Vacuum for thermal insulation of cryogenic equipment

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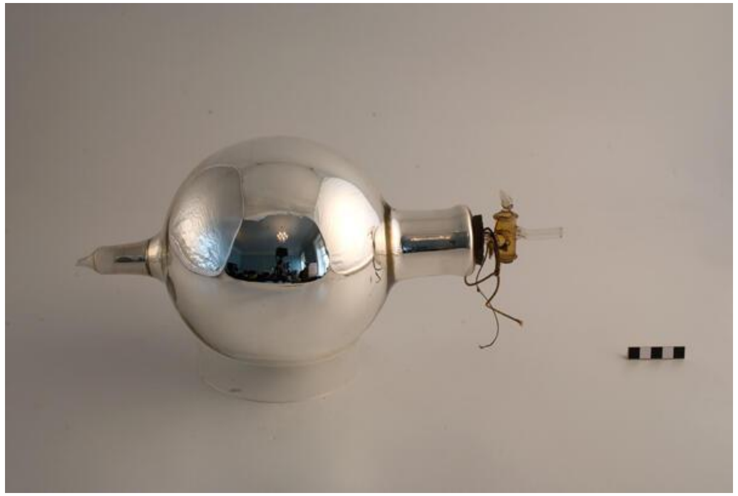
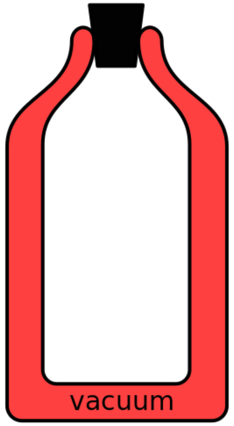
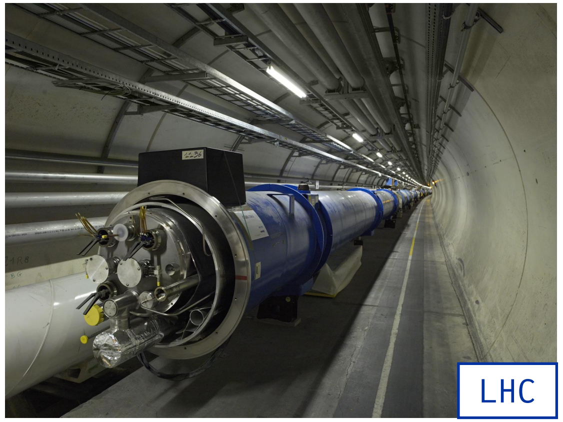
What is a cryostat?

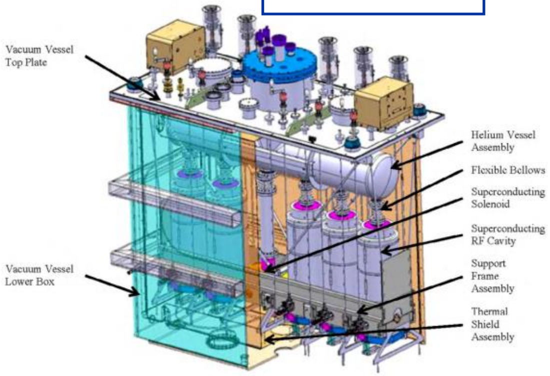
- A cryostat (from *cryo* meaning cold and *stat* meaning stable) is a device used to maintain low cryogenic temperatures of samples or devices mounted within the cryostat [Wikipedia]
- 1892 James Dewar invents the “Dewar”. 1898 allows him to liquify H_2
- Vacuum for thermal insulation

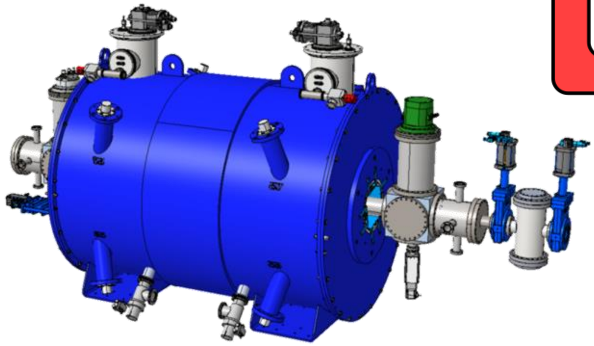




Examples:


LHC


HIE-ISOLDE


PUMA experiment

Cryostat functions (for accelerators)

- **Mechanical housing of cryogenic devices (supporting systems):**
  - Supporting of (sometimes heavy) devices (i.e. superconducting magnet)
  - Accurate & reproducible positioning (almost always)
  - Precise alignment capabilities
  - Accommodate thermal contraction during cooldown and vacuum forces.
- **Thermal efficiency of the cryostat (heat loads as low as possible):**
  - Cooling capability
  - **Insulation vacuum** (pumping system)
  - Thermal radiation shielding (screens, MLI)
  - Low heat conduction (low thermal conductivity materials)

Often conflicting → Design optimization

Other considerations:

- ☐ Instrumentation (vacuum, cryogenic, magnet, beam, etc.)
- ☐ Cryogenic piping
- ☐ Safety elements (burst disks, safety valves, etc.)
- ☐ Transport
- ☐ …

Cryostat design

Heat transfer

Mechanics

Cryogenics

Vacuum

Integration

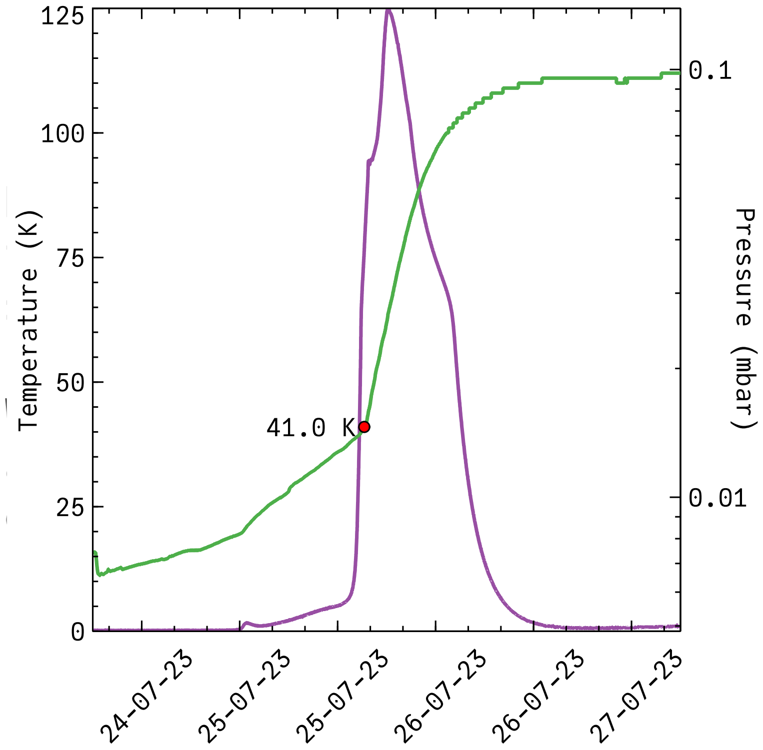
Superconductivity

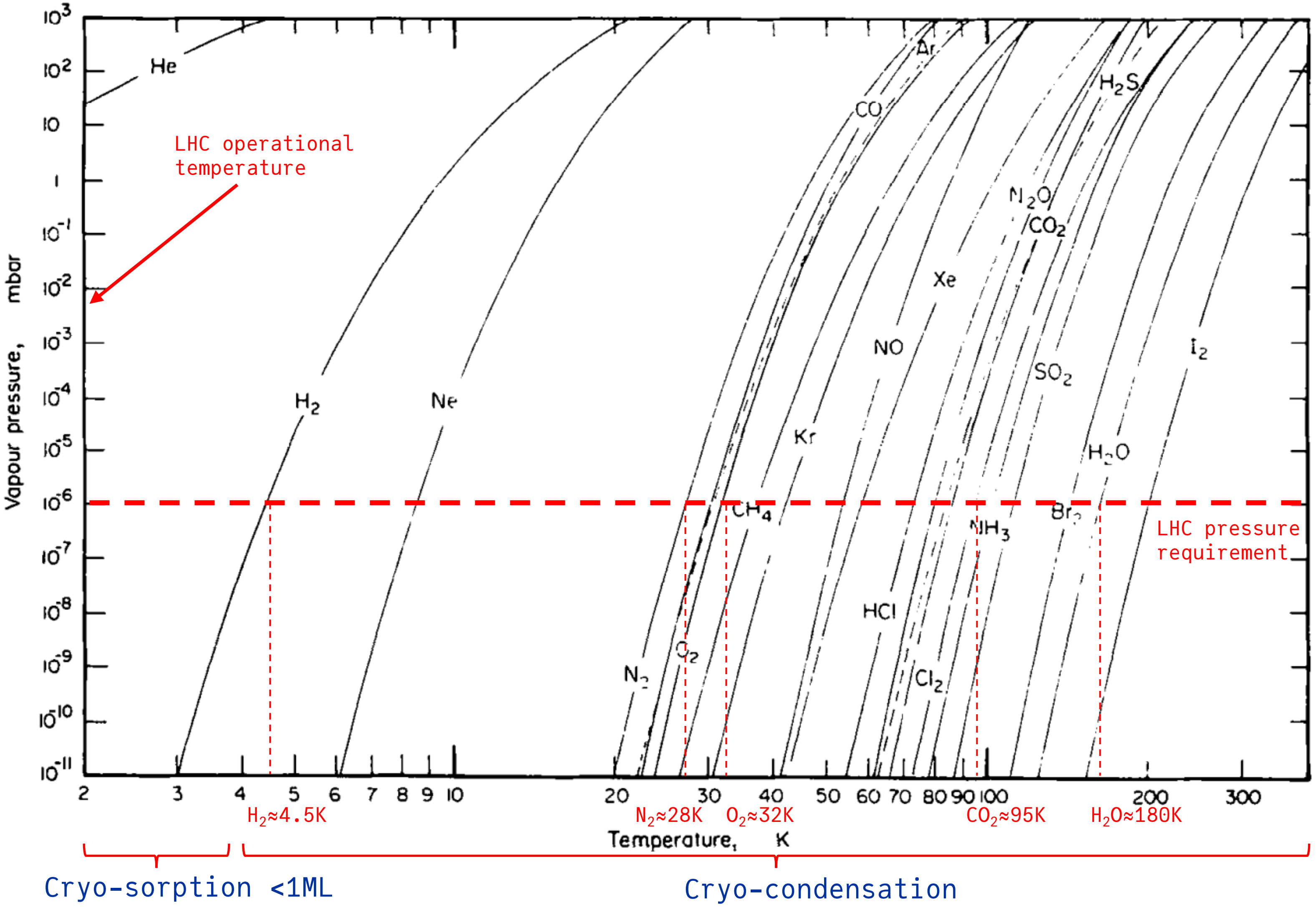
Insulation vacuum requirements

- Operational temperature(s) (defined by the magnet, SC cavity, etc.)
- Maximum operational pressure (thermal insulation and cooling power)
- Components under vacuum (outgassing rate at room temperature, vacuum quality, dust, etc.)
- Operation during transient events (i.e. quench creates temperature excursions → Pressure excursions)

These aspects define the type of pumping and pumping capacity

Temperature and operational pressure





- Cryo-condesed gases can create big pressure excursions during transient events → Degradation of insulation vacuum

Outgassing

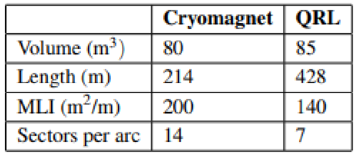
- ❑ **The main gas sources of any vacuum system are:**
  - ❑ Outgassing of materials
  - ❑ Leaks (air to vacuum and He to vacuum)
  - ❑ Permeation (elastomer seals)
- ❑ **Outgassing: Material and temperature**
  - ❑ Polymers (MLI, instrumentation, cabling, seals, etc.) → high outgassing
  - ❑ Metals: Low carbon steel, stainless steel, aluminium
  - ❑ At cryogenic temperature → No outgassing

Main considerations about outgassing:

- ❖ Room temperature outgassing defines the first pumpdown (time, water vapor, etc.). Material selection important for insulation vacuum!
- ❖ Pumping big flows of water vapor → Ballast, oil recovery, etc.
- ❖ No cryo-pumping at room temperature → Insulation vacuum should be good enough for first cooldown
- ❖ Outgassing of hydrocarbons (contamination) can impact delicate elements sharing insulation vacuum (i.e. superconducting cavities)
- ❖ Room temperature surfaces will outgas (even measured pressure is low)

MLI (Multi-Layer insulation)

Table 5.2: Main characteristics of the insulation vacuum sectors.



