Cold / sticky system

Vincent Baglin

CERN AT-VAC, Geneva

Cold / sticky system ??

Vacuum ??

Eureka ??

Cold / sticky system

Outline

1. Cryopumping
2. Adsorption isotherms
3. Cryosorbers in cold systems
4. He leaks in cold systems

1. Cryopumping

Desorption probability

- The desorption probability is a function of the binding energy, E and the temperature, T (first order desorption, Frenkel 1924). The surface coverage, θ, varies like :

$$\frac{d\theta}{dt} = -\theta\,\nu_0\,e^{-\frac{E}{kT}}$$

($\nu_0 \sim 10^{13}$ Hz, $k = 86.17\ 10^{-6}$ eV/K)

- The desorption process is caracterised by the sojourn time, τ :

$$\tau = \frac{e^{\frac{E}{kT}}}{\nu_0}$$

- For large E and small T, molecules remains onto the surface : CRYOPUMPING

- For some combination of E and T, the molecule is desorbed (bake out)

Sojourn time

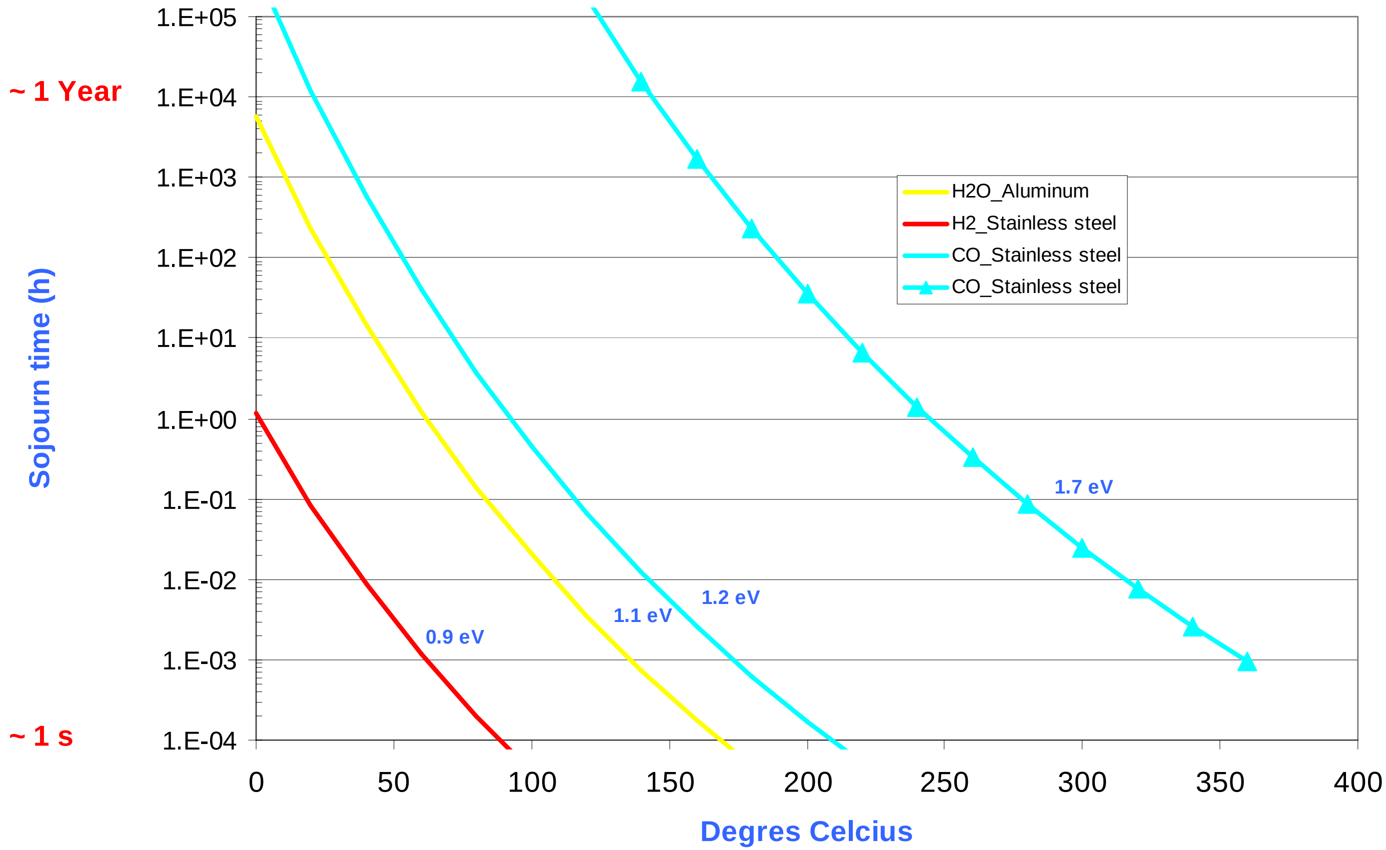
Chemisorbed molecules

- At room temperature :

  H_2O dominates

  > 100 ºC to remove H_2O

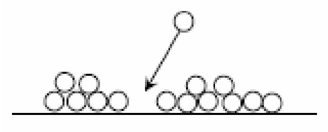
- A bake out up to 300 ºC removes molecules with large binding energies which could be desorbed by stimulated desorption



Cryopumping regimes

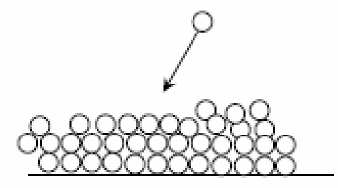
Physisorption

- Sub-monolayer coverage : attractive force (van der Waals) between a gas molecules and a material
- Binding energy for physical adsorption
- H_2 from 20 to 85 meV for smooth and porous materials resp.
- 1 h sojourn time at 5.2 K and 26 K for smooth and porous materials resp.



Condensation

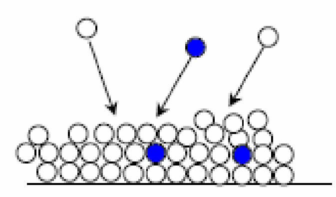
- For thick gas coverage, only forces between gas molecules
- Energy of vaporisation 9 to 175 meV for H_2 and CO_2 resp.
- 1 h sojourn time at 2.8 K and 53.4 K for H_2 and CO_2 resp.



➔ sub-monolayers quantities of gas can be *physisorbed* at their boiling temperature
(ex : H_2 boils at 20.3 K and a bake-out above 100 ºC removes water)

Cryotrapping

- Use of a easily condensable carrier (e.g. Ar) to trap molecules with high vapor pressure (e.g. He, H_2)

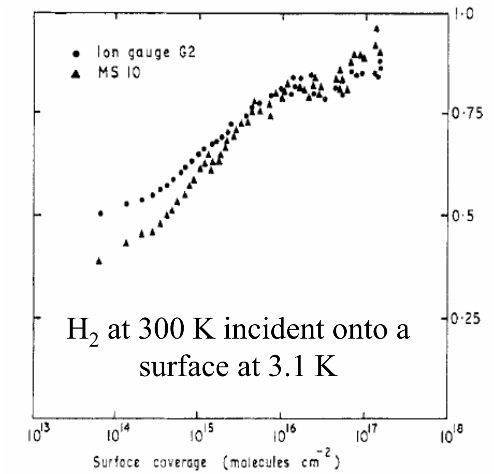


Sticking probability/coefficient

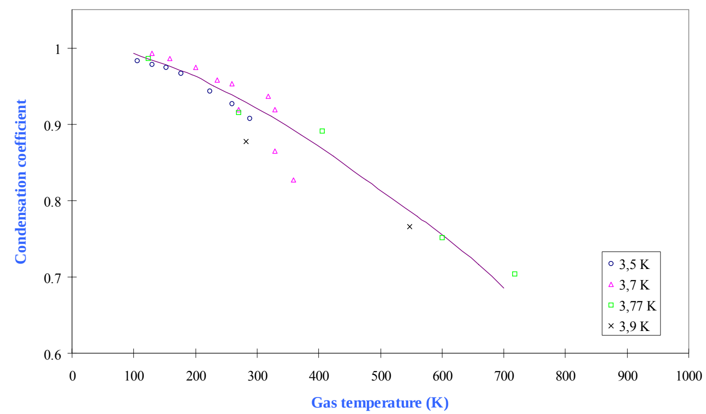
- Probability : $0 < \sigma < 1$
  ν collision rate (molecules.s^{-1}.cm^{-2})

$$\sigma = \frac{\nu_{\text{incident}} - \nu_{\text{departing}}}{\nu_{\text{incident}}} = \frac{\nu_{\text{sticking}}}{\nu_{\text{incident}}}$$

- Function of gas, surface, surface coverage, temperature of gas and surface temperature



J.N. Chubb *et al*. J. Phys. D, 1968, vol 1, 361



J.N. Chubb *et al*. Vacuum/vol 15/number 10/491-496

- Pumping speed

$$S = \frac{1}{4}\sigma\left(1 - \frac{P}{P_{sat}}\right) A\,\bar{v} \approx \frac{1}{4}\sigma\,A\,\bar{v}$$

i.e : σ times the conductance of a surface

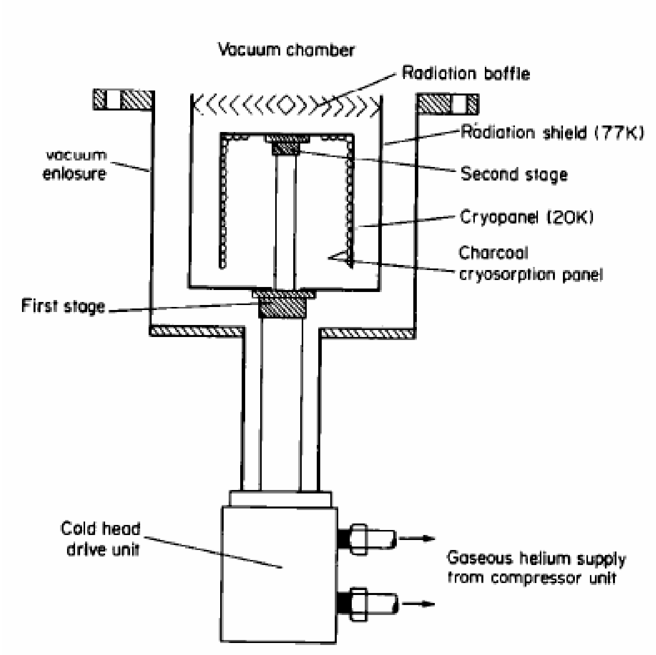
$$S\left[\text{l.s}^{-1}.\text{cm}^{-2}\right] = 3.63\,\sigma\sqrt{\frac{T}{M}}$$

- H_2 and CO at 4.2 K :
  $S_{H2} = 5.3$ l.s^{-1}.cm^{-2}
  $S_{CO} = 1.4$ l.s^{-1}.cm^{-2}

Capture factor, C_f

- Takes into account the geometry of the system :

Baffle in a cryopump



$C_f \sim 0.3$

R. Haefer. J. Phys. E : Sci. Instrum., Vol 14, 1981, 273-288

Holes in the electron shield of the LHC beam screen

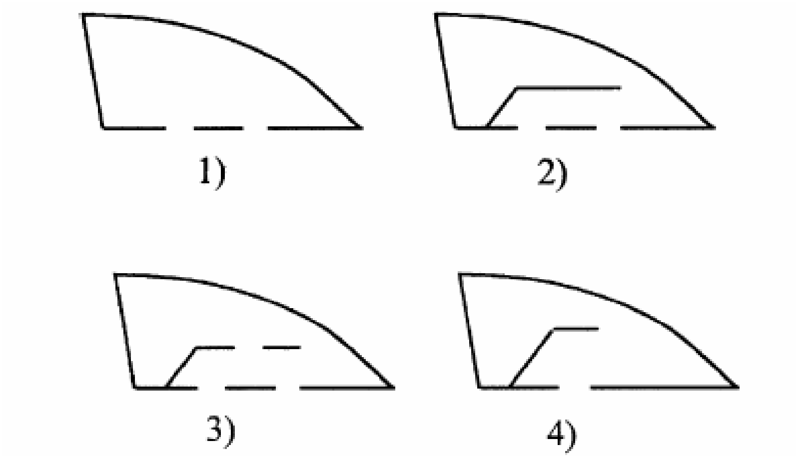


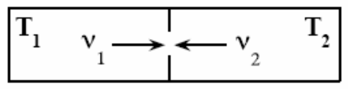
Fig. (1) Two slots in the beam screen, without electron shield, (2) two slots in the beam screen, electron shield without slot, (3) two slots in the beam screen, electron shield with slot, (4) only one slot in the beam screen, electron shield without slot.

