CERN

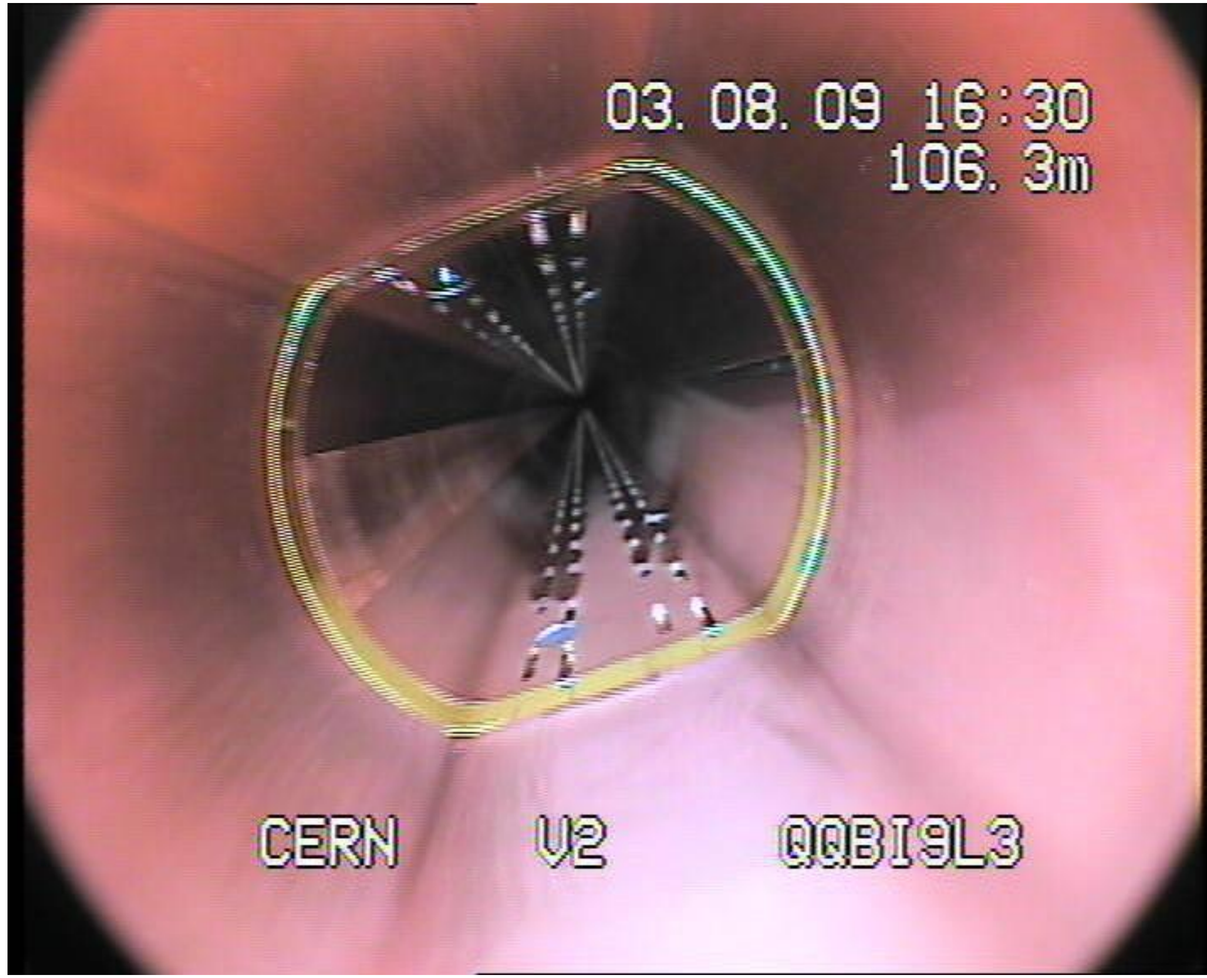
Cryopumping & Vacuum Systems

V. Baglin

CERN TE-VSC, Geneva

Cryopumping: do you wonder?

- What is this white stain?
- Why it is on the LHC beam screen?
- What is then the expected gas density in this expensive vacuum system ?
- How to avoid the growth of this stain?
- How to get rid of it?
- What will happen when the beam will circulates?