	Cryomagnet	QRL
Volume (m^3)	80	85
Length (m)	214	428
MLI (m^2/m)	200	140
Sectors per arc	14	7

Outgassing in cryostats is normally dominated by MLI

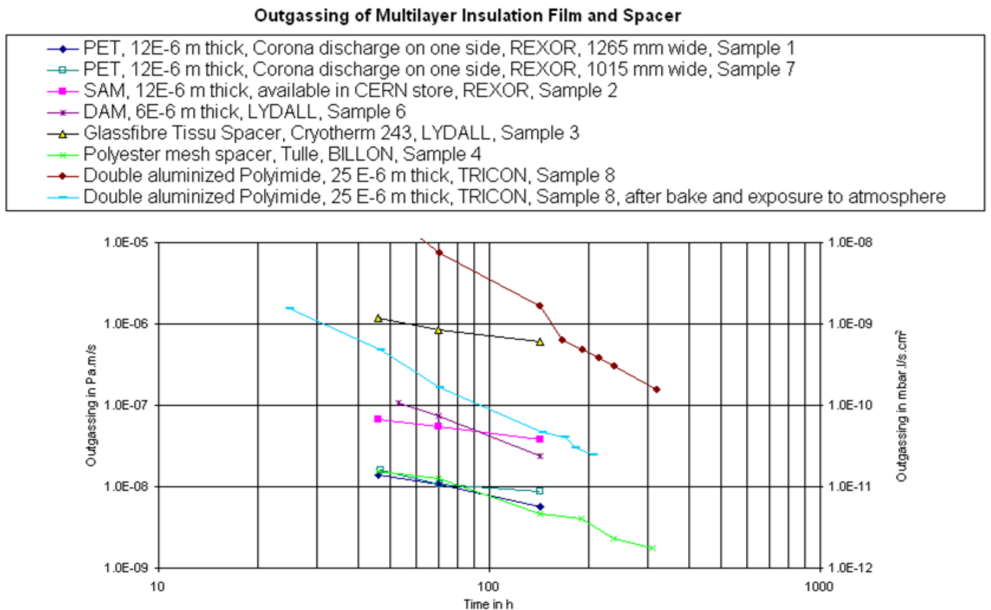
For an LHC insulation vacuum sector:

Area: 250 m^2/m

Length of MLI 214 m → 7.5 football fields (53000 m^2)

Exposed to ambient air for several weeks → ~ 10^{-3} mbar at RT after ~ 200 hrs pumping S ≈ 100 l/s

Equivalent to ~2×10^{-10} mbar×l/s/cm^2 → SS outgassing at 200h ~1.5×10^{-11} mbar×l/s/cm^2



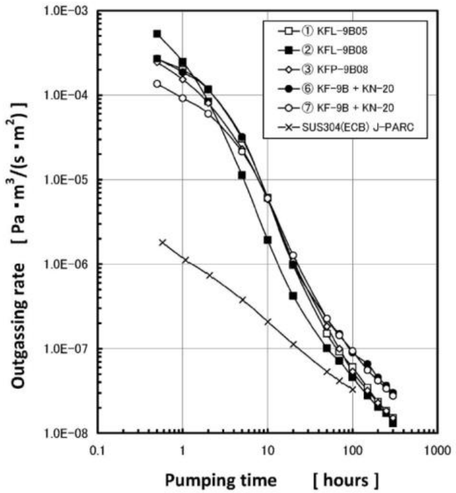


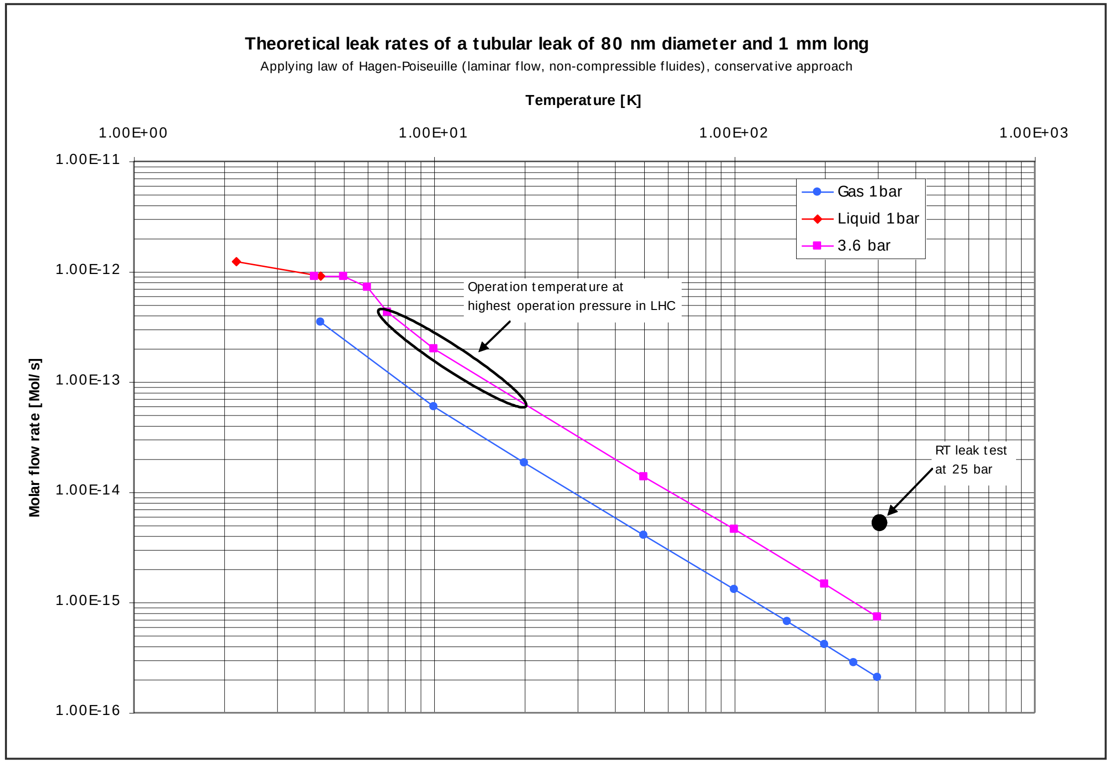
Fig. 6 Outgassing rates for MLIs. Results for three new materials (KFL–9B05, KFL–9B07, and KFP–9B08), and a conventional MLI (KF–9B + KN–20) are shown. As a reference, the rate for stainless steel processed by electrochemical buffing is also shown.

LHC Features:

- ❑ 1 blanket (10 reflective layers) on cold masses (1.9K)
- ❑ 2 blankets (15 reflective layers each) on Thermal Shields (50-65K)
- ❑ Reflective layer: double aluminized polyester film
- ❑ Spacer: polyester net
- ❑ Stitched Velcro™ fasteners

Maximum leak rate (LHC)

- Maximum insulation vacuum degradation $<10^{-4}$ mbar
- Assume no pumping, accumulation for 200 days
- One vacuum sector capacity ~ 100 mbar×l of He (53000 m^2)
- Maximum leak rate < 5×10^{-6} mbar×l/s
- Apply cold/warm correlation for leak rates (x1000 at cold) < 5×10^{-9} mbar×l/s (total leak rate)
- For individual components $<10^{-11}$ mbar×l/s
- Fixed turbopumps during thermal cycles and as ‘backup’ in case the tightness specification cannot be immediately reached



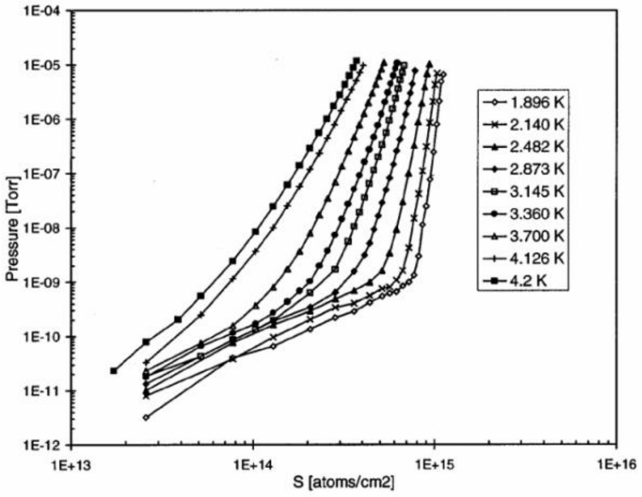
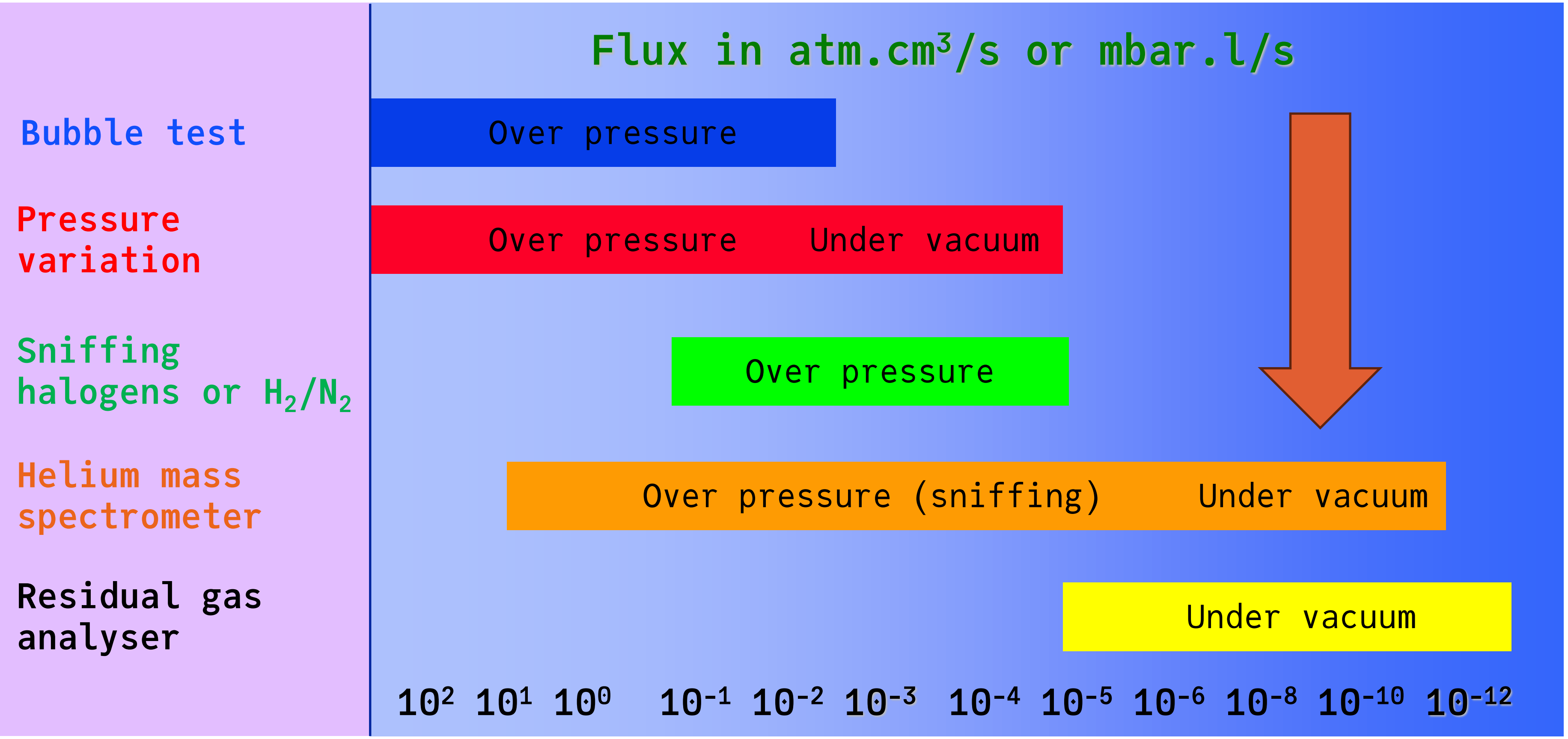


Fig. 11: Helium adsorption isotherm measured on a stainless-steel tube from 1.9 to 4.2 K [47].