σ	1	2	3	4
0.1	0.48	0.26	0.39	0.43
1	0.68	0.36	0.51	0.57

A.A. Krasnov. Vacuum 73 (2004) 195-199

Thermal transpiration

- Vacuum gauges are located at room temperature to reduce heat load
- For small aperture, the collision rate, ν, is conserved at the cold / warm transition



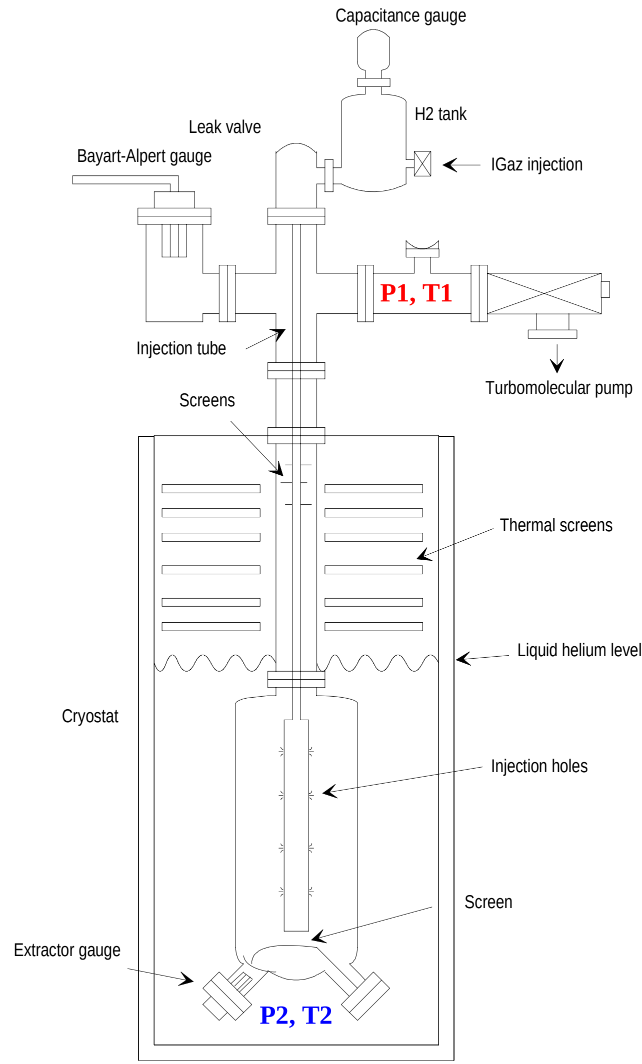
$$\nu = \frac{1}{4} n \bar{v}$$

- Since the average velocity scales like √T

$$\frac{P_1}{P_2} = \sqrt{\frac{T_1}{T_2}}$$

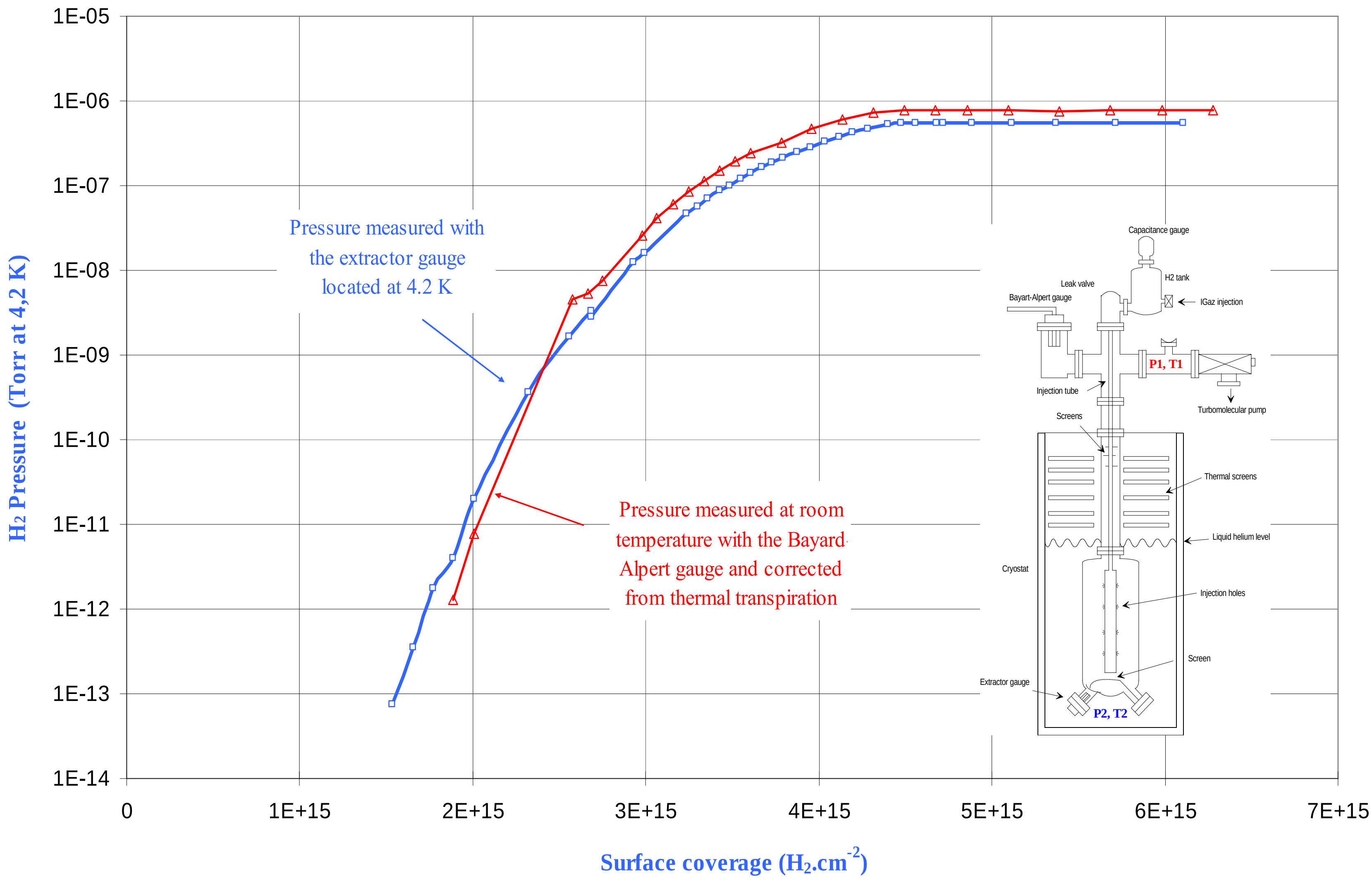
$$\frac{n_1}{n_2} = \sqrt{\frac{T_2}{T_1}}$$

T (K)	4.2	77
P_1/P_2	8	2



Experimental evidence of thermal transpiration

Static conditions



V. Baglin *et al.* CERN Vacuum Technical Note 1995

2. Adsorption isotherms

Adsorption isotherm

- Measurement, at constant temperature, of the equilibrium pressure for a given gas coverage, θ
- Varies with:
  molecular species
  surface temperature (under 20 K only H_2 and He)
  surface nature
  gas composition inside the chamber
  ...
- Models :

Henry's law for low surface coverage

$$\theta = c\,P$$

DRK (Dubinin, Radushkevich and Kaganer) for metalic, glass and porous substrate. Valid at low pressure. Good prediction with temperature variation

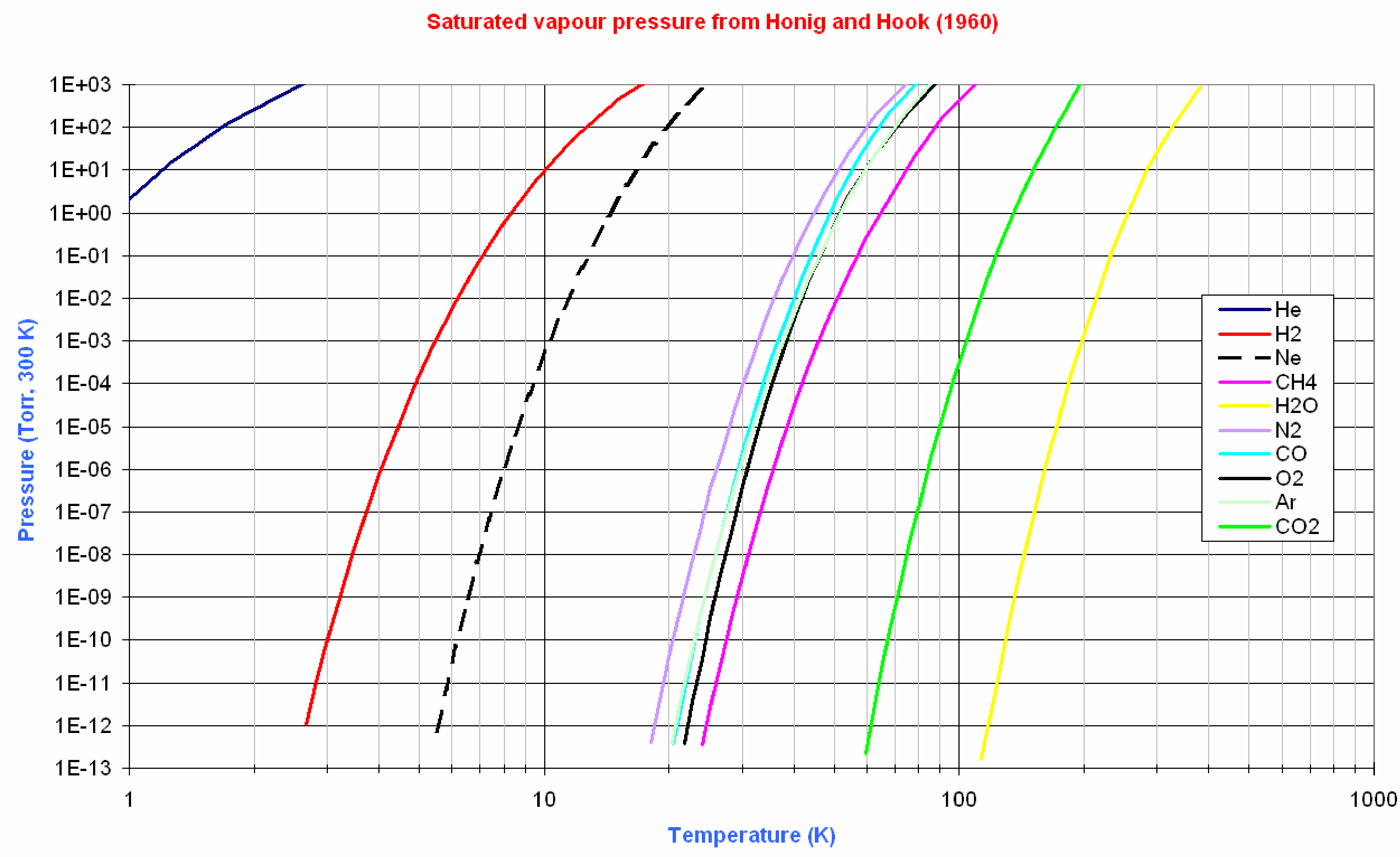
$$\ln(\theta) = \ln(\theta_m) - D\left(kT\,\ln\left(\frac{P_{Sat}}{P}\right)\right)^2$$

BET (Brunauer, Emmet and Teller). Multi-monolayer description

$$\frac{P}{\theta\,(P - P_{Sat})} = \frac{1}{\alpha\,\theta_m} + \frac{(\alpha - 1)}{\alpha\,\theta_m}\,\frac{P}{P_{Sat}}$$

Saturated vapour pressure

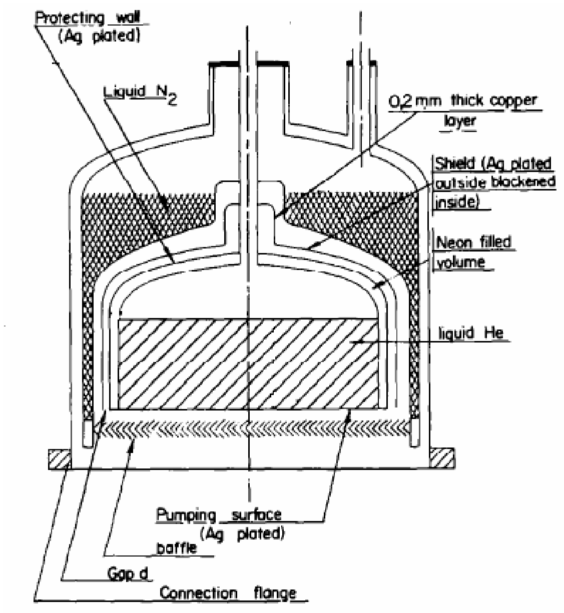
- Pressure over liquid or gas phase (many monolayers condensed)
- Clausius-Clapeyron equation : $\text{Log } P_{sat} = A - B/T$



