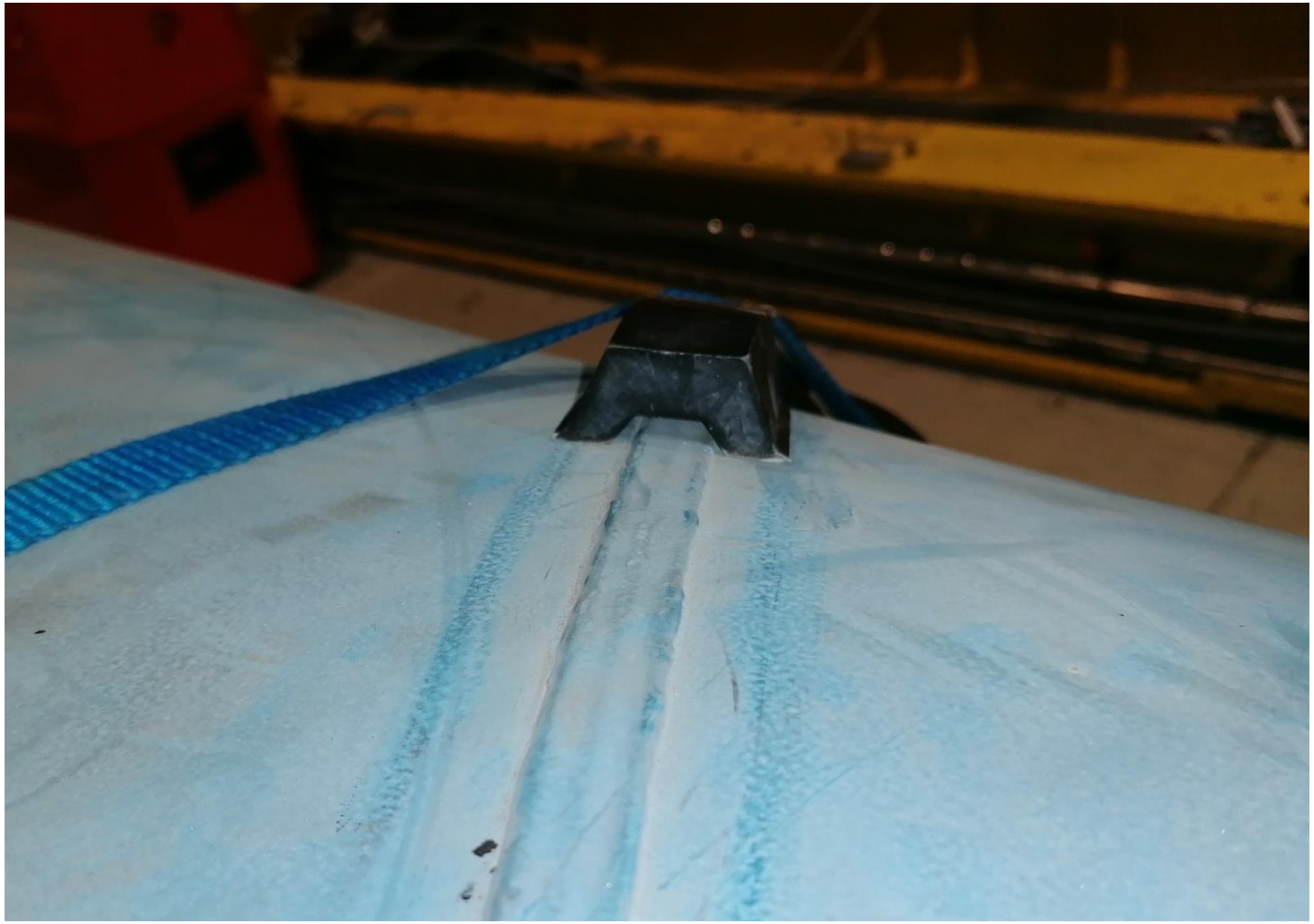
# Summary

- Good engineering is better than good leak detection.
- We can build upon the leak testing experience (good & bad) from existing GWD and LHC type accelerators.
- Standard leak testing equipment and methods can be applied, but care must be taken with large volumes.
- Different leak testing strategies can be considered – each has its merits and drawbacks with respect to duration, cost, risk…..and we need to remain flexible based on return of experience.
- Testing strategy will strongly depend on the Pipe manufacturing & installation techniques, together with our confidence level wrt to leak occurance
- Solutions exist to close vacuum vessels without flanges.
- Cost (gu)estimates should be considered as a starting point for discussions. Need to check double counting of vacuum equipment costs eg mobile pumping groups already included elsewhere.
- There are no showstoppers, so "Let's get to work………" on more brainstorming.

Thanks for your attention !

# Air leak: impact on total pressure



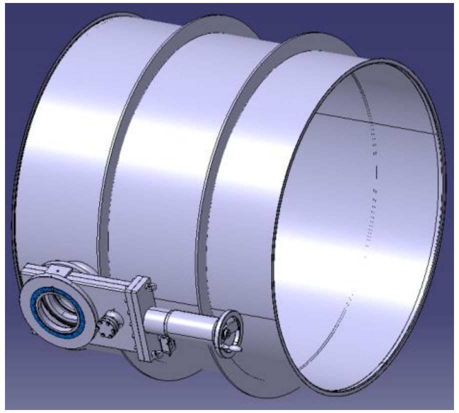


| Duration(days) | 312 m String - leak test activities |
|---|---|
| 1 | installation temporary end caps, fixed points, mobile pumping systems |
| 1 | roughing (Saturday) |
| 1 | turbo (Sunday) |
| 1 | leak test (including system calibration) |
| 1 | leak test |
| 1 | margin, problem solving, |
| 1 | vent, removal fixed points, transport to next test zone |
| **7** | |

| Duration (days) | 5 km Vacuum Sector - leak test activities |
|---|---|
| 4 | Clamshell test of each Pump Mod weld |
| 6 | Roughing (8 edays), moile pumping groups |
| 3 | Turbo pumping |
| 5 | Leak test (including system calibration) |
| 1 | Margin, problem solving, |
| 2 | Mobile equipment removal, transfer to next zone |
| **21** | |

1 CHF = 1 Euro = 1 USD

# Leak Testing Cost Estimate – Pumping Modules



- Pumping Modules (1m components)
  - Equipment costs for leak test bench
    - 1 bench 40k, 1 pumping system 40k, 1 leak detector 20k = 100 kCHF
  - Manpower
    - 1 vacuum technician producing 1 leak test/day = 0.5 kCHF/test

⇨ 400 Pumping Modules in 400 days: 100 kCHF & 200 kCHF (+ 1% NC)