Leak detection methods

TEST METHOD



Flux in atm.cm^3/s or mbar.l/s

Bubble test: Over pressure

Pressure variation: Over pressure Under vacuum

Sniffing halogens or H_2/N_2: Over pressure

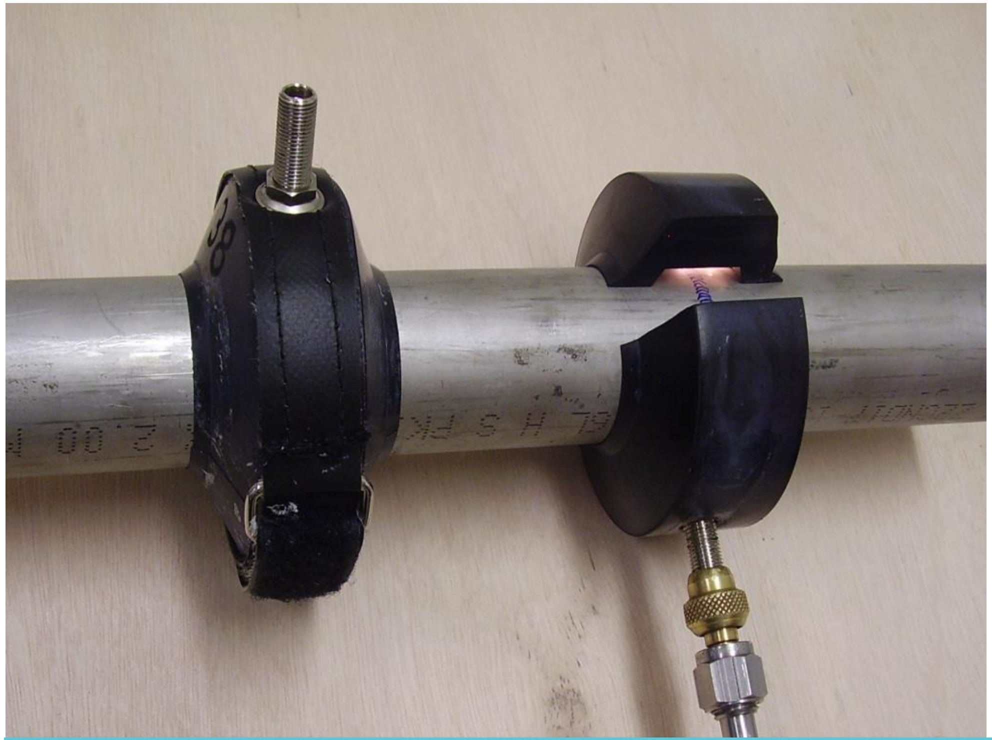
Helium mass spectrometer: Over pressure (sniffing) Under vacuum

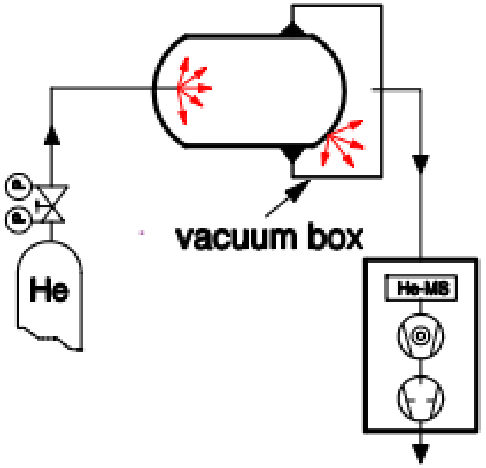
Residual gas analyser: Under vacuum

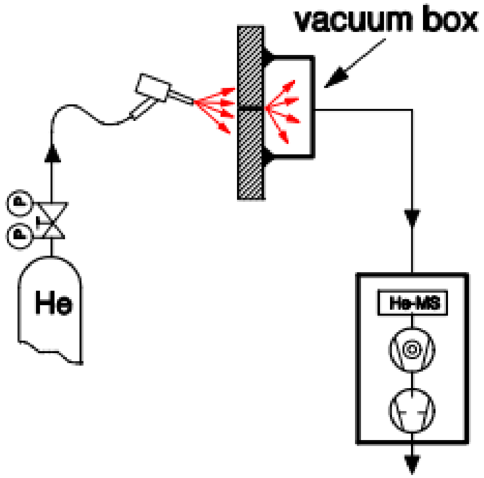
10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-8} 10^{-10} 10^{-12}

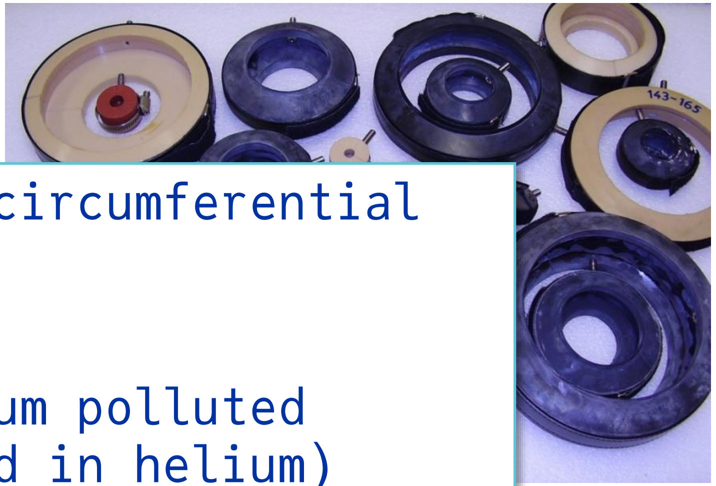
Leak detection with clam-shell

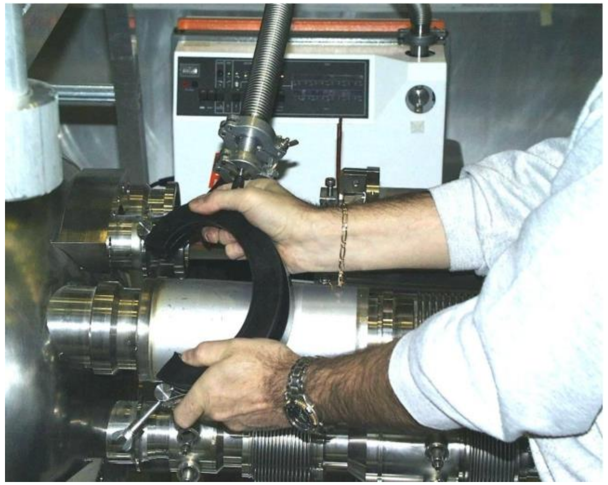
EN 1779:1999





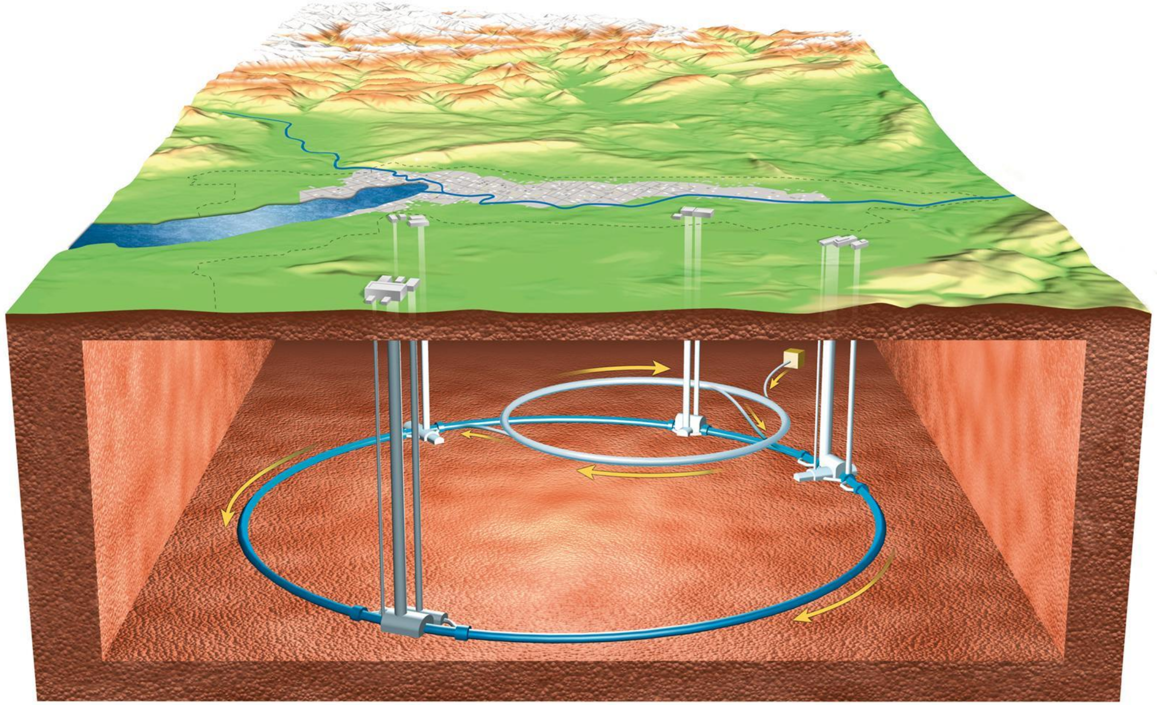






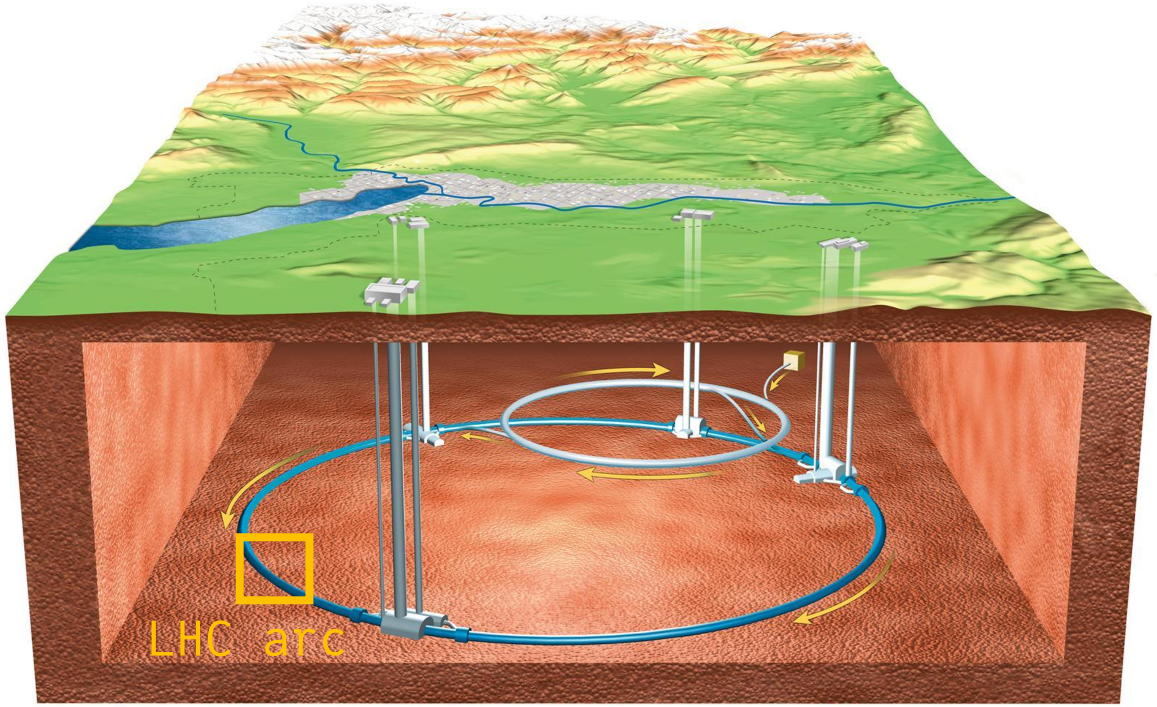
- ☐ A practical detection method for circumferential welds
- ☐ Pumping of reduced volumes
- ☐ Particularly interesting for helium polluted circuits (i.e. magnets cold tested in helium)