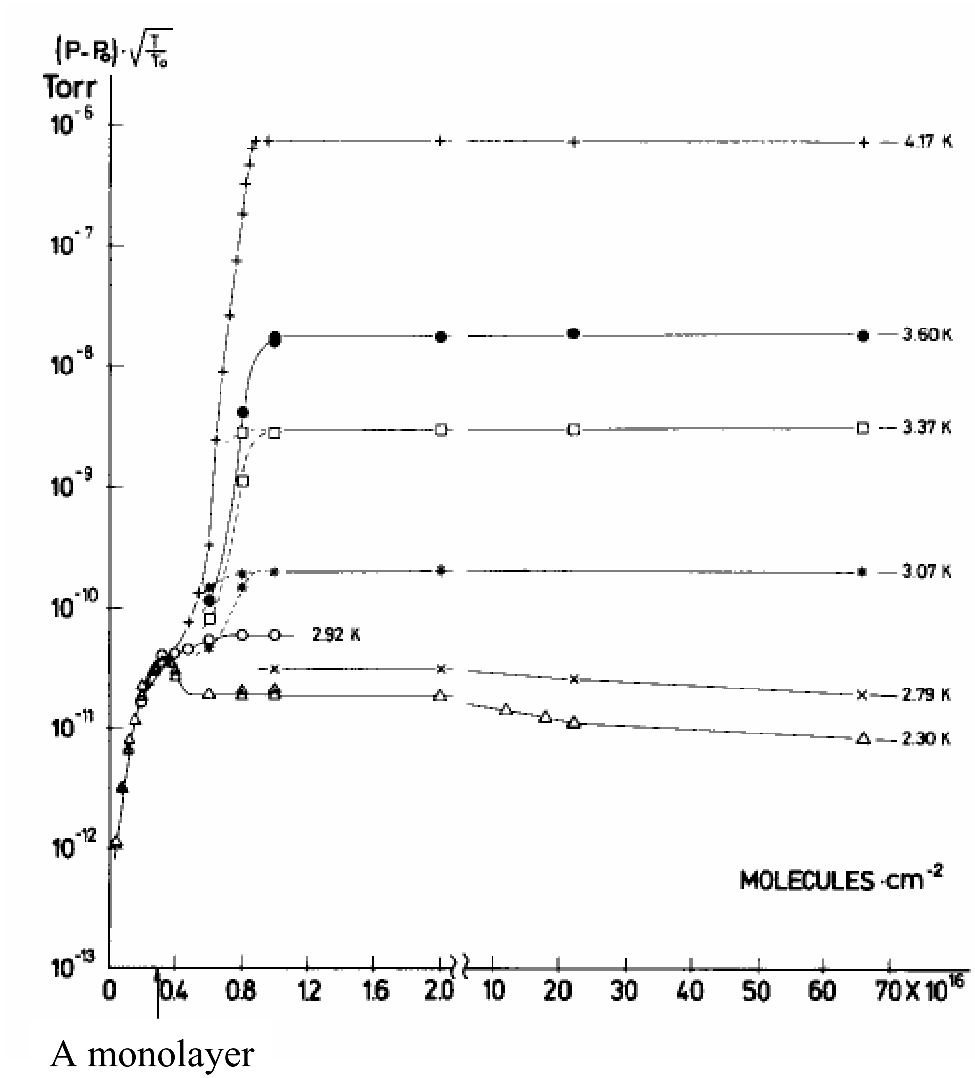
H_2 adsorption isotherm on stainless steel

- Condensation cryopumps allows to pump large quantities of H_2

- CERN ISR condensation cryopump operated with liquid He at 2.3 K (50 Torr on the He bath)



C. Benvenuti *et al*. Vacuum, 29, 11-12, (1974) 591



C. Benvenuti *et al*. J.Vac.Sci. 13(6), Nov/Dec 1976, 1172-1182

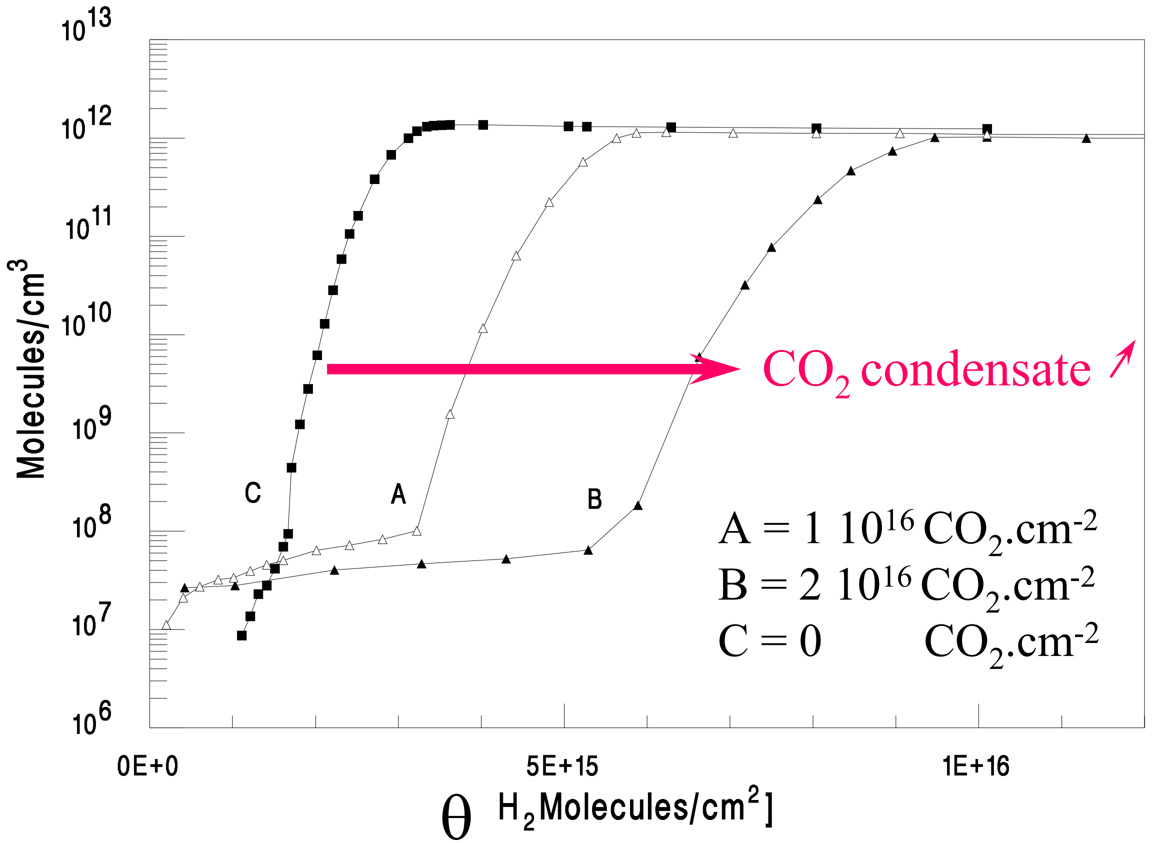
H_2 adsorption isotherm at 4.2 K on CO_2 condensat

- Packing growth for CO_2 films

  ⇒ Porous layer

- DRK adsorption capacity :
  0.3 H_2/CO_2

- Electroplated Cu

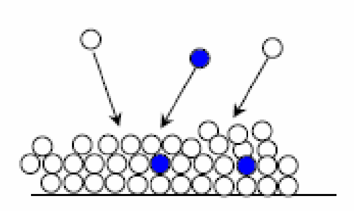


E. Wallén, JVSTA 14(5), 2916, Sep./Oct. 1996

H_2 adsorption isotherm at 4.2 K in co-adsorption with CO_2

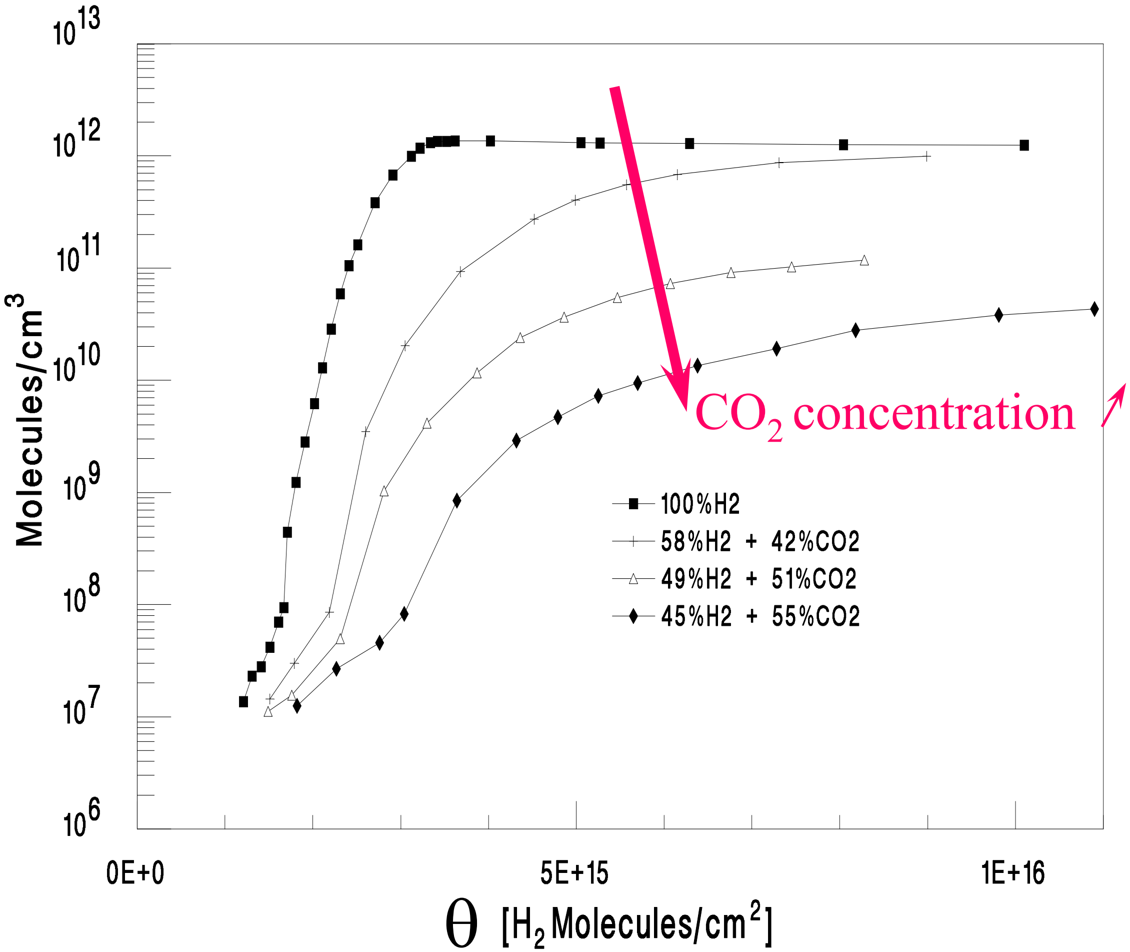
- Reduction of the saturated vapour pressure by orders of magnitude