Outline

1. Elements of cryopumping
2. Adsorption isotherms
3. Cryo-vacuum systems
4. Summary

1. Elements of cryopumping

Desorption of a molecule

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

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

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

- The desorption process is characterized 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)
- See P. Chiggiato lecture

Sojourn time at cryogenic temperature

- Cryosorption occurs till ~ 100 k

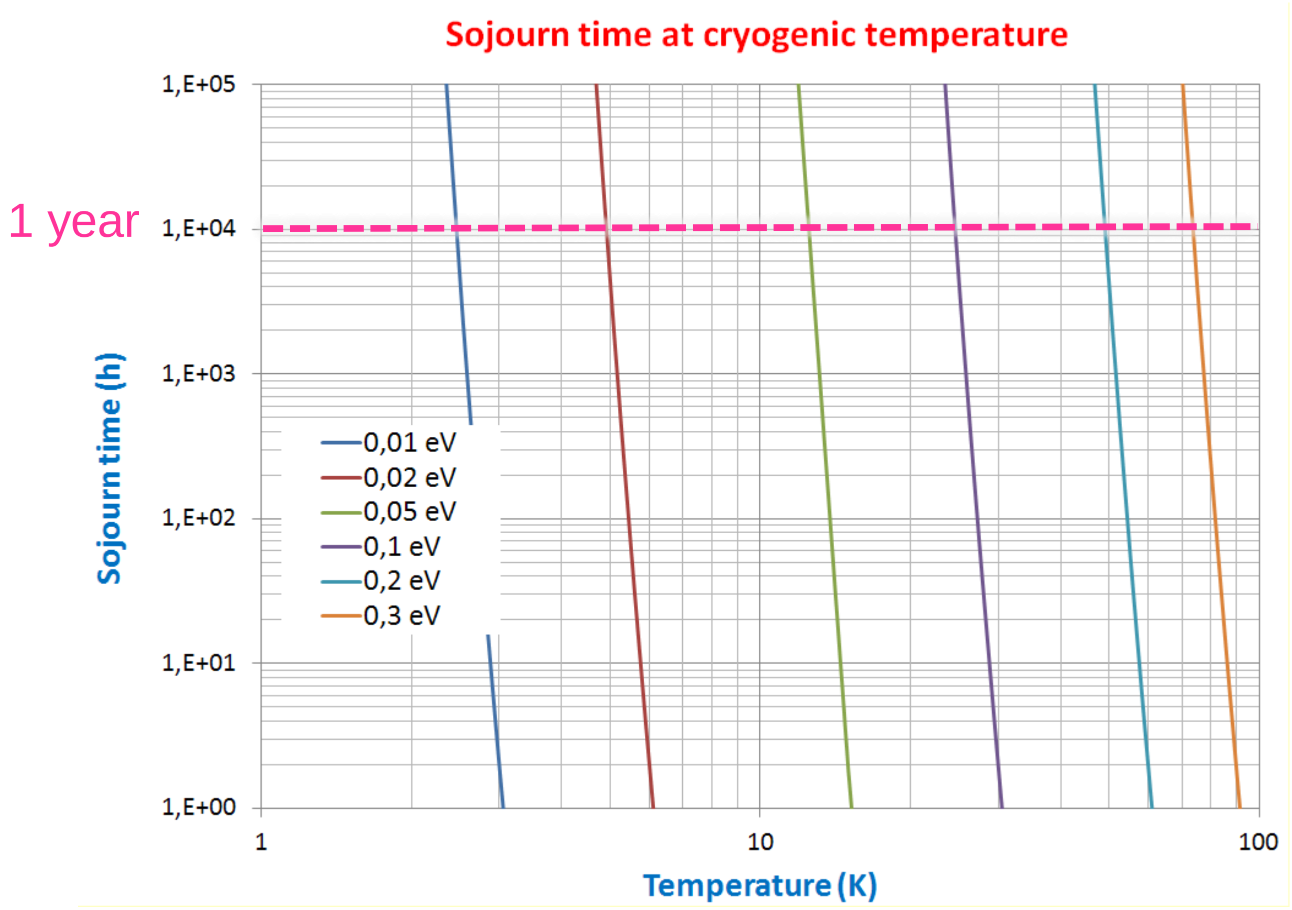
E(eV)	1.9 K	4.2 K	50 K	70 K
0.01	$1\ 10^6$ years	0.1 s	1 ps	0.5 ps
0.02	∞	$3\ 10^3$ years	10 ps	2 ps
0.15	∞	∞	130 s	6 ms
0.21	∞	∞	5 years	130 s
0.3	∞	∞	$1\ 10^4$ years	12 years

- Sojourn time given by:

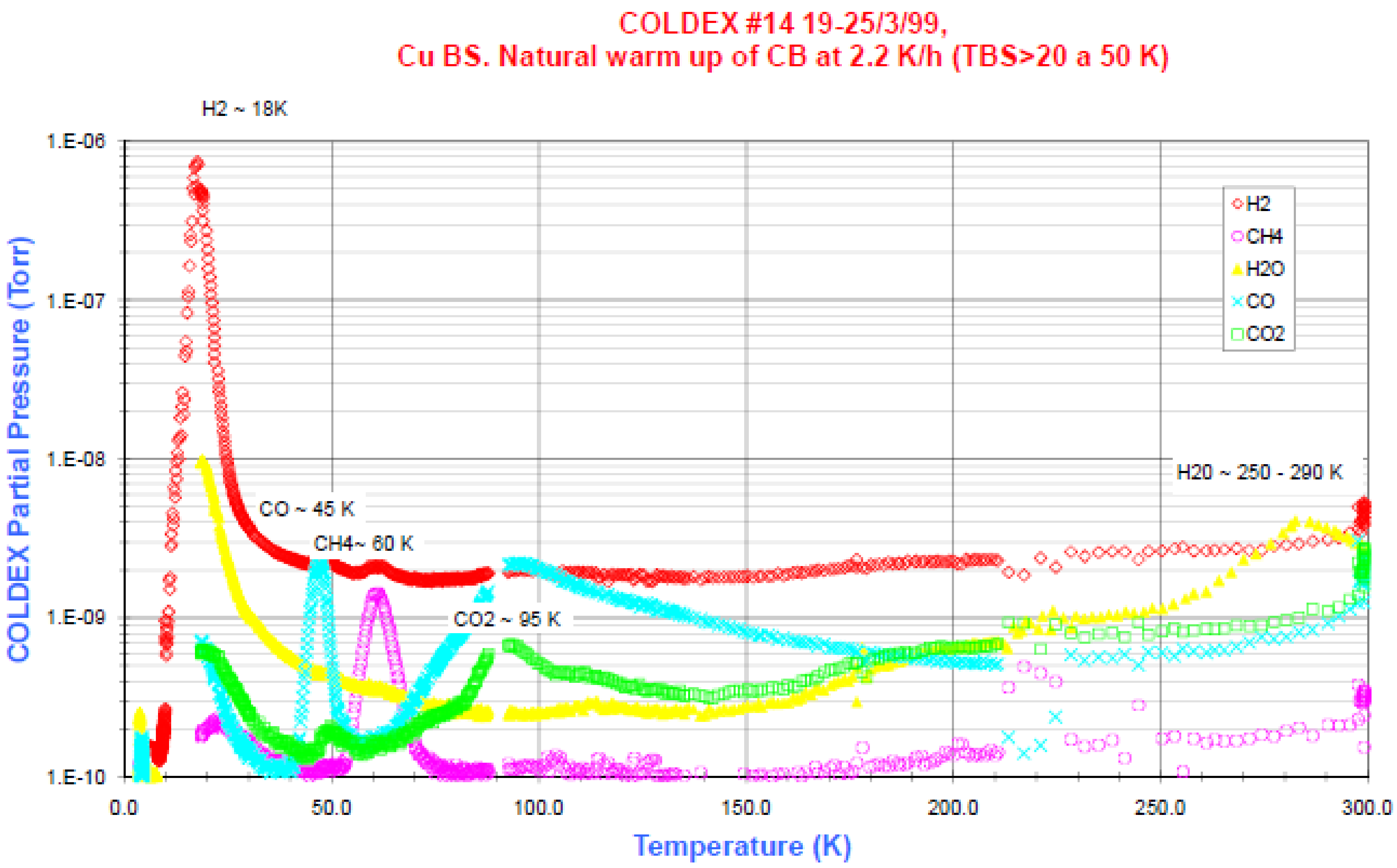
$$\tau = \frac{e^{\frac{E}{kT}}}{\nu_0}$$

Sojourn time - Physisorbed molecules

- Physisorption occurs:
  - below 20 K for binding energies < 0.1 eV
  - below 50 K for binding energies < 0.2 eV
  - below 70 K for binding energies < 0.3 eV



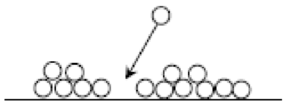
A Natural Warm Up of a St. Steel Cold Bore



Cryopumping regimes

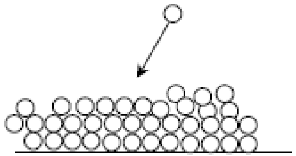
Physisorption

- 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

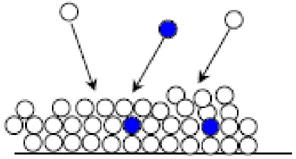
- For thick gas coverage, only forces between gas molecules
- Energy of vaporisation 9 to 175 meV for H_2 and CO_2 resp.
- 1 h sojourn time at 2.8 K and 53.4 K for H_2 and CO_2 resp.