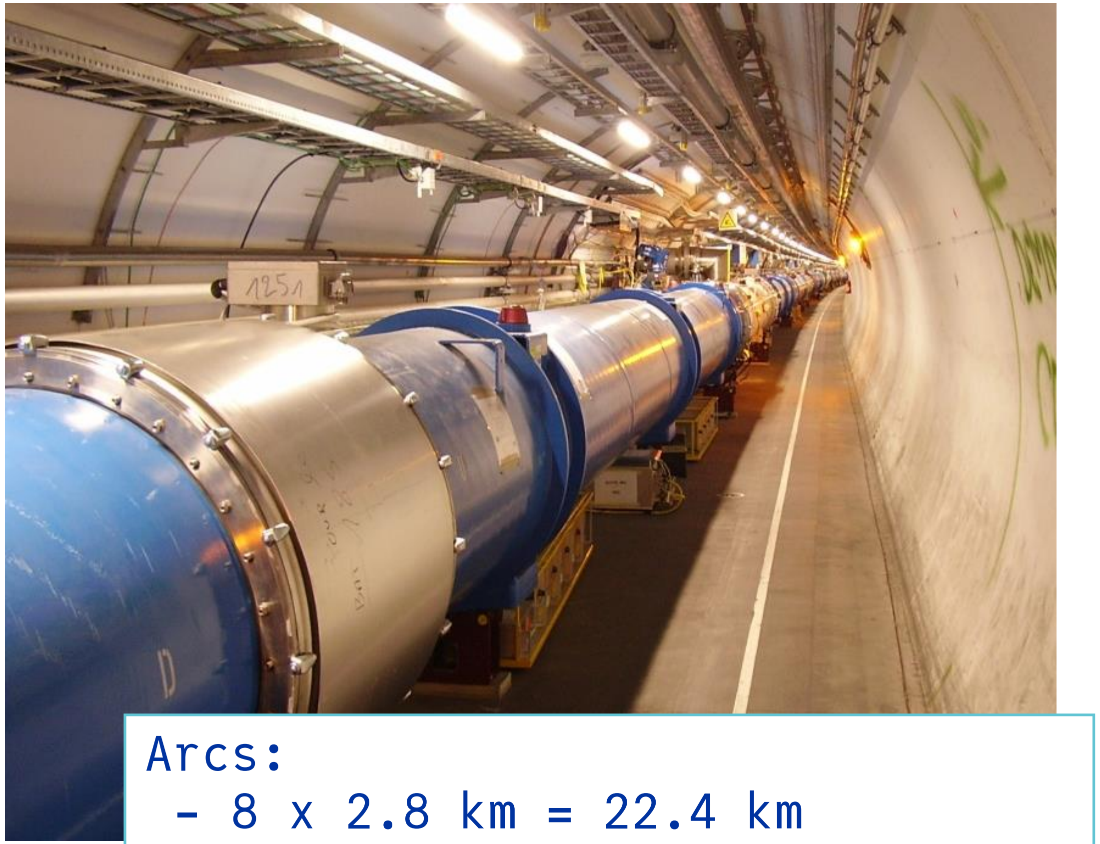
LHC arcs and LSS (Long Straight Section)



Cryogenic distribution line: QRL

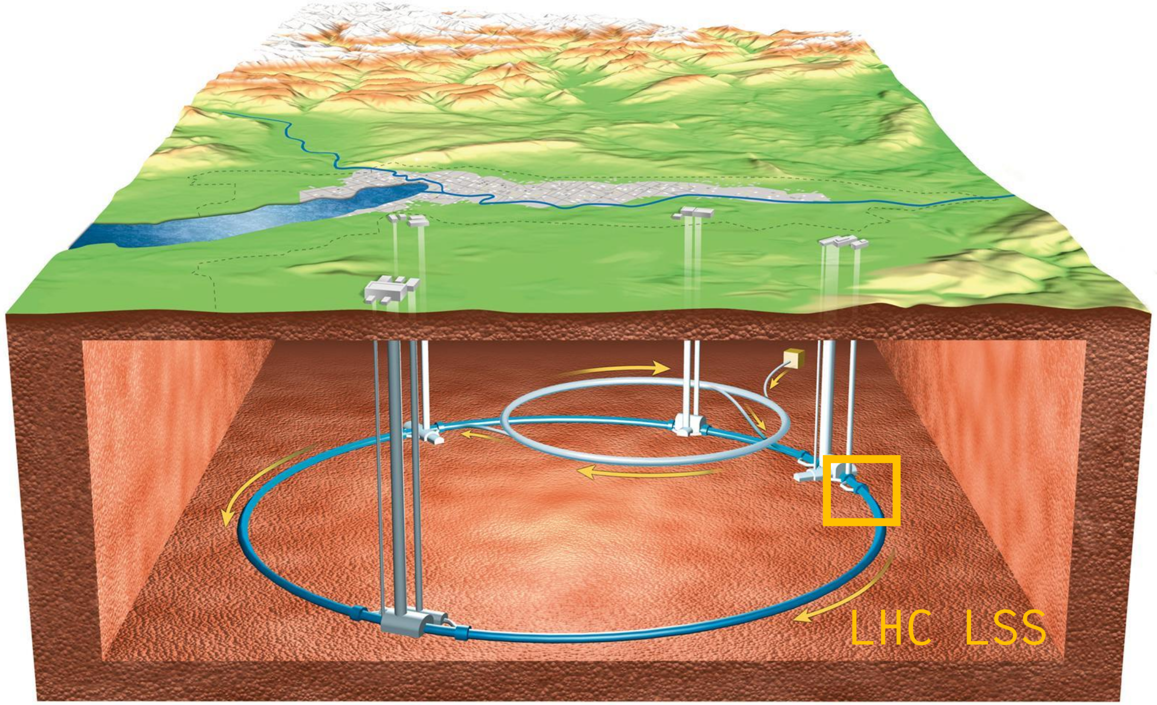
LHC arcs and LSS (Long Straight Section)

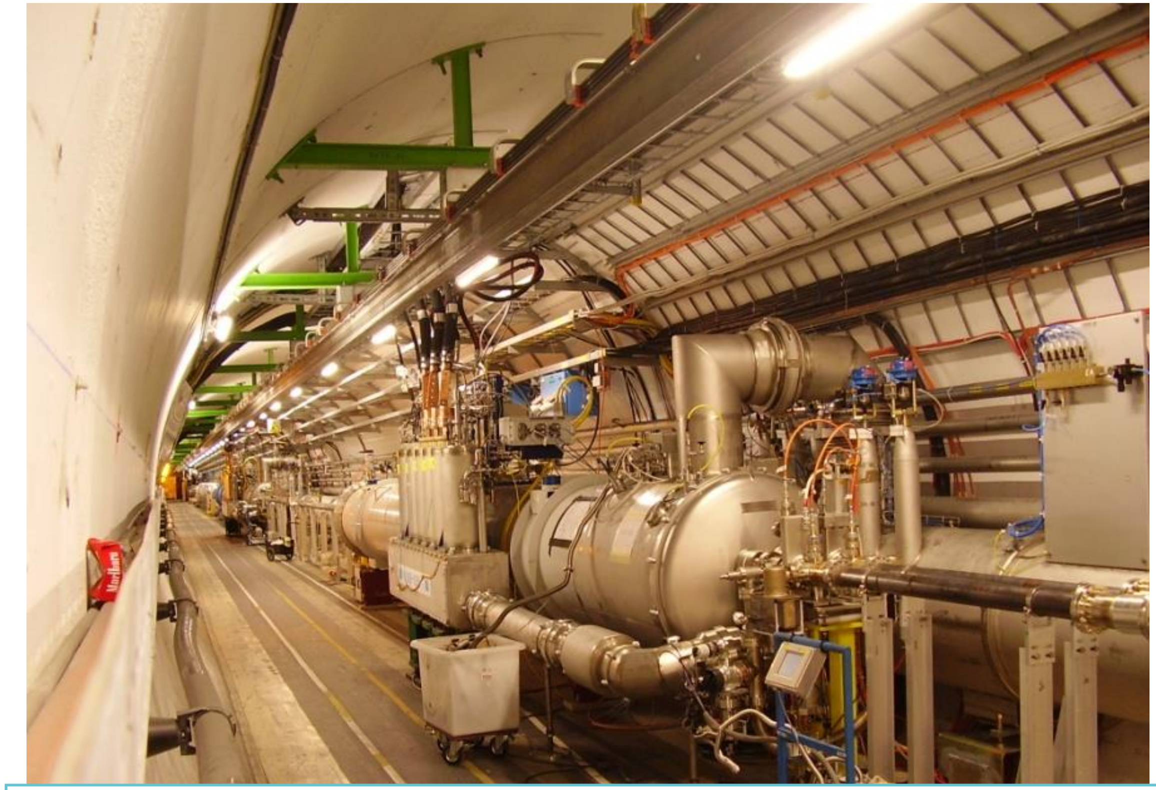




Arcs:
- 8 x 2.8 km = 22.4 km
- SC magnets in a continuous cryostat

LHC arcs and LSS (Long Straight Section)