⇒ Cryotrapping



- Electroplated Cu

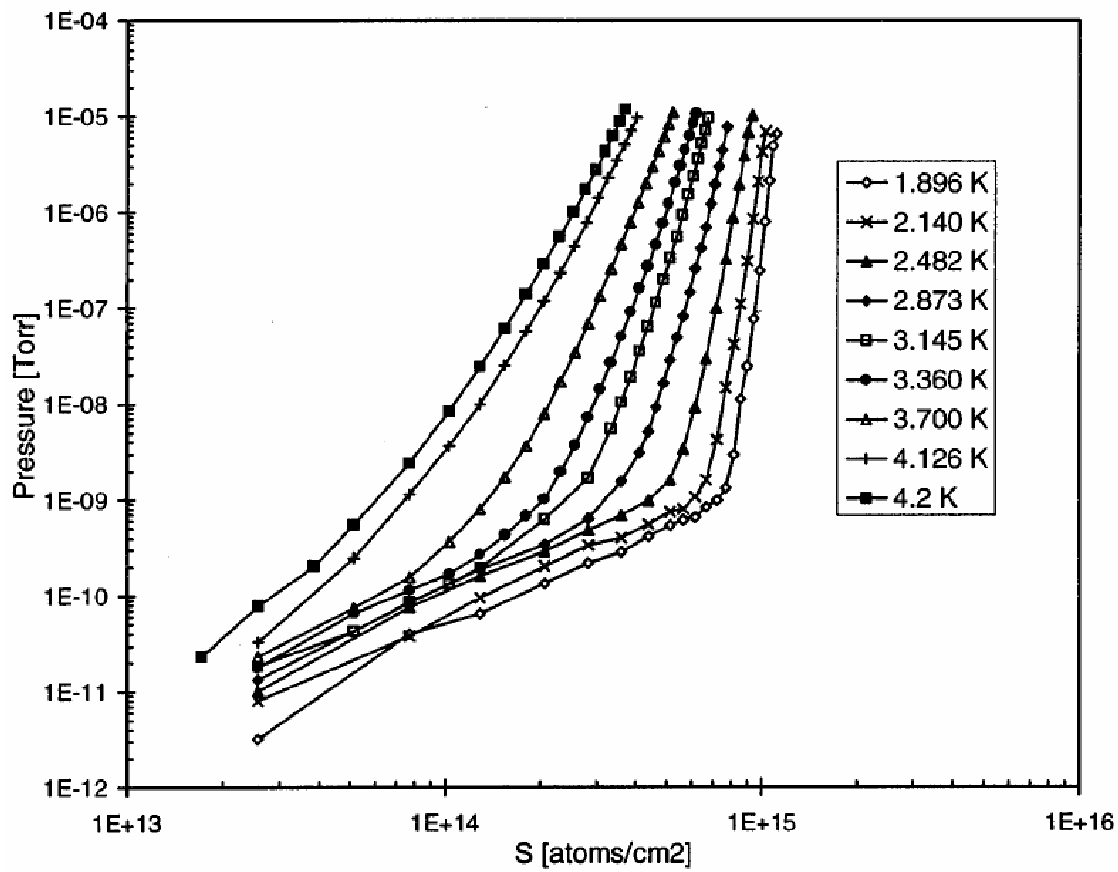
- In cryopumps CO_2 is admitted to enhance the pumping of H_2 and He



E. Wallén, JVSTA 14(5), 2916, Sep./Oct. 1996

He adsorption isotherm from 1.9 to 4.2 K

- Sub-monolayer range
- Approach of Henry's law at low coverage
- The isotherms are well described by the DRK model
- $\theta_m \sim 1.3\ 10^{15}\ H_2/cm^2$
- Stainless steel



E. Wallén. J.Vac.Sci.A 15(2), Mar/Apr 1997, 265-274.

Cryosorbing materials

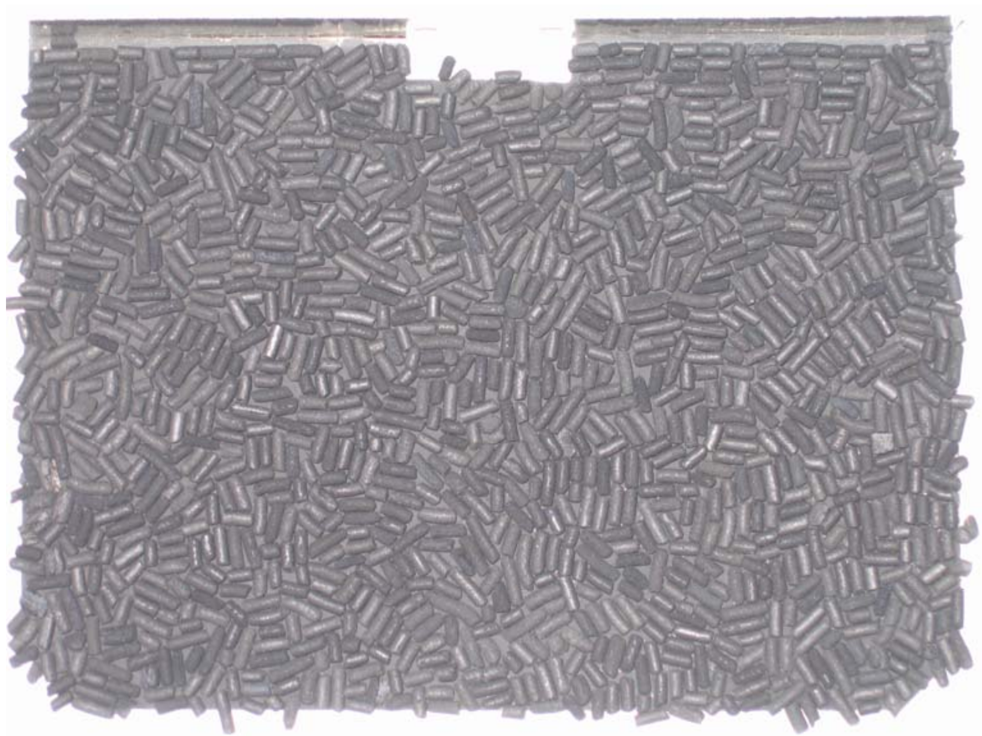
- Large capacity
- Large pumping speed
- Large temperature working range (up to ~ 30 K)

e.g. **Activated Charcoal** used for cryopumps (see cryopumps talk)

Capacity ~ 10^{22} H_2/g *i.e.* 10^{21} monolayers (P. Redhead, Physical basis of UHV,1968)

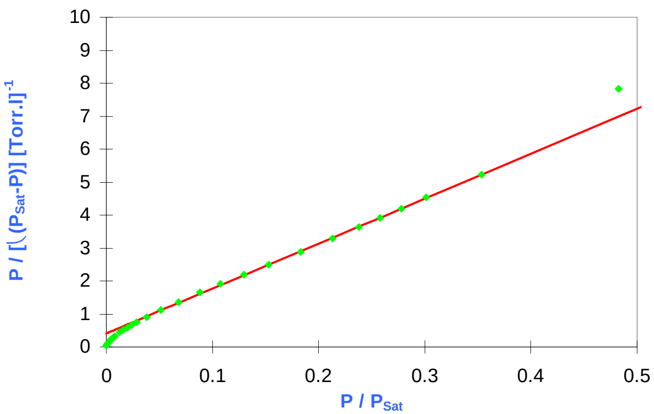
Sticking coefficient ~ 30 % at 30 K (T. Satake, Fus. Tech. Vol 6., Sept. 1984)

20 K cryopanels



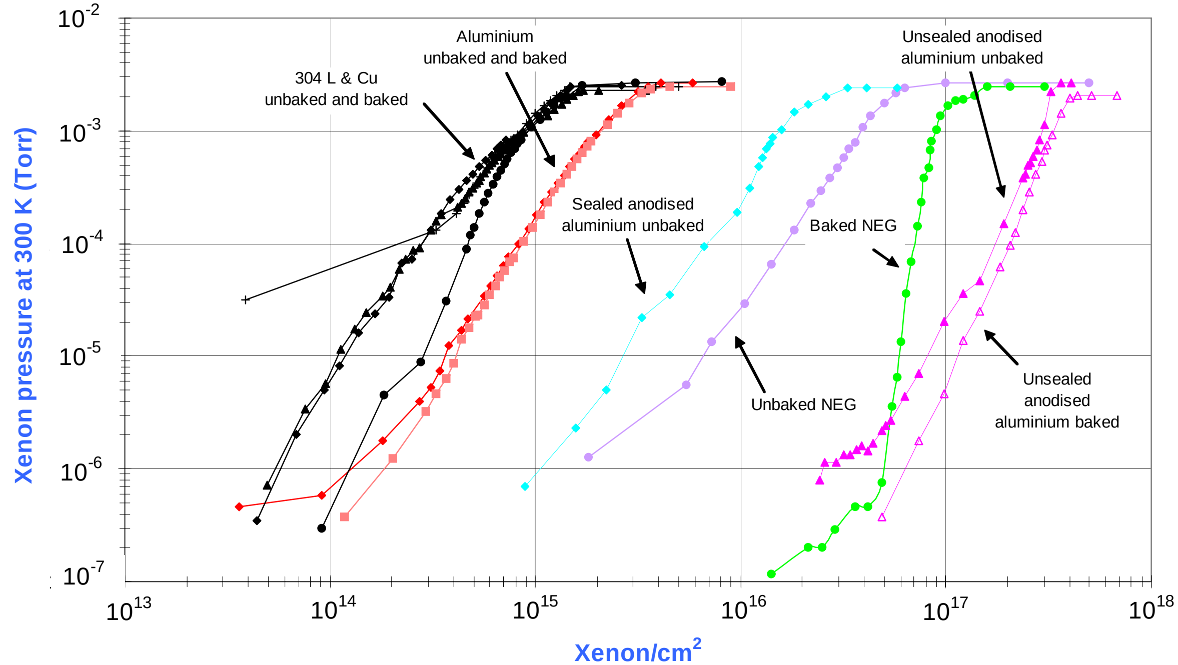
B.E.T surface area – Roughness factor

- Multi-monolayers theory
- Valid for $0.01<P/P_{sat}<0.3$
- BET monolayer = θ_m
- $\alpha = \exp(\Delta E/kT) >> 1$



$$\frac{P}{\theta\,(P - P_{Sat})} = \frac{1}{\alpha\,\theta_m} + \frac{(\alpha - 1)}{\alpha\,\theta_m}\frac{P}{P_{Sat}} \approx \frac{1}{\theta_m}\frac{P}{P_{Sat}}$$

$$R = \frac{A_R}{A_G} = \frac{A \times \theta_m}{A_G}$$

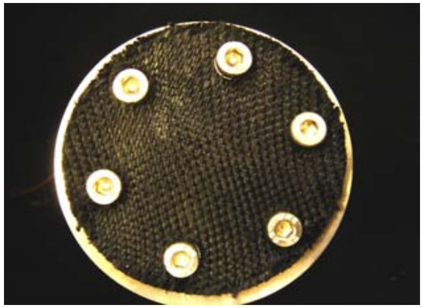


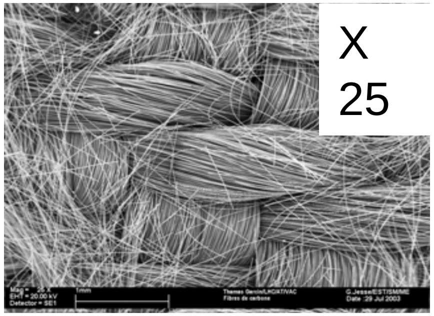
V. Baglin. CERN Vacuum Technical Note 1997

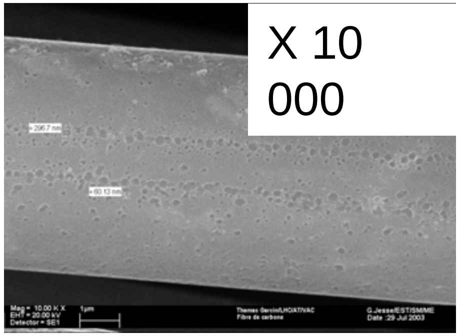
Technical surface	Unbaked	Baked at 150 ºC
Copper Cu-DHP acid etched	1,4	1,9
Stainless steel 304 L vacuum fired	1,3	1,5 (at 300 ºC)
Aluminium degreased	3,5	3,5
Sealed anodised aluminium 12 V	24,9	not measured
Unsealed anodised aluminium 12 V	537,5	556,0
NEG St 707	70,3	156,3

H_2 adsorption isotherm on cryosorbers

Woven carbon fiber developed by BINP





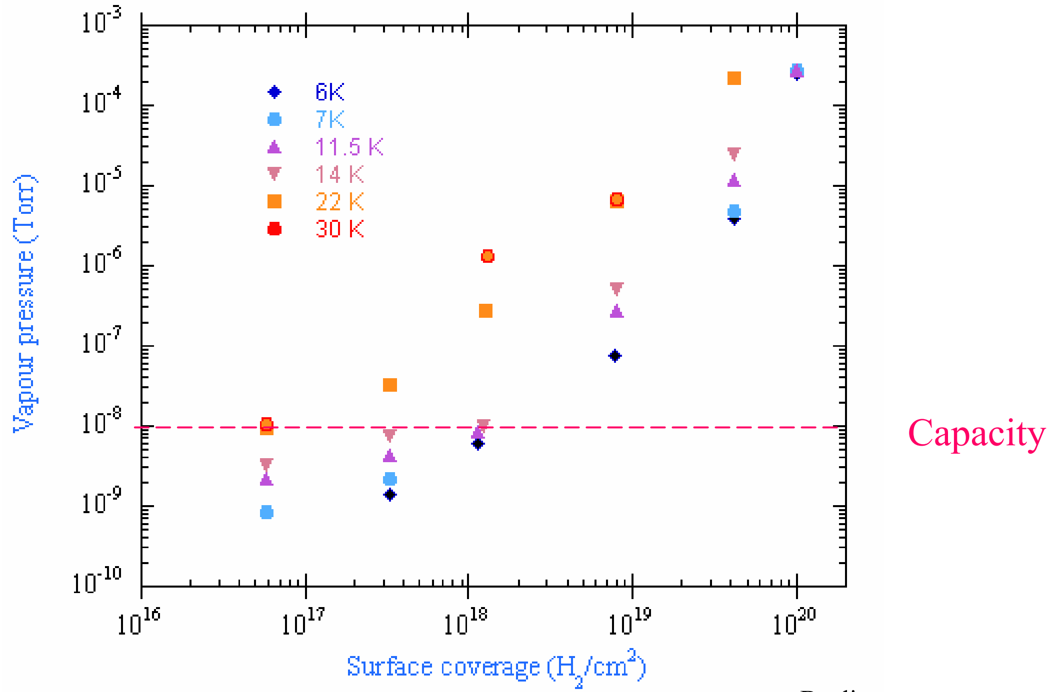


V. Anashin *et al.* Vacuum 75 (2004) 293-299

- Capacity :

10^{18} H_2/cm^2 at 6 K
10^{17} H_2/cm^2 at 30 K

$R \sim 10^3 R_{Cu}$



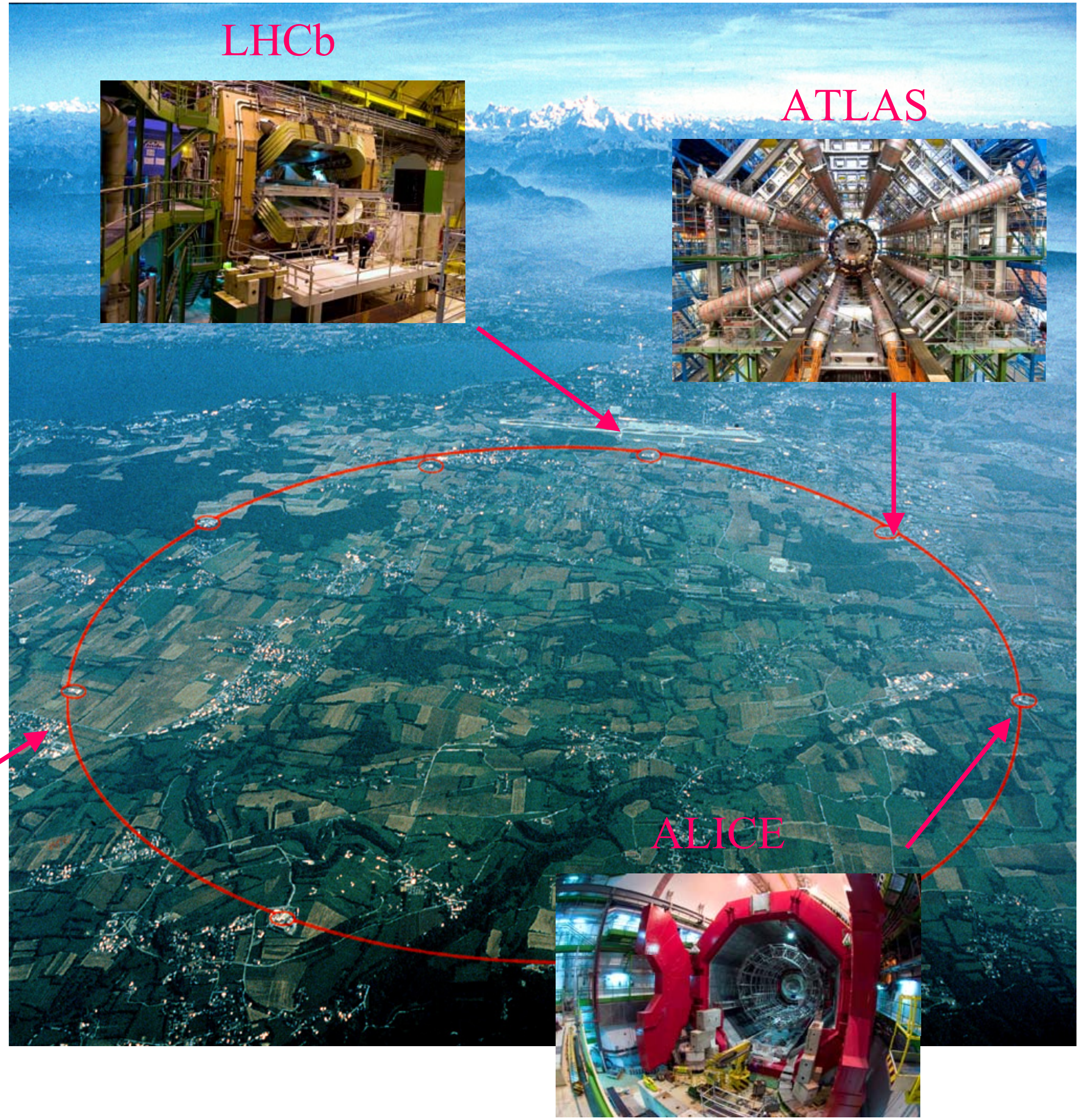
V. Baglin *et al.* EPAC'04, Luzern 2004.

3. Cryosorbers in cold systems.

Case of the LHC superconducting magnets operating at 4.5 K

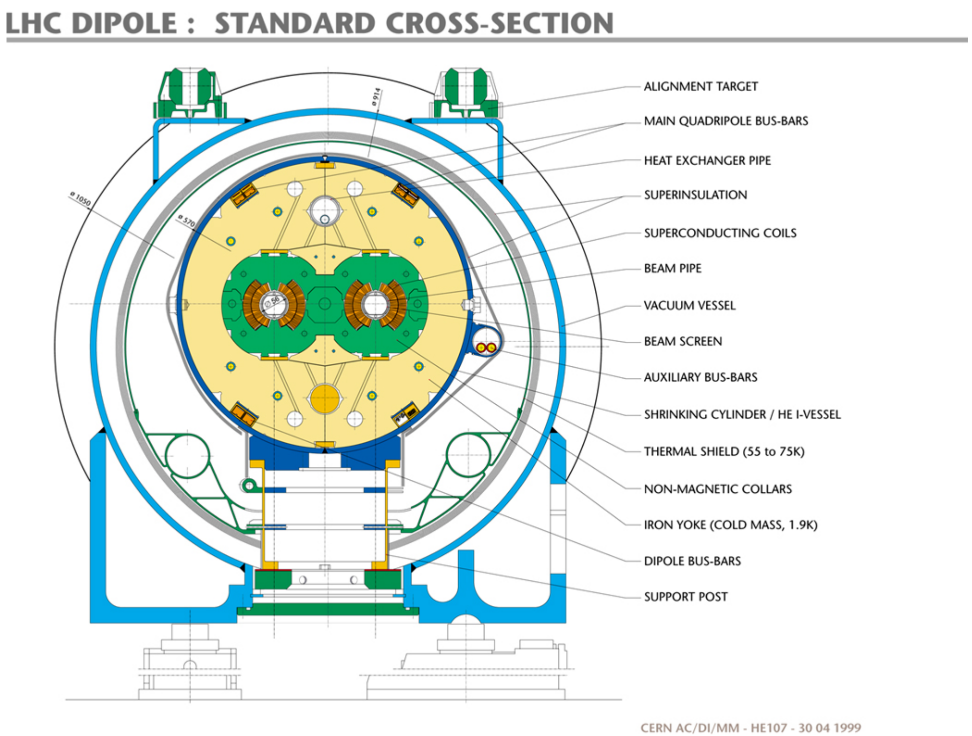
The CERN Large Hadron Collider (LHC)

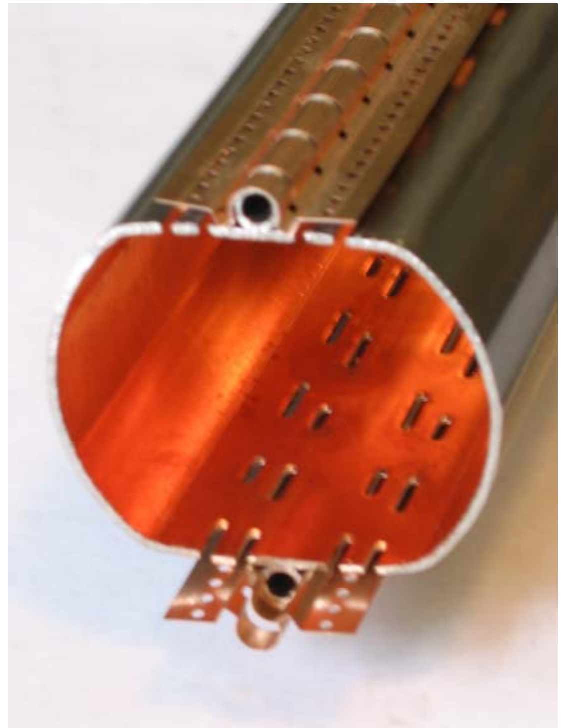
- 26.7 km circumference
- 8 arcs of 2.8 km
- 8 long straight sections of 575 m
- 4 experiments
- 7 TeV
- 1st beam in summer 2007



LHC dipole vacuum system

- Cold bore (CB) at 1.9 K
- Beam screen (BS) at 5-20 K (intercept thermal loads)





LHC vacuum system principle

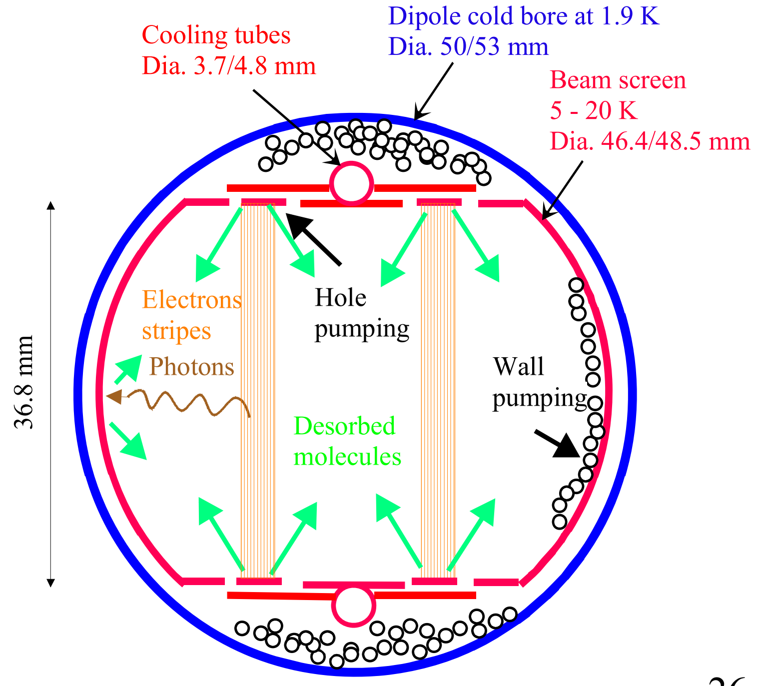
- Molecular desorption stimulated by photon, electron and ion bombardment (see beam-vacuum talks)
- Desorbed molecules are pumped on the beam vacuum chamber
- 100 h beam life time (nuclear scattering) equivalent to ~ 10^{-8} Torr H_2 at 300 K

In room temperature elements

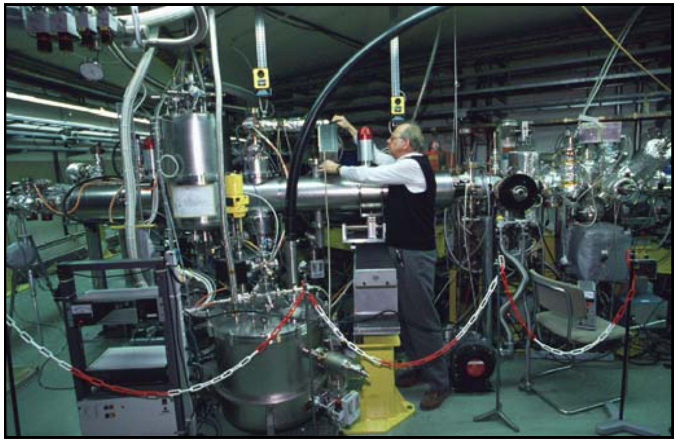
- Molecular chemisorption on NEG coating and in sputter ion pump (see getter talks)