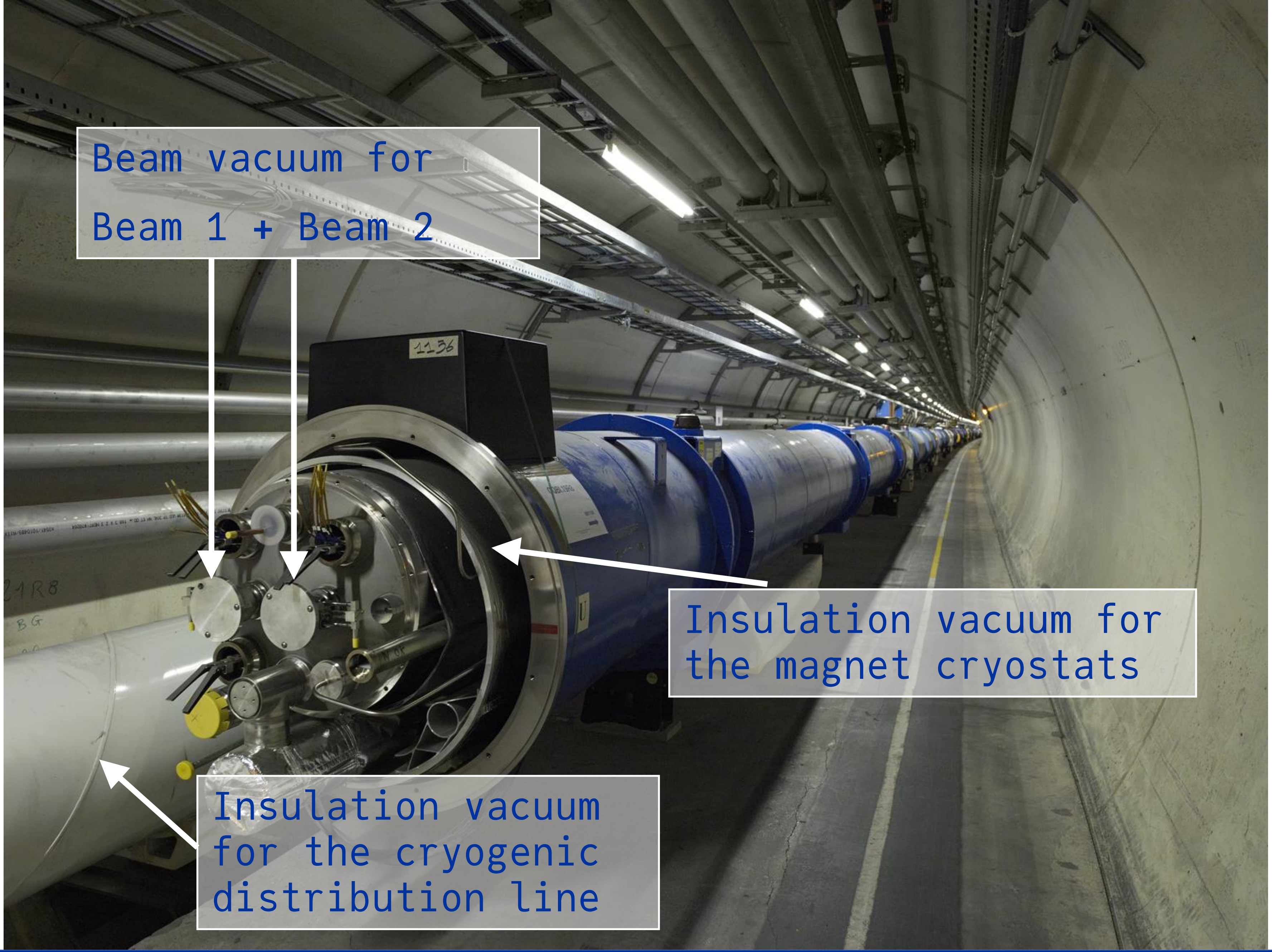




LSS (Long Straight Sections):
- up- and downstream of the experiments
- 8 x 2 x 250 m = 4 km
- room temp and standalone cryo-magnets

LHC insulation vacuum

Characteristic	**Quantity for LHC machine & distribution line (QRL)**
Insulation vacuum system length	22,4 km & 25 km
Welds	~ 250 000 (90 000 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



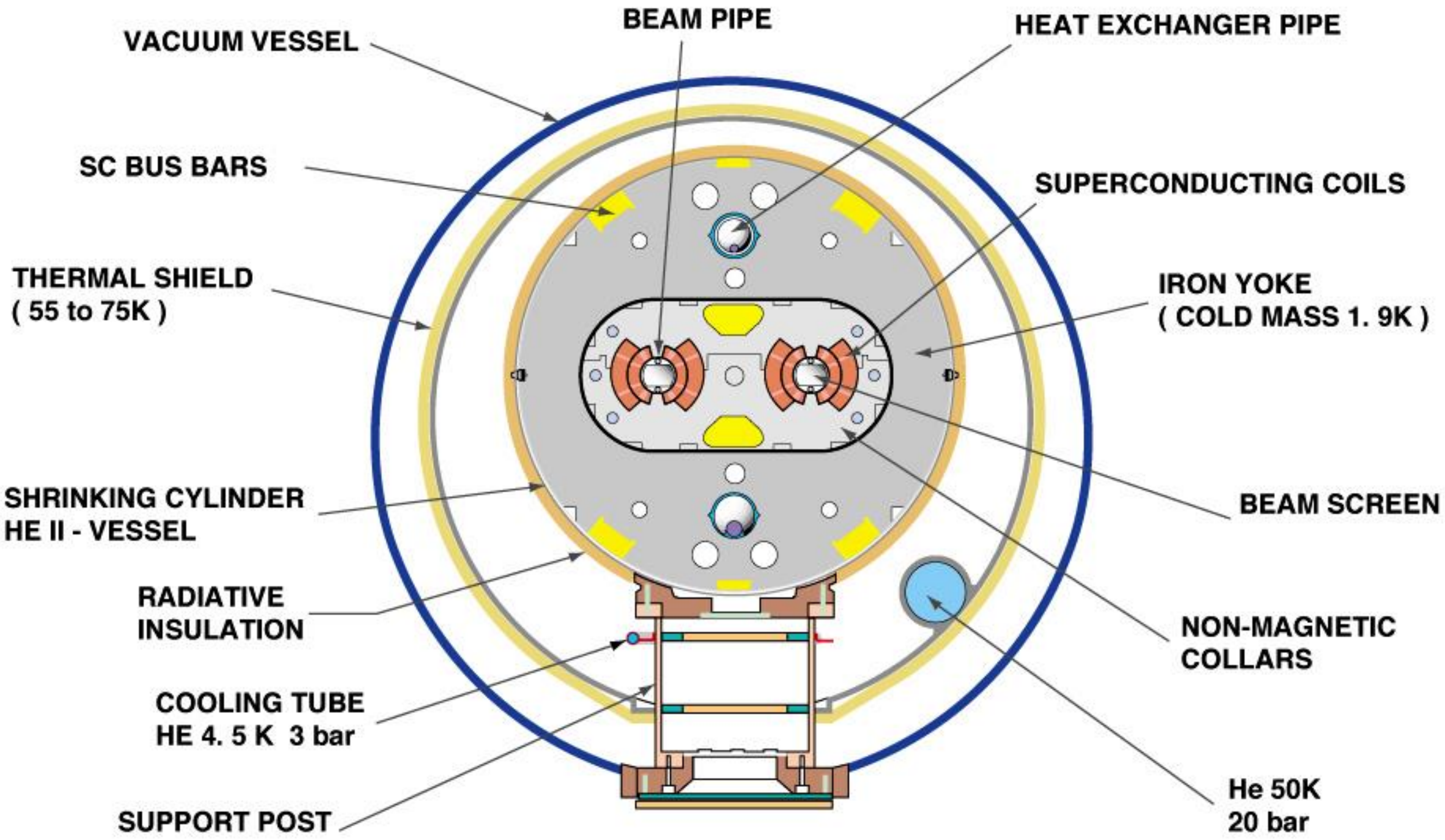
Beam vacuum for

Beam 1 + Beam 2

Insulation vacuum for the magnet cryostats

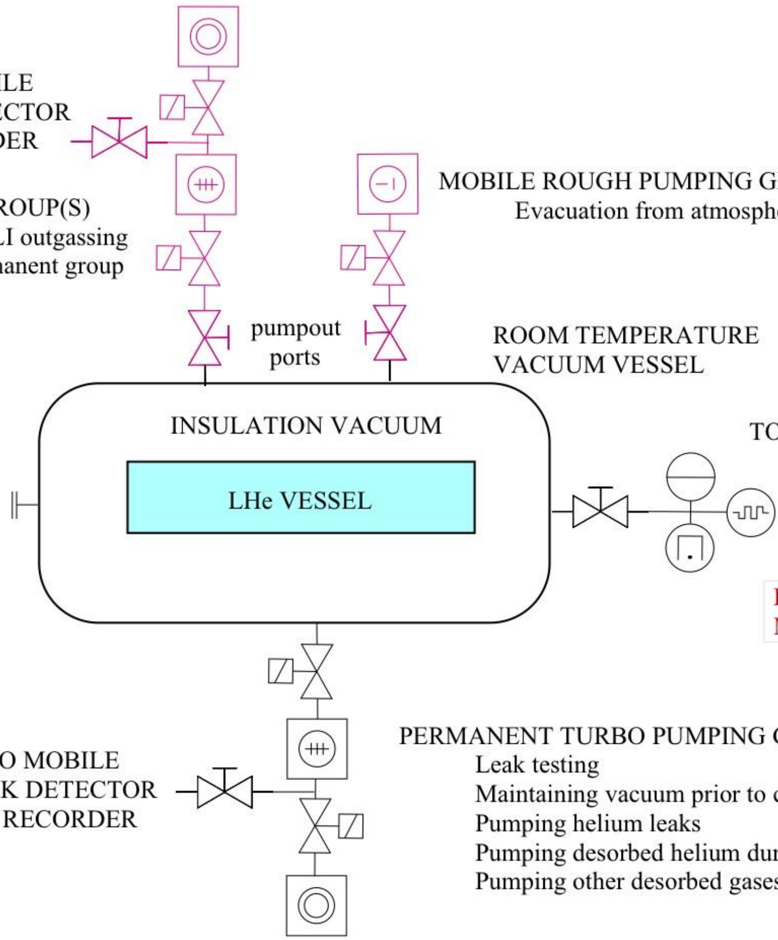
Insulation vacuum for the cryogenic distribution line

CROSS SECTION OF LHC DIPOLE



CERN AC _HE107A_ V02/02/98

Layout IV vacuum sector



MOBILE TURBO PUMPING GROUP(S)
Leak testing with high MLI outgassing
Reduce work load of permanent group

MOBILE ROUGH PUMPING GROUP(S)
Evacuation from atmospheric pressure

ROOM TEMPERATURE
VACUUM VESSEL

SAFETY VALVE
opening < 0.5 bar dp

TOTAL PRESSURE GAUGES
Pressure monitoring
OK to cool down
Interlock to cryogenics
Start/stop turbo pumping group

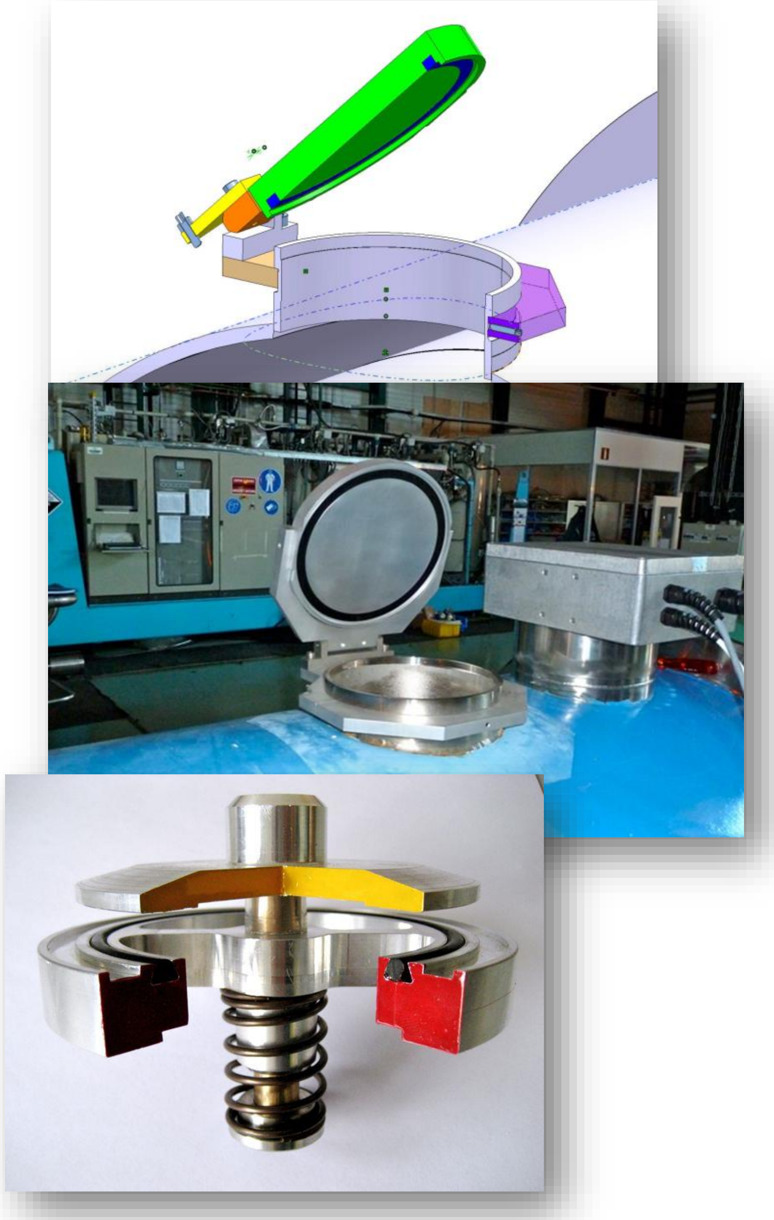
Pirani (VGR) alarm	> 0.1 mbar
Membrane (VGM) alarm	> 500 mbar

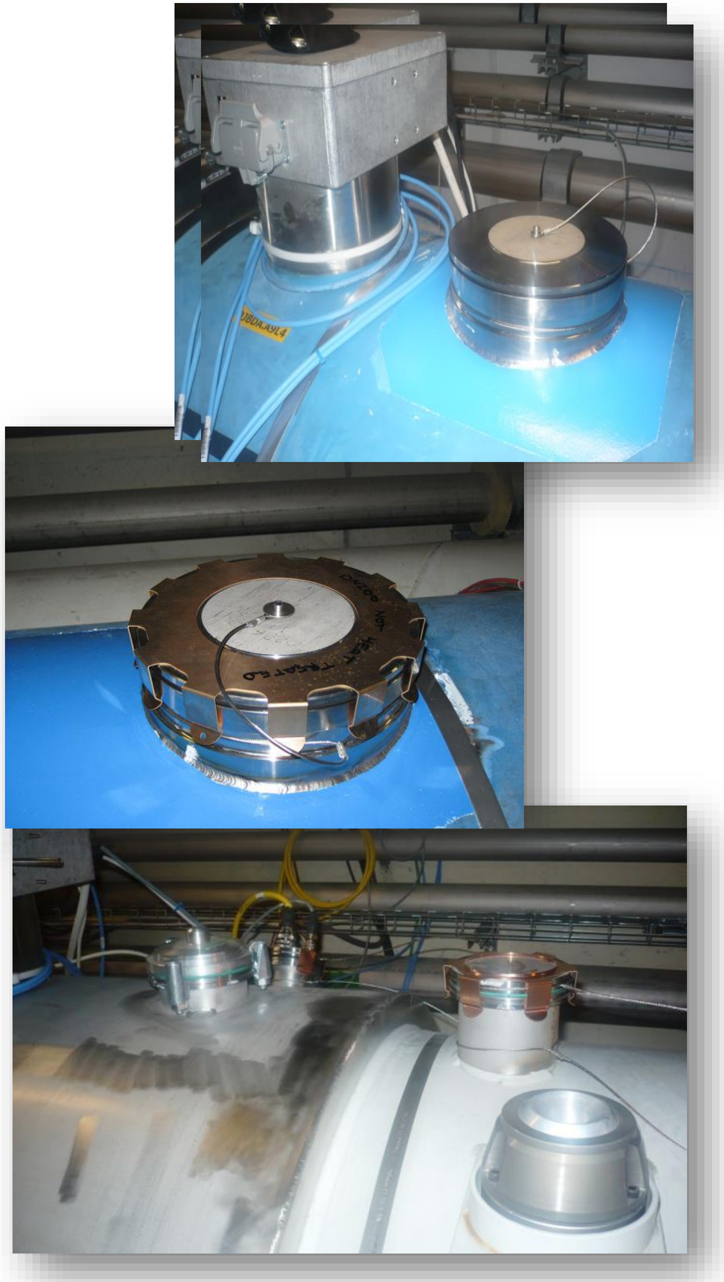
PERMANENT TURBO PUMPING GROUP :
Leak testing
Maintaining vacuum prior to cooldown
Pumping helium leaks
Pumping desorbed helium during warmups
Pumping other desorbed gases during warmups

LEAK TEST	< 1 E-2 mbar
OK TO COOL DOWN	< 1 E-2 mbar
NOMINAL OPERATION	~ 1 E-6 mbar
DEGRADED OPERATION	< 1 E-4 mbar

Typ_ins2, P. Cruikshank 22/01/08

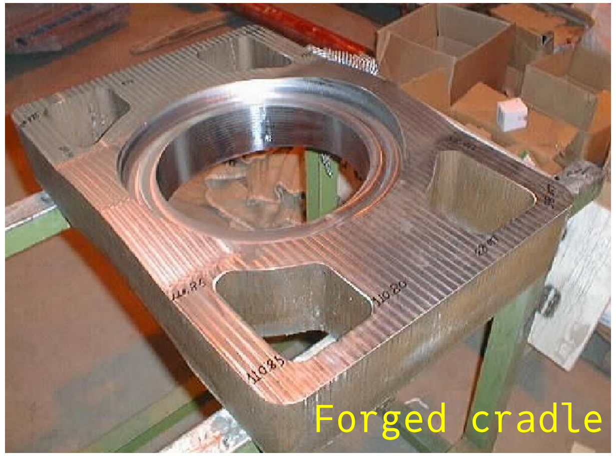
Safety valves





Example LHC dipole cryostat procurement


Stress relieving


Forged cradle

Main features:
- Pipeline standard size: **36-inch OD (1013 mm)**, **12-mm thick**, low carbon steel (DIN GS-21 Mn5) tubes
- St. steel extremity flanges
- Material resilience: > 28 J/cm2 at -70ºC
- Forged cradles, welded rings reinforcements
- Dimensional stability:
  - Stress relieving
  - Final machining to achieve tolerances at interface

Production:
- 1250 units
- 2 firms
- 4 yrs of production


Out-doors storage at CERN


Final lathe machining

Other cryogenic systems: HIE-ISOLDE

- Beam vacuum and insulation vacuum common space → UHV requirements! (cleaning, etc.)
- In contact with RF superconducting cavities → Clean room assembly (ISO 5)
- Dust movements have to be considered during pumping and venting
- Thermal screen actively cooled. Helium gas at 50K@12 bar.
- Liquid helium at 4.5 K to common reservoir, distributed to cavities, solenoid and support frame.

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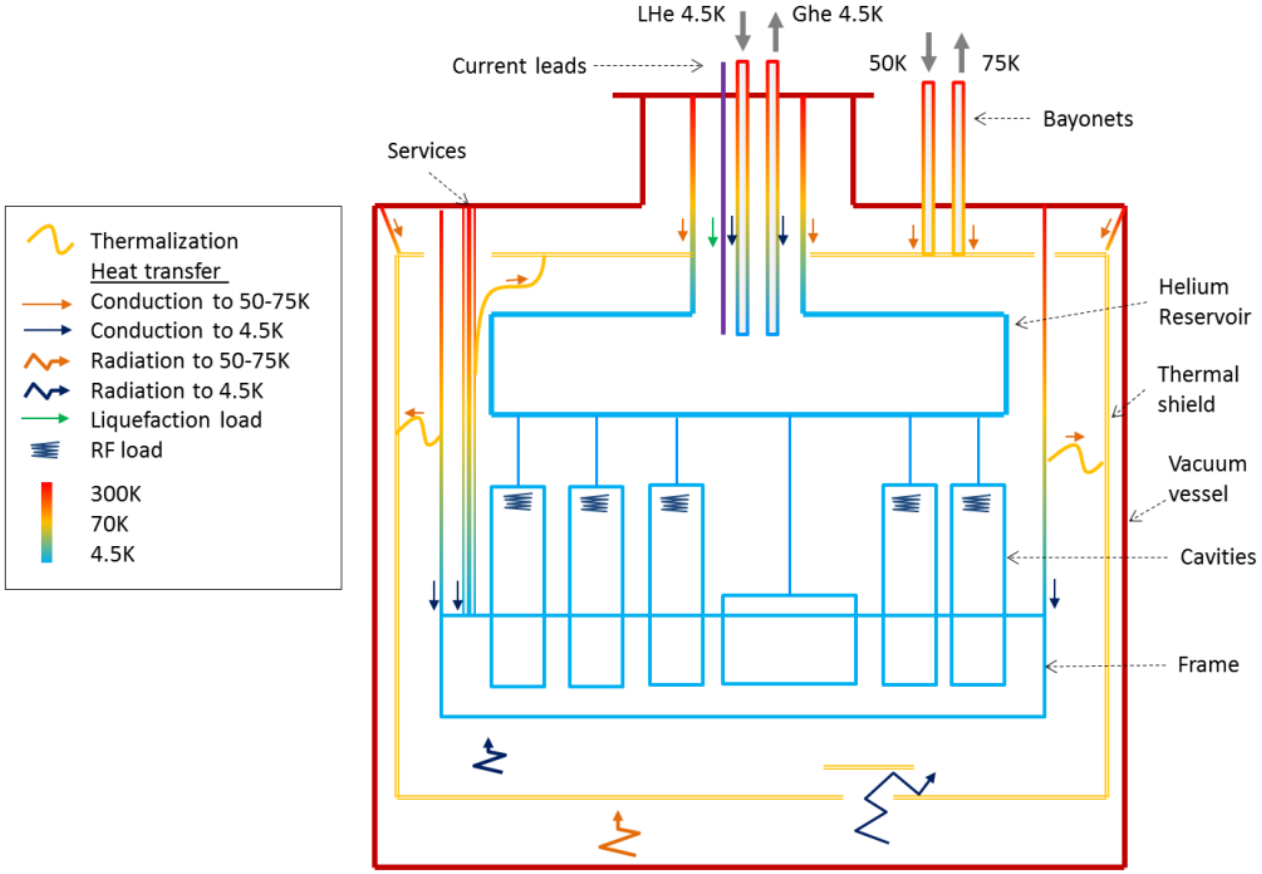
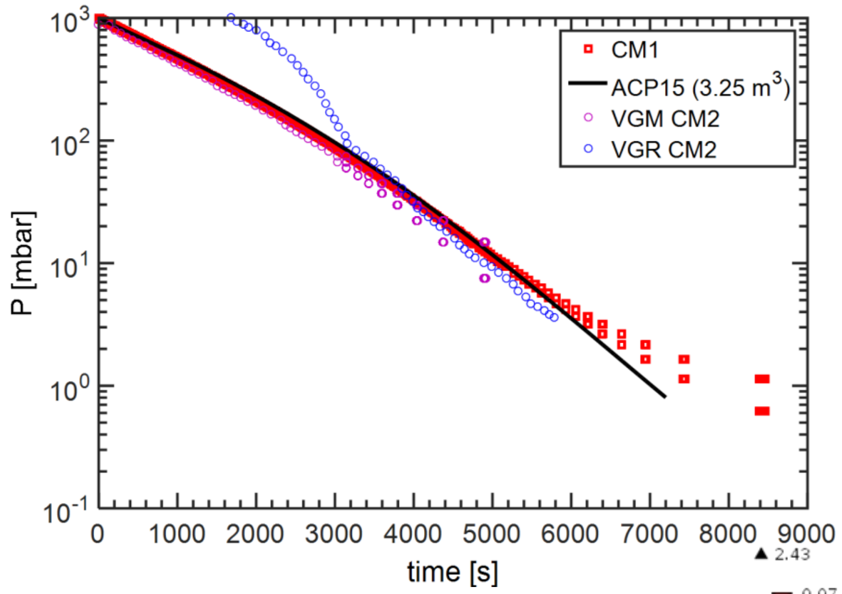
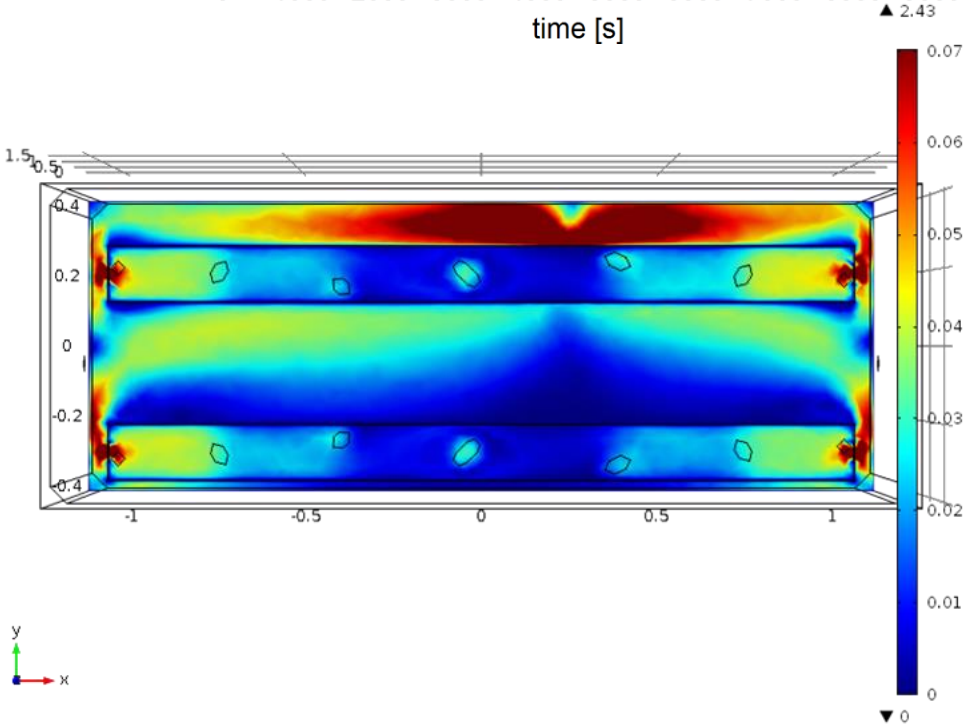