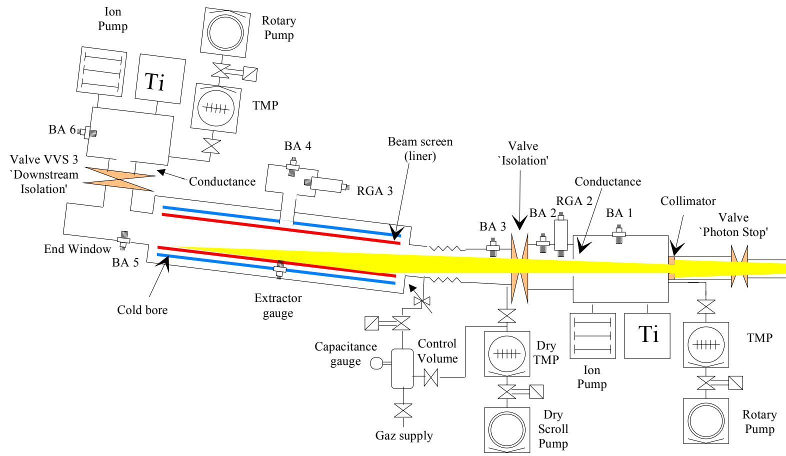
In cryogenic elements

- Molecular physisorption onto cryogenic surfaces (weak binding energy)
- Molecules with a low recycling yield are first physisorbed onto the beam screen (CH_4, H_2O, CO, CO_2) and then onto the cold bore
- H_2 is physisorbed onto the cold bore

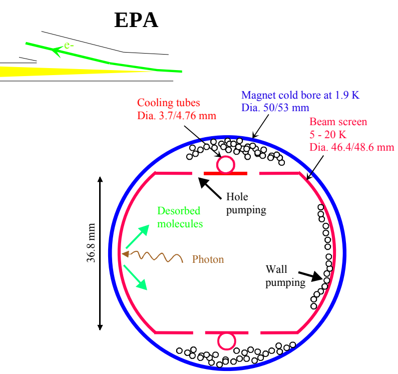


LHC dynamic pressure with perforated beam screen





- E_C = 194 eV
- 3 10^{16} photons.s^{-1}.m^{-1}
- BS ~ 5 - 100 K
- CB ~ 2.5 - 4.2 K

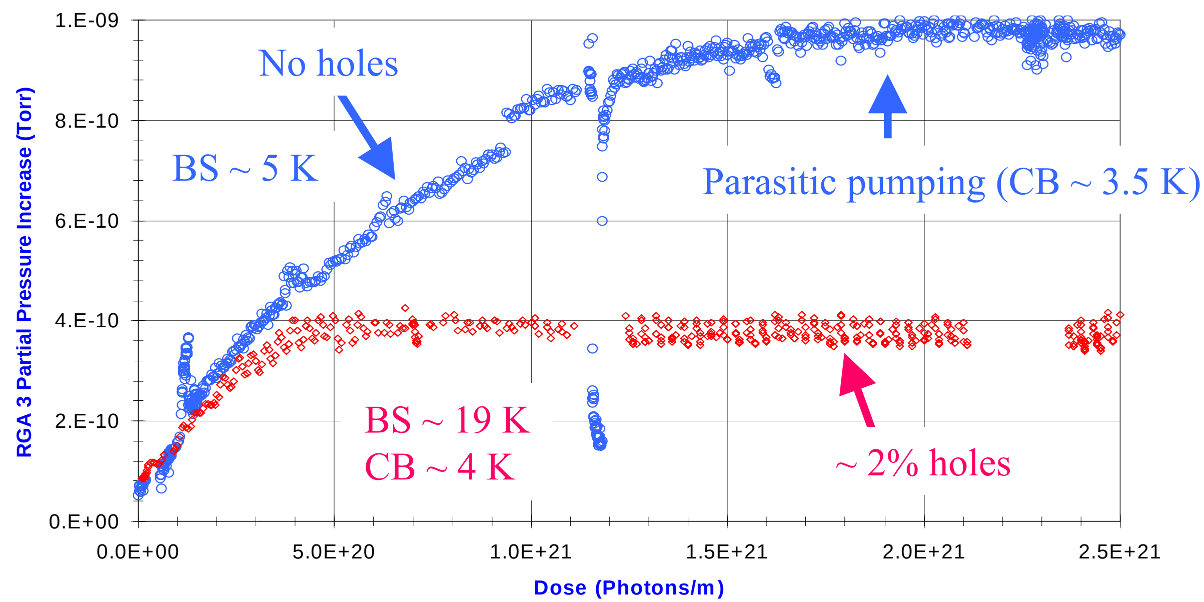


- Equilibrium pressure

$$n_{eq} = \frac{\eta\dot{\Gamma}}{C}$$

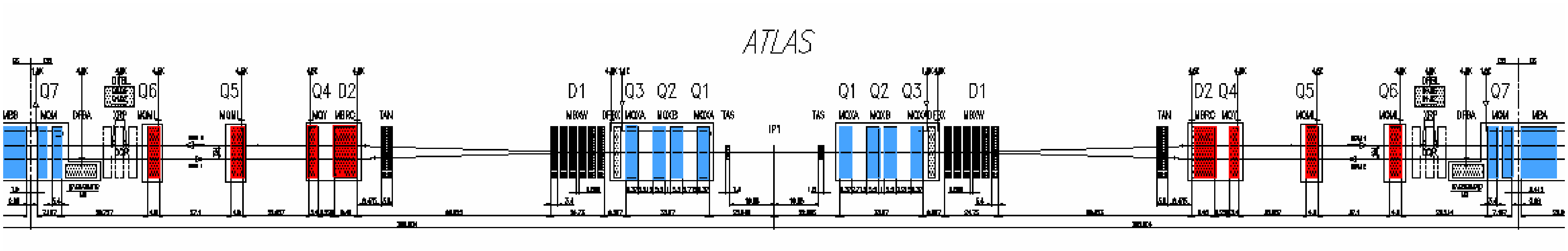
- Equilibrium coverage

$$\theta_{eq} = \left(\frac{\sigma S}{C}\frac{\eta}{\eta_0^{'}}\right)\theta_m$$



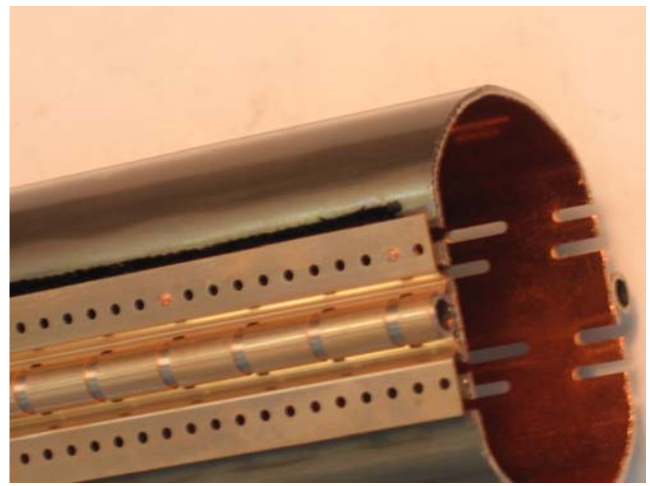
V. Baglin *et al.* EPAC'00, Vienna 2000.

LHC Long straight section vacuum system



- Dynamic vacuum ⇒ perforated beam screens

- 1.9 K cold bore (~660 m, arc beam screen technology)
- ~ 4.5 K cold bore (~ 740 m) ⇒ cryosorbers

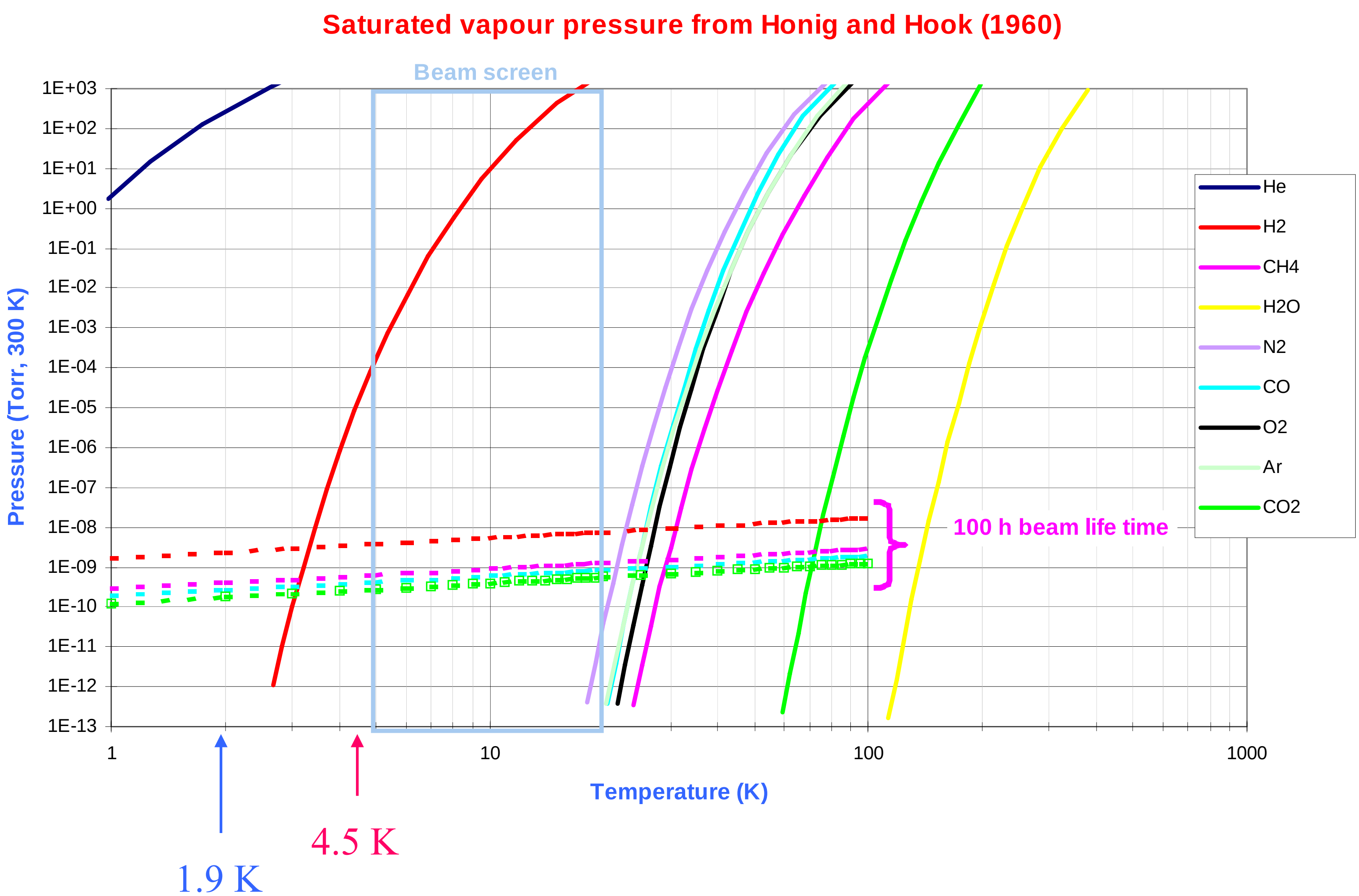


- Required performances (for installation of 200 cm^2/m):
  - Operates from 5 to 20 K
  - Capacity larger than 10^{18} H_2/cm^2
  - Capture coefficient larger than 15 %

Why cryosorbers ?