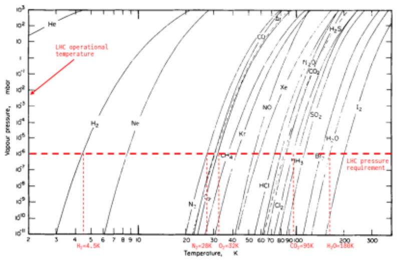
Cryo-module slow pumpdown

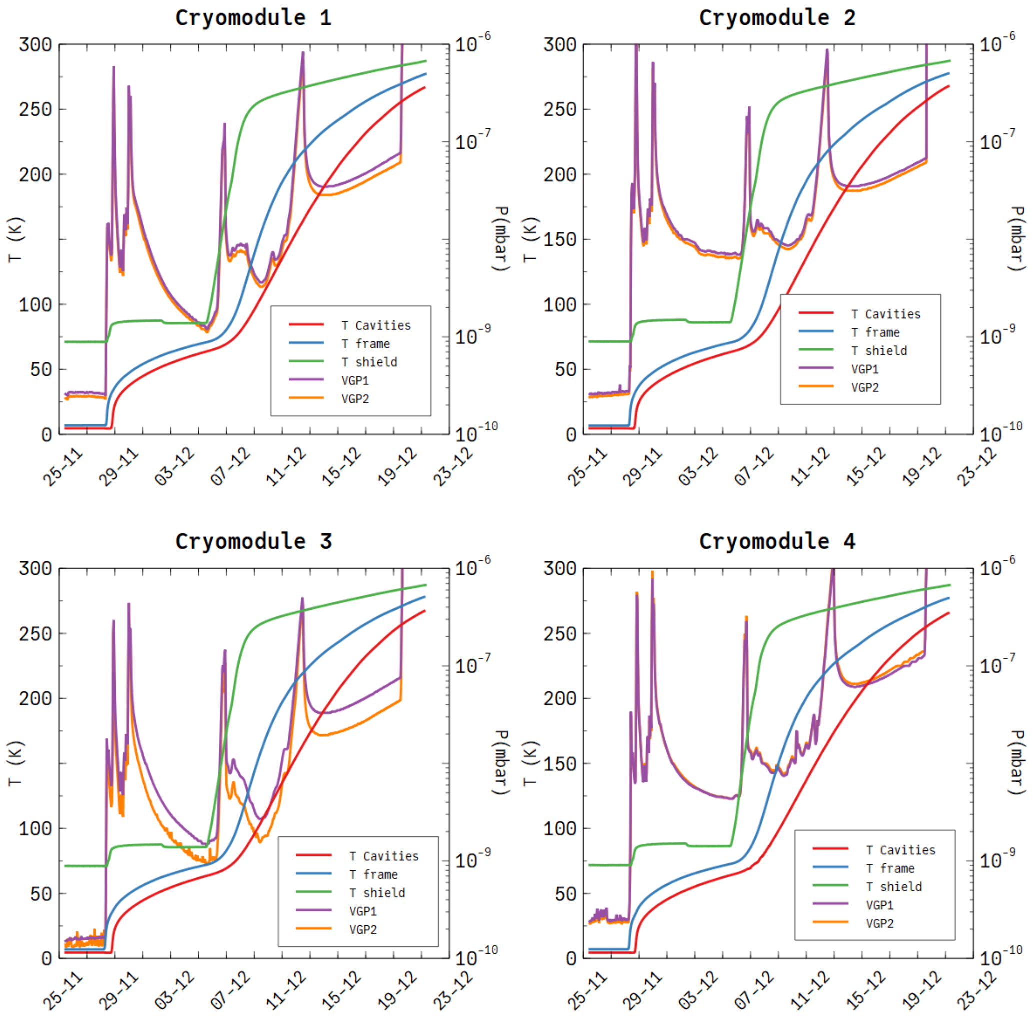
- To prevent dust transport → slow pumpdown required
- Big volume of the vessel (3,5 m^3)
- 3D laminar flow simulation using COMSOL
- One dry pump $S<30\ m^3/h$ → flow speed $< 10^{-2}$ m/s around cavities ($Re<200$)
- Each cryomodule equipped with 2×700 l/s turbopumps to cope with possible He leaks → Operation with leaks $<10^{-6}$ mbar×l/s

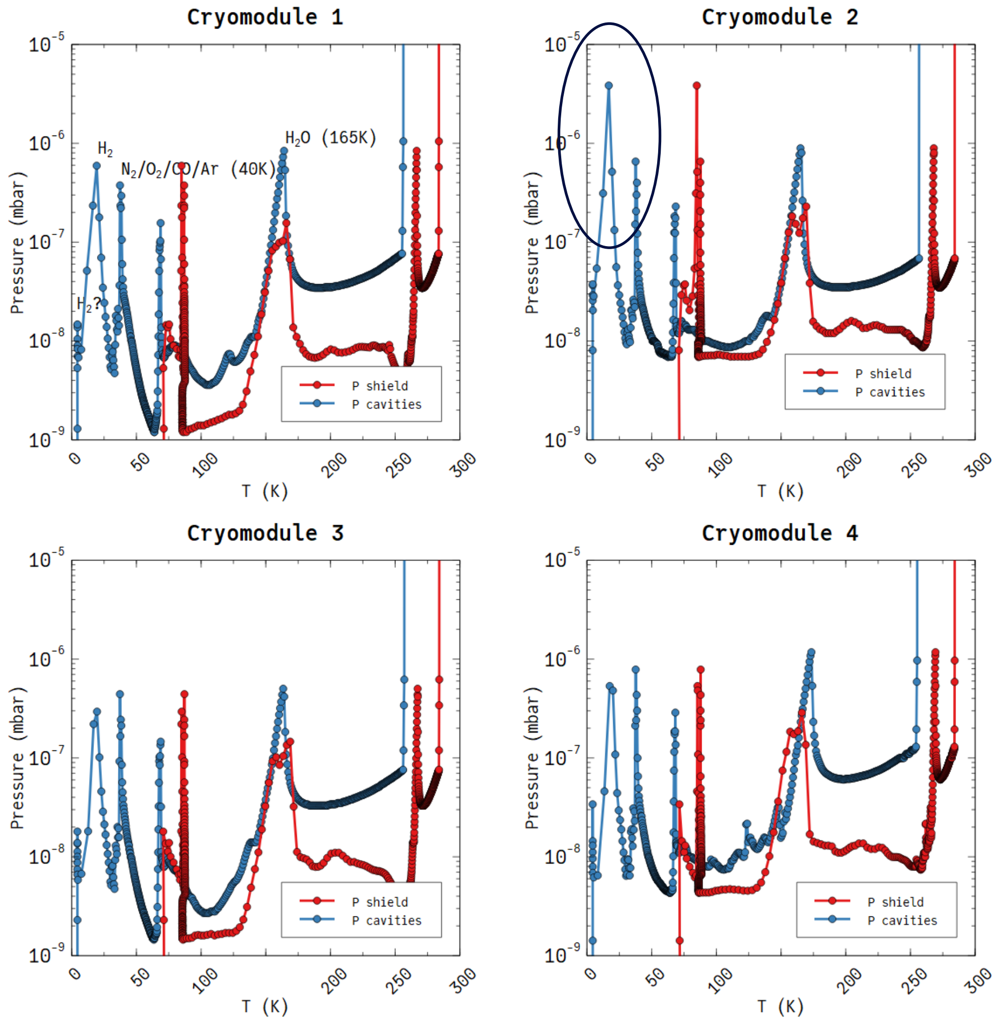




Operation: Warm-up analysis

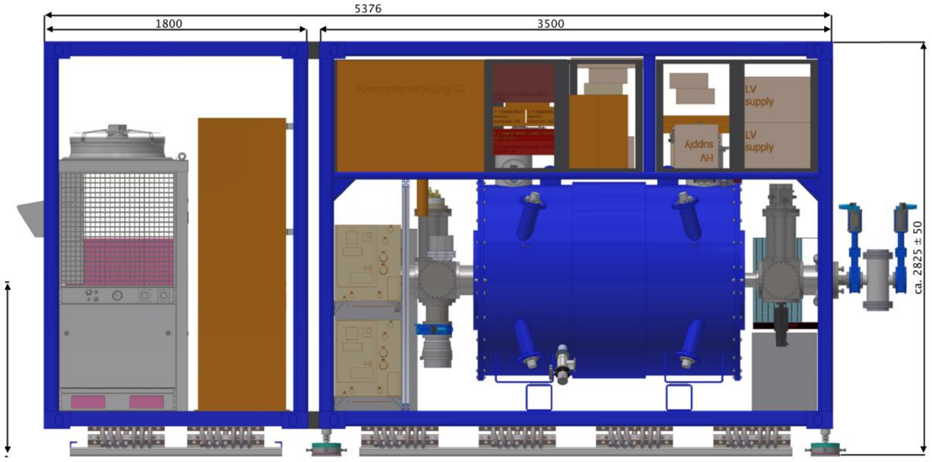


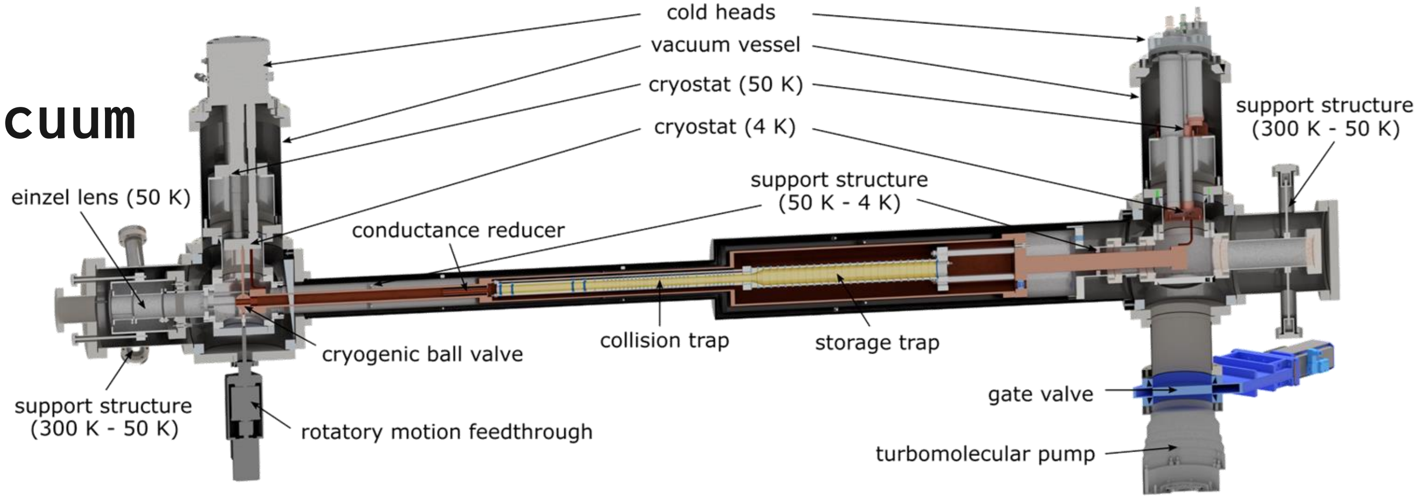


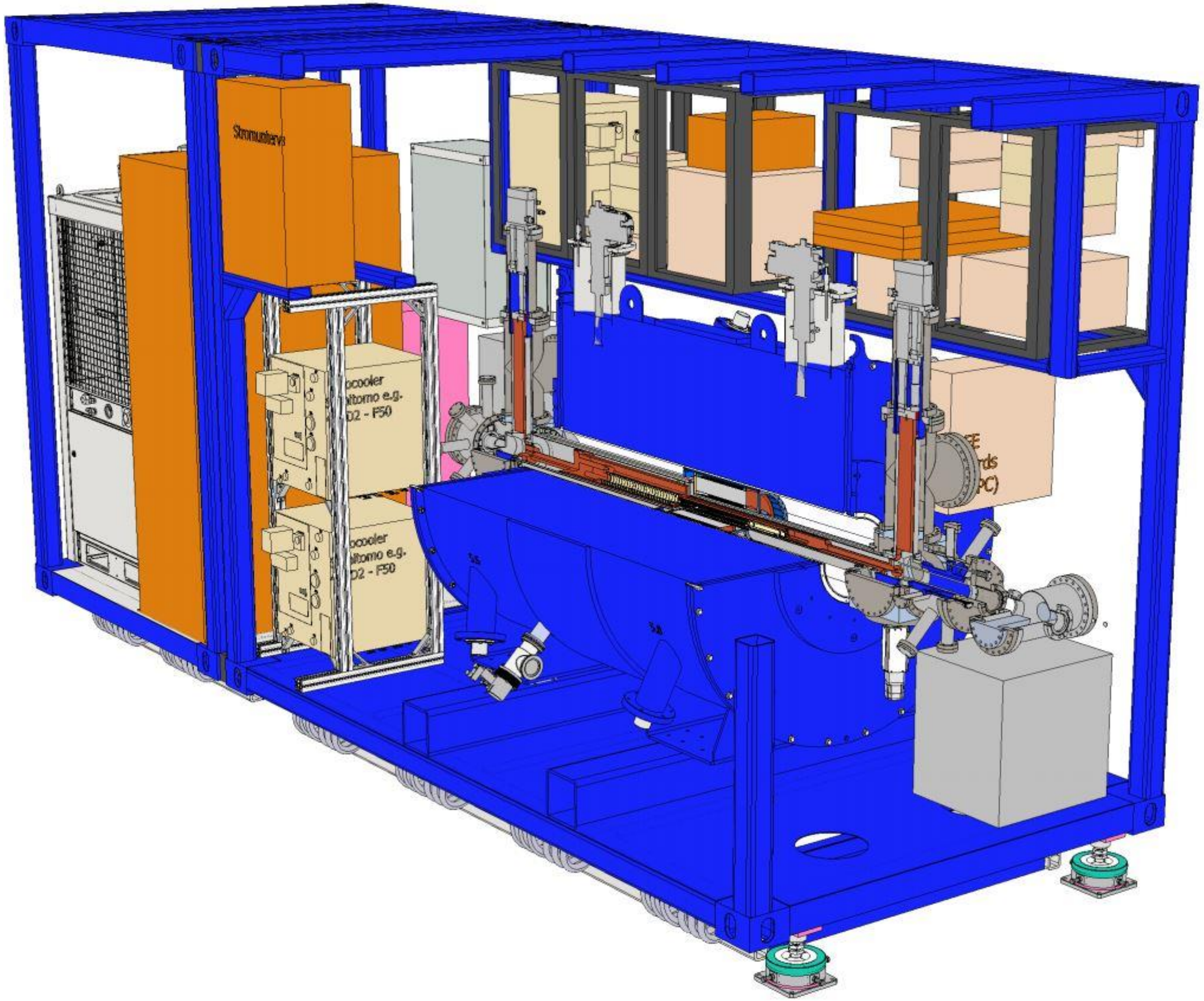


Other cryogenic systems: PUMA

- Open cryotrap → Objective pressure 10^{-17} mbar inside the trap to store antiprotons
- Dry cryostat (cryocoolers) at 50K/4K
- Portable trap for transport to a different facility
- No risk of He leaks
- Common beam and insulation vacuum



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ocooler
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PUMA: Modelling pressure evolution (cryo-sorption)

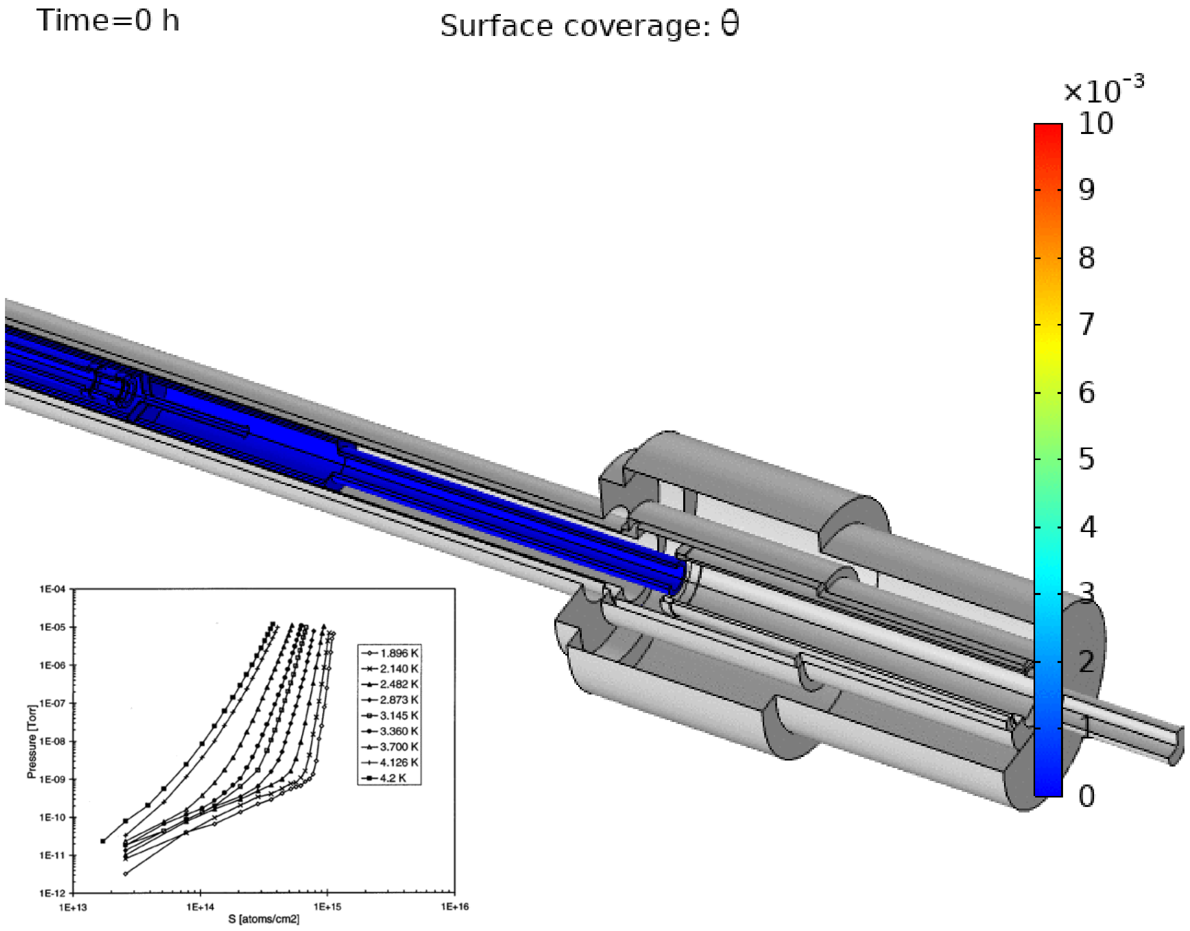
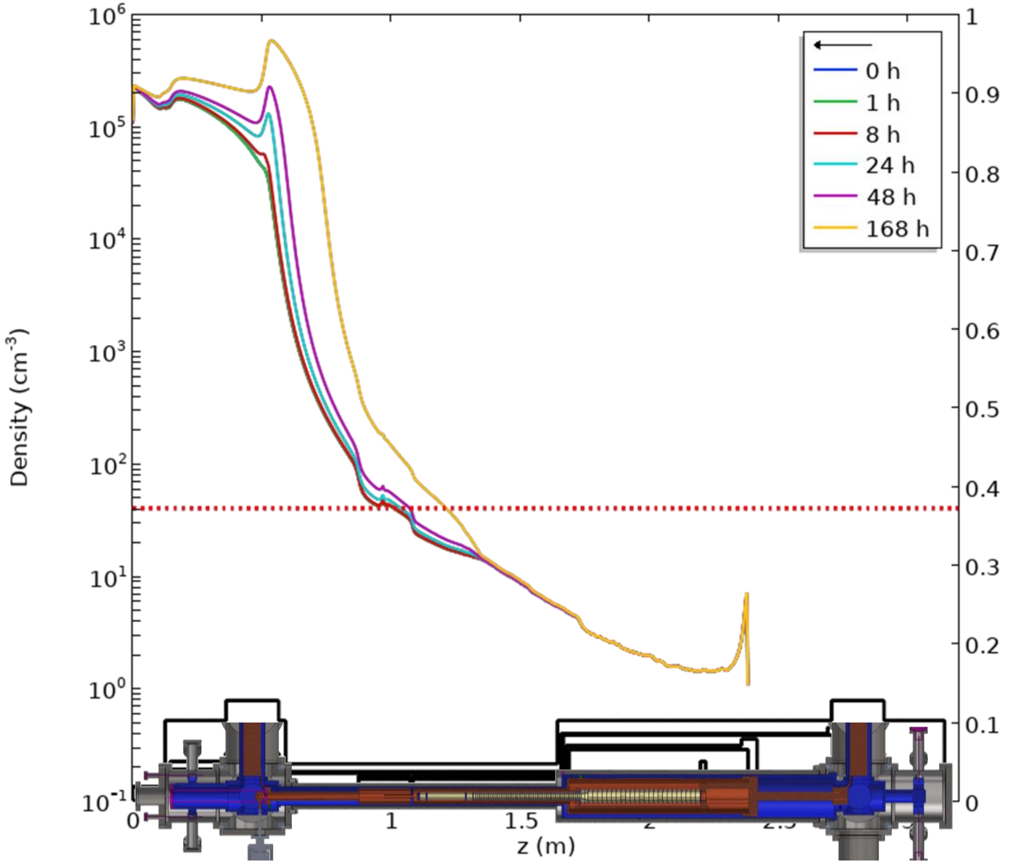


Fig. 11: Helium adsorption isotherm measured on a stainless-steel tube from 1.9 to 4.2 K [47].



Summary

- ❑ **Insulation vacuum is required primarily for thermal insulation**
- ❑ **Two main design aspects:**
  - ❑ Maximum admissible leak rate
  - ❑ Required pumping type and speed for pumpdown at room temperature, operation and transients ←→ Outgassing rate. From continuous mechanical pumping to cryo-condensation and cryo-sorption
- ❑ **The main driver for the definition of those aspects is the required operational temperature and pressure**
- ❑ **Other aspects: vacuum quality (beam vacuum?), dust presence, etc.**
- ❑ **Strong interconnection with all other systems (cryogenics, magntes, RF, alignment, etc.)**

Thank you for your attention!

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