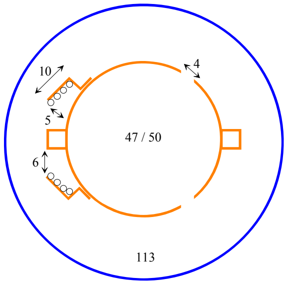
Design requires > 100 h life time with 4.5 K cold bore and thick surface coverage

⇒ porous surface

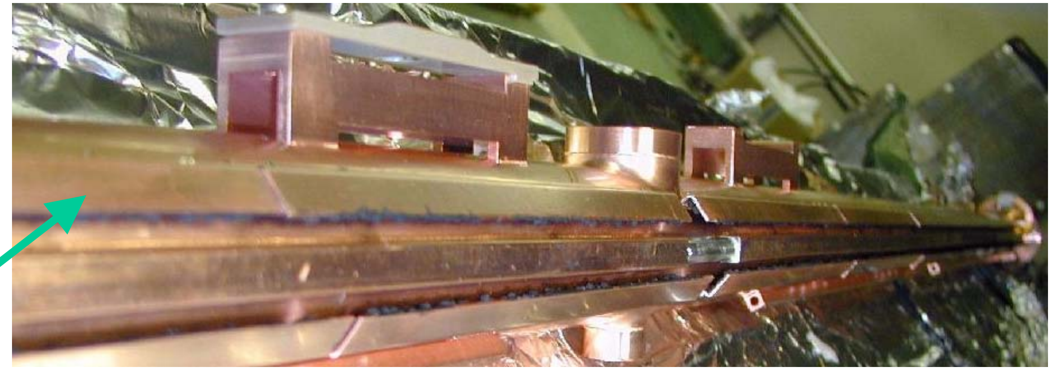


Performance with perforated cryosorbing screens

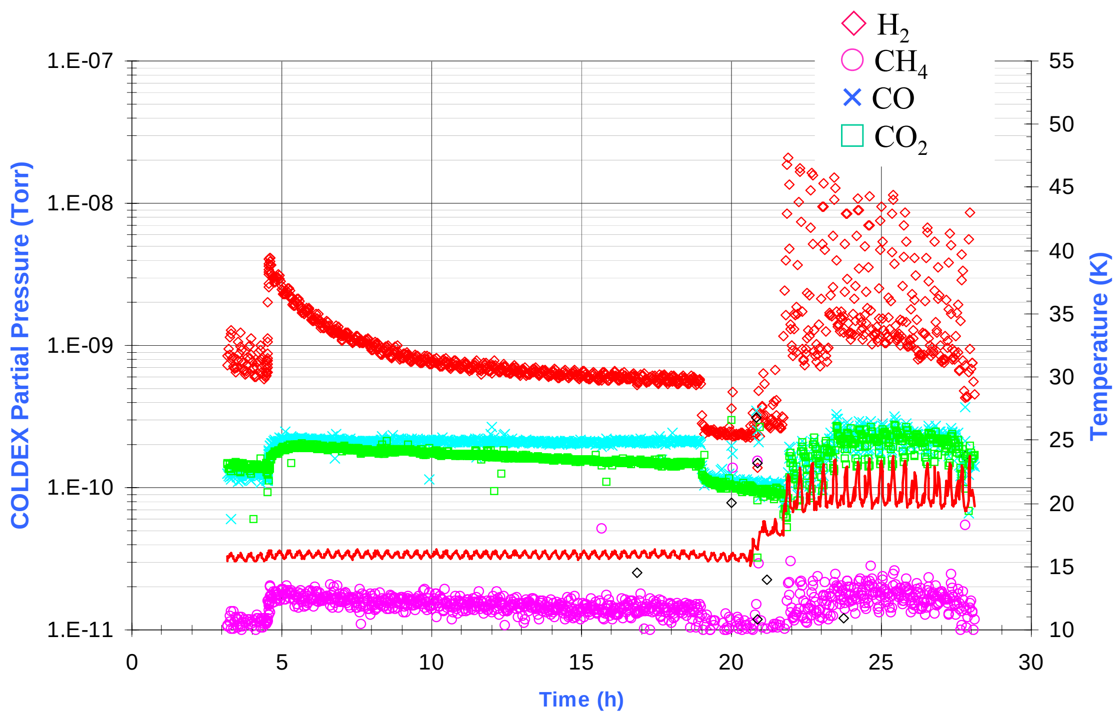
- ~ 2 % holes
- Charcoal cryosorber
- 206 $cm^2.m^{-1}$
- OFE Cu
- 2.2 m
- ID 47 mm



Strips with charcoal



- 100 monolayers of H_2 condensed onto the beam screen prior SR irradiation
- 2 10^{19} H_2/cm^2 condensed onto the cryosorber (20 x required capacity)
- CB > 70 K
- BS ~15 and 20 K
- Below design pressure (10^{-8} Torr)



V. Baglin *et al.* EPAC'02, Paris 2002.

LSS cryosorbers regeneration

Principle of operation

- The cryosorbers installed onto the back of the BS provide the required capacity and pumping speed for H_2. They are located in cryoelements operating with 4.5 K cold bores

- A regeneration during the annual shutdown for removing the H_2 is required

- The active charcoal is regenerated at ~ 80 K

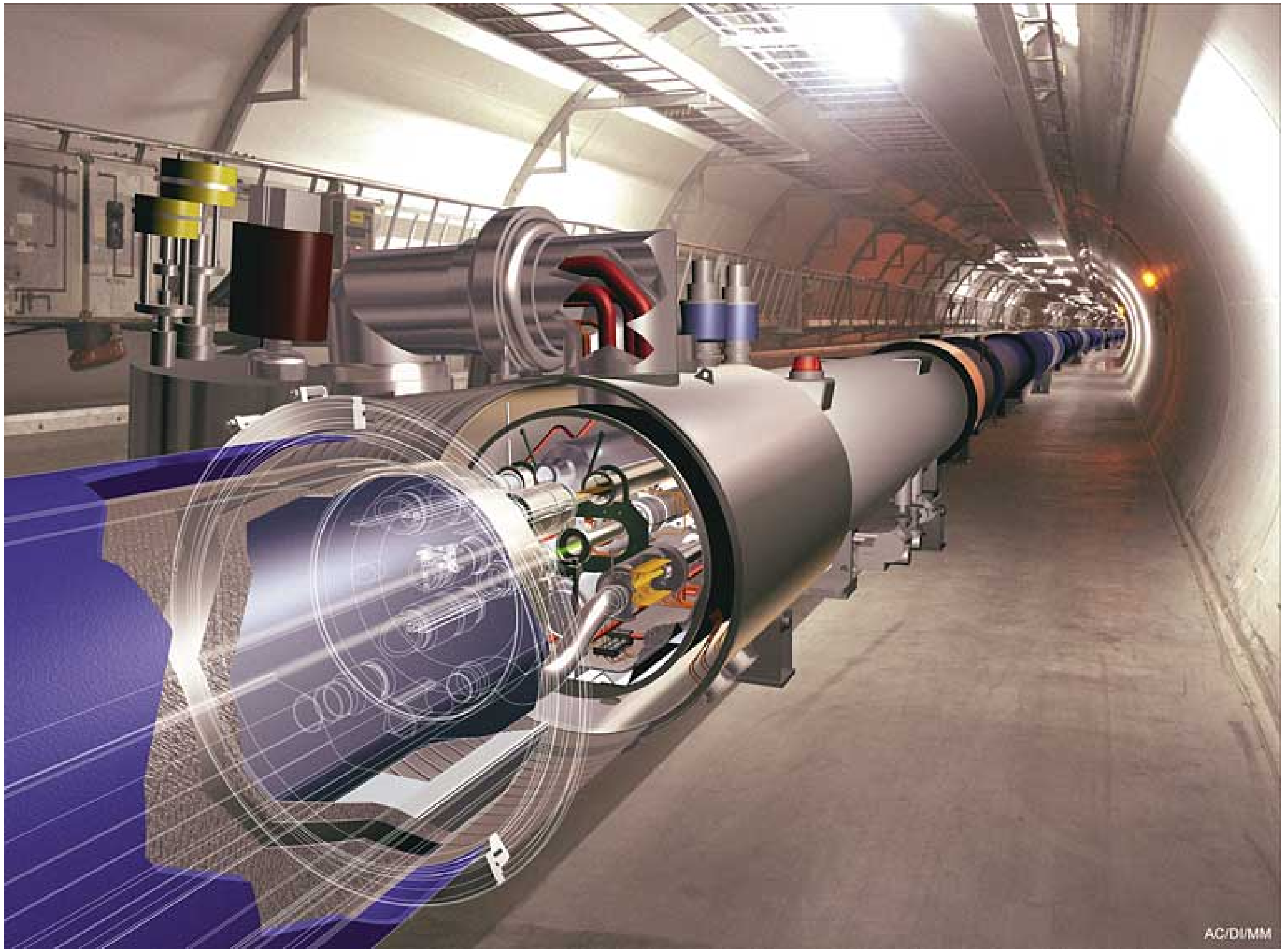
- While regenerating, the beam is OFF and the BS should be warmed up to more than 80 K and the CB held at more than 20 K (emptying cold mass)

- While the H_2 is desorbed from the cryosorbers, it is pumped by an external pumped system.

4. He leaks in cold systems.

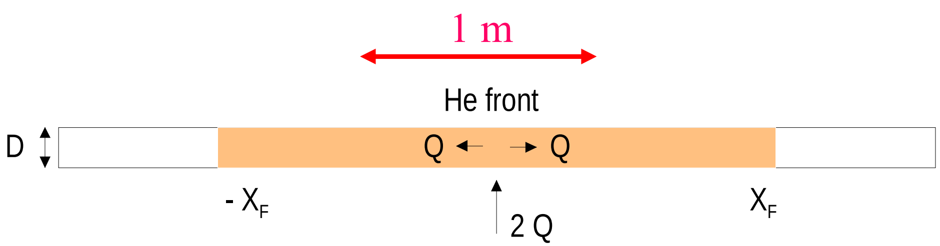
LHC beam tube case

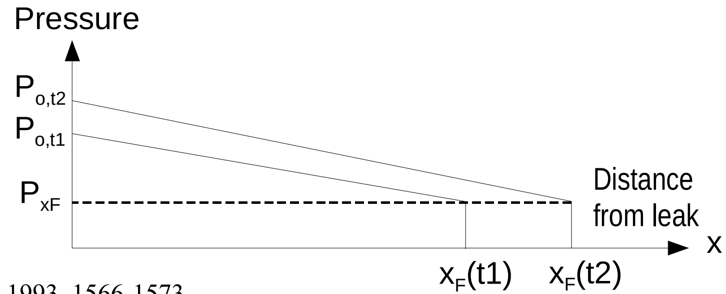
LHC : Superconducting technology



- Air leak or He leaks could appear in the beam tube during operation : the consequences are risk of magnet quench, pressure bump and radiation dose

Description of a He leak





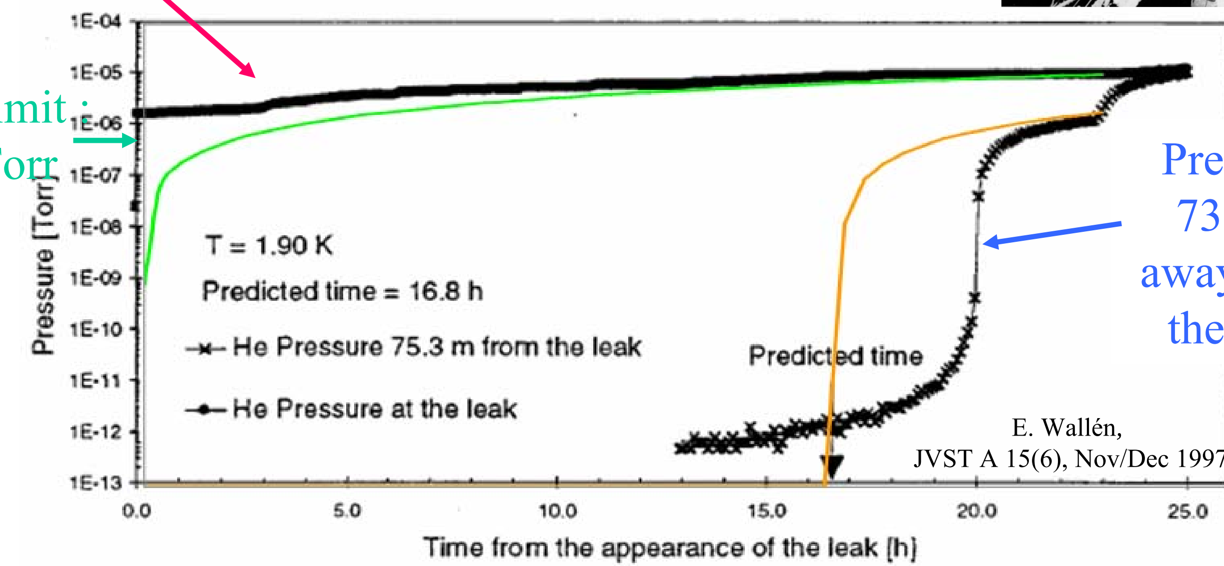
P. Hobson *et al*. J.Vac.Sci. A. 11(4), Jul/Aug 1993, 1566-1573

- A He pressure wave is developed with time along the beam vacuum chamber
- The He wave can span over several tens of meter without being detected
- The local pressure bump gives a local proton loss (risk of quench)

Example : LHC Test string
Leak rate 6 10^{-5} Torr.l/s
Distance 75.3 m

Pressure at the level of the leak

Quench limit : 4 10^{-7} Torr



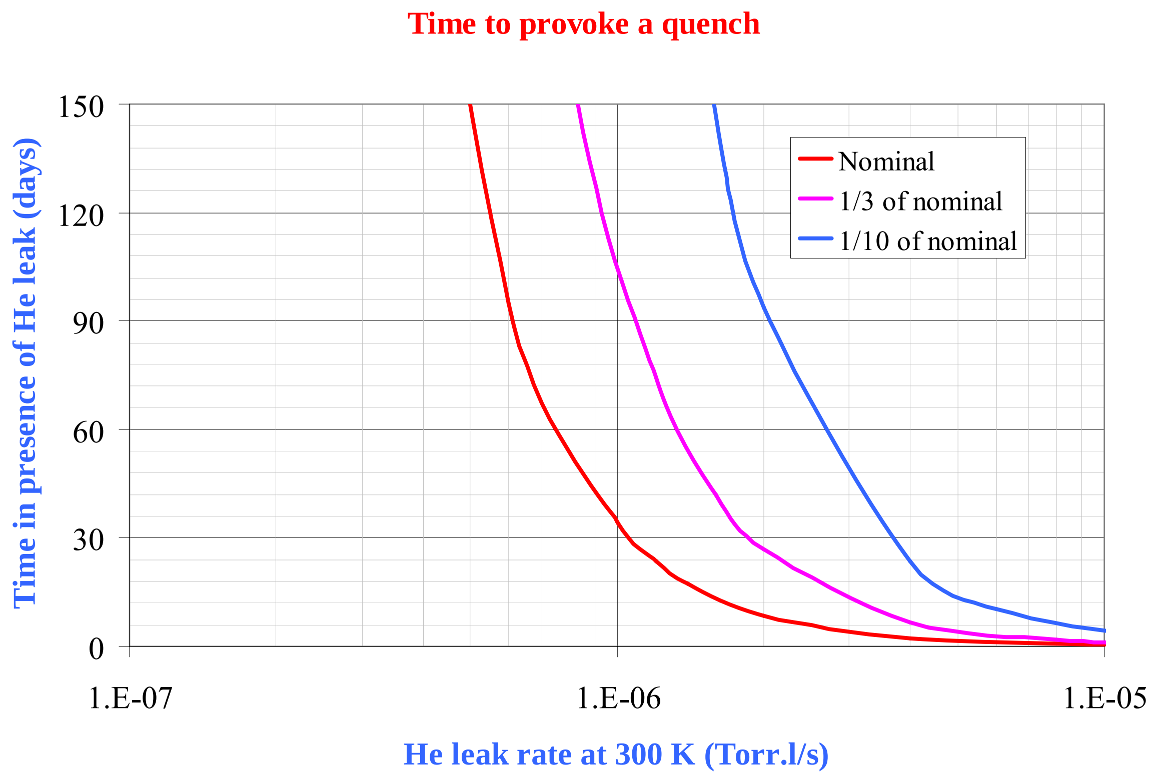
Pressure 73.5 m away from the leak

E. Wallén, JVST A 15(6), Nov/Dec 1997

He leak rate with risk of quench

- 1 year of operation ~ 150 days

Helium leak rate above $5\ 10^{-7}$ Torr.l/s shall be detected to avoid the risk of a quench



- Lower leak rate :

  Require a pumping of the beam tube on the yearly basis (cold bore >~4K)

- Larger leak rate will provoke a magnet quench within :

  30 to 100 days beam operation for He leak rate of 10^{-6} Torr.l/s

  A day of beam operation for He leak rate of 10^{-5} Torr.l/s

Vacuum gauge diagnostic

- By design, a vacuum gauge is placed every 3 or 4 cells (320-428 m) i.e. 6 to 8 gauges per arc

- Small probability to detect a He leak in the arcs

- At nominal beam current, leak rates **below** 2 10^{-7} Torr.l/s are systematically detected by the arc vacuum gauges before a quench occurs

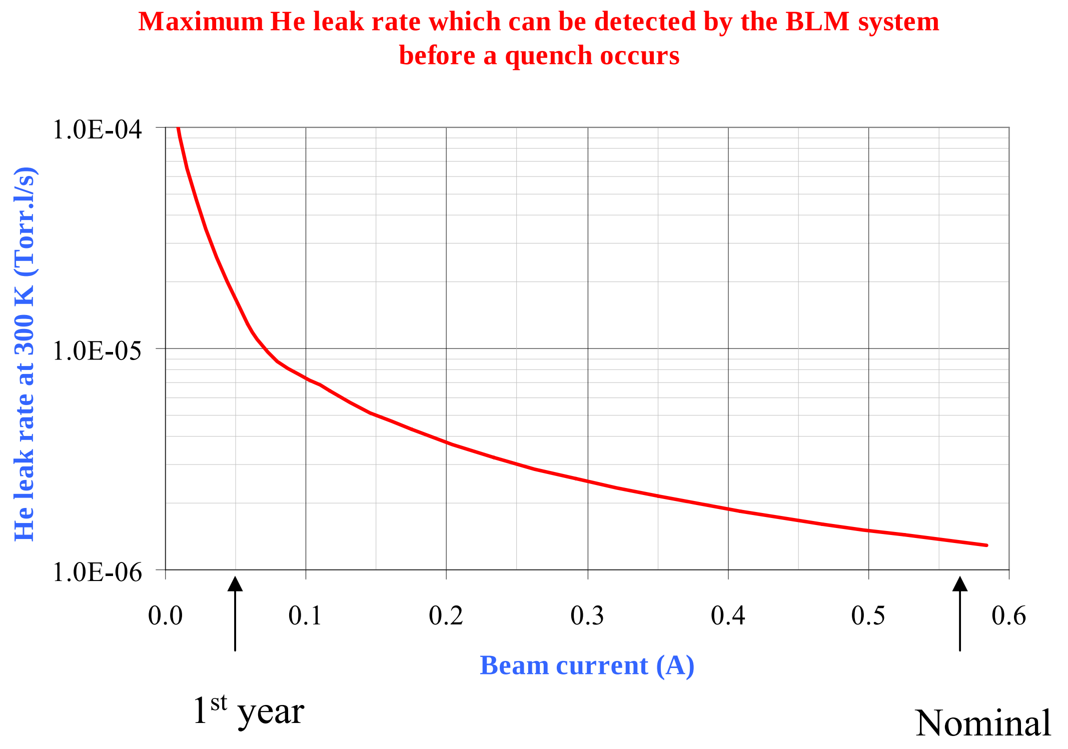
The vacuum gauges does not allow a systematic on line detection of the He leaks in the LHC arc !

- So, one needs to find other diagnostic means

Beam loss monitor based diagnostic

- BLM provide a measurement every 53 m at each arc quadrupole
- All quench due a He wave half-length larger than 26 m are detected by the BLM

At nominal beam current, leak rates below 1.3 10^{-6} Torr.l/s are systematically detected by the BLM system before a quench

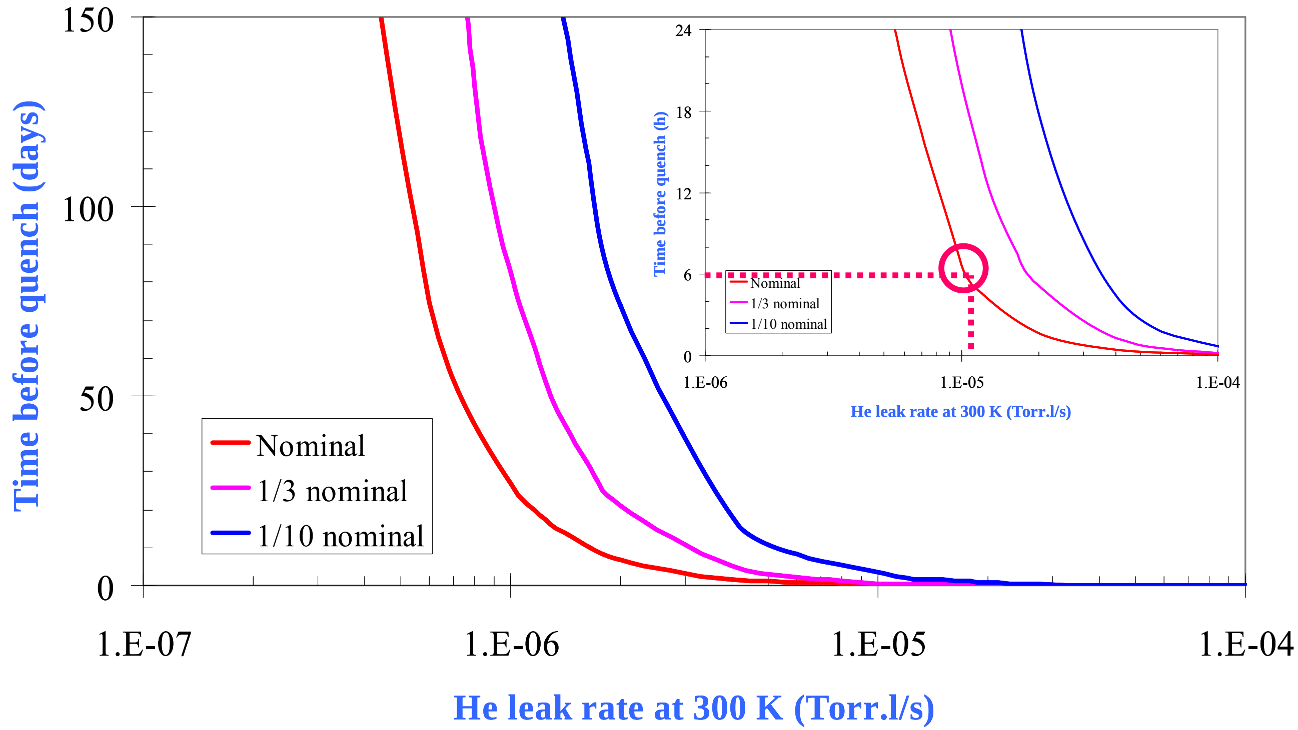


Cryogenic based diagnostic

- Per cell (102 m), a power of ~ 1 W/m can be measured in the cold masses
- Requires stable operation to integrate over a long time (~ 6h)

At nominal beam current, leak rates below 1 10^{-5} Torr.l/s are systematically detected by the cryogenic system before a quench

Remaining time, after the dissipation of 1 W/m in the cold mass, before a quench occurs



Suspected leak in a given area

(1)

- If possible, the cold mass temperature shall be temporarily increased to 4 K to move the He front towards the nearest short straight section

- Vacuum gauge or residual gas analyser can be locally installed, at this short straight section, in the tunnel for a leak detection

(2)

- Mobile radiation monitors can be installed to monitor a "radiation front" while the beam is circulating

In case of a quench

- After a quench, the faulty magnet is identified by the triggered diode.
- The cold bore is warmed up to more than 30-40 K during the quench
- The He is flushed to the nearest unquenched magnet and condensed over ~ 10 m
- The He shall be flush to the nearest SSS to perform a leak detection with a RGA

Repair

- Warm up of the cold bore to > 4 K and pump out of the He every month allows to operate with leak rates up to:
  - $2\ 10^{-6}$ Torr.l/s and 1/3 of nominal beam current
  - $4\ 10^{-6}$ Torr.l/s and 1/10 of nominal beam current
- Time estimate ~ 1 day

- Leak rates larger than $4\ 10^{-6}$ Torr.l/s require an **exchange of the magnet**

Exchange of a magnet

Time estimate ~ few weeks !

BE SURE that the OBSERVED QUENCH is due to a He LEAK at THE GIVEN MAGNET

… otherwise …

Exchange of a magnet

Lyn Evans

LHC Project Leader

BE SURE that the OBSERVED QUENCH is due to a He LEAK at THE GIVEN MAGNET

… otherwise …

The guy responsible of the magnet exchange will be …

Thank you for your attention !!!