➔ 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 a high vapor pressure gas (*e.g.* He, H_2)



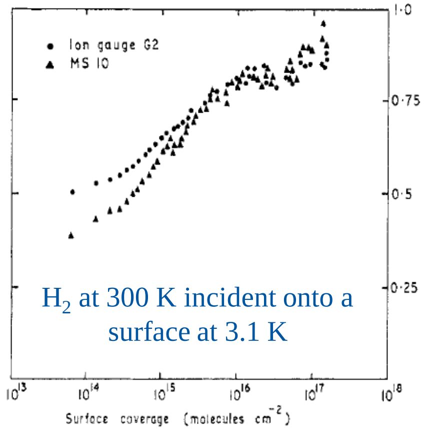
Sticking probability/coefficient

- Probability : $0 < \sigma < 1$

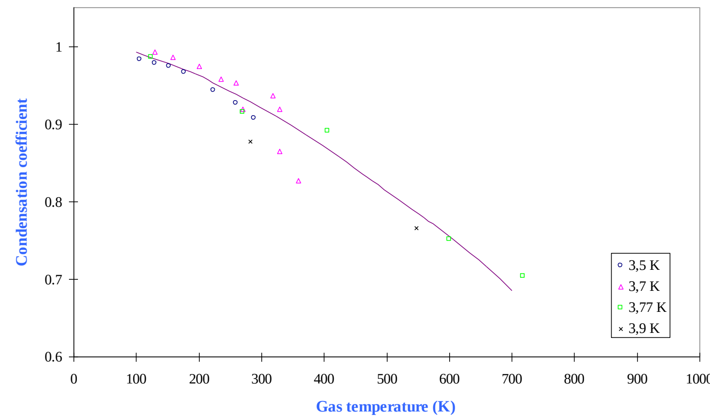
  ν collision rate (molecules.s^{-1}.cm^{-2})

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

- 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}

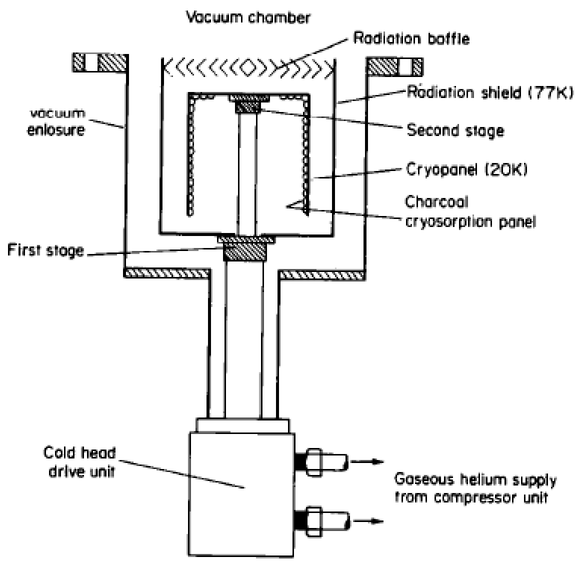
  S_{CO} = 1.4 l.s^{-1}.cm^{-2}

Capture factor, C_f

- The capture factor takes into account the geometry (conductance) of the system :

$$C_f = \frac{C\sigma}{C+\sigma}$$

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

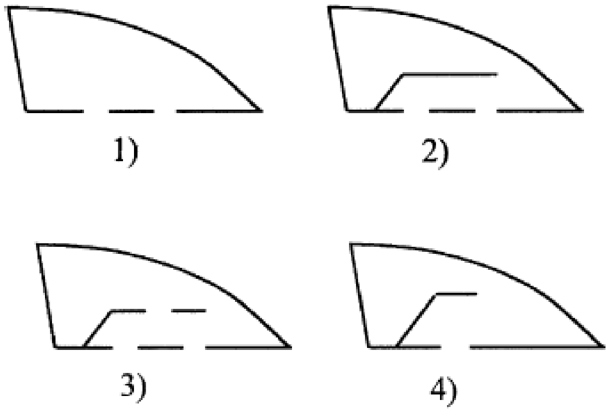


Fig. (1) Two slots in the beam screen, without electron shield, (2) two slots in the beam screen, electron shield without slot, (3) two slots in the beam screen, electron shield with slot, (4) only one slot in the beam screen, electron shield without slot.

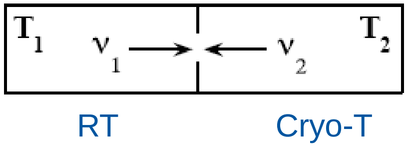
σ	1	2	3	4
0.1	0.48	0.26	0.39	0.43
1	0.68	0.36	0.51	0.57

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

- See R. Kersevan lecture for angular coefficient method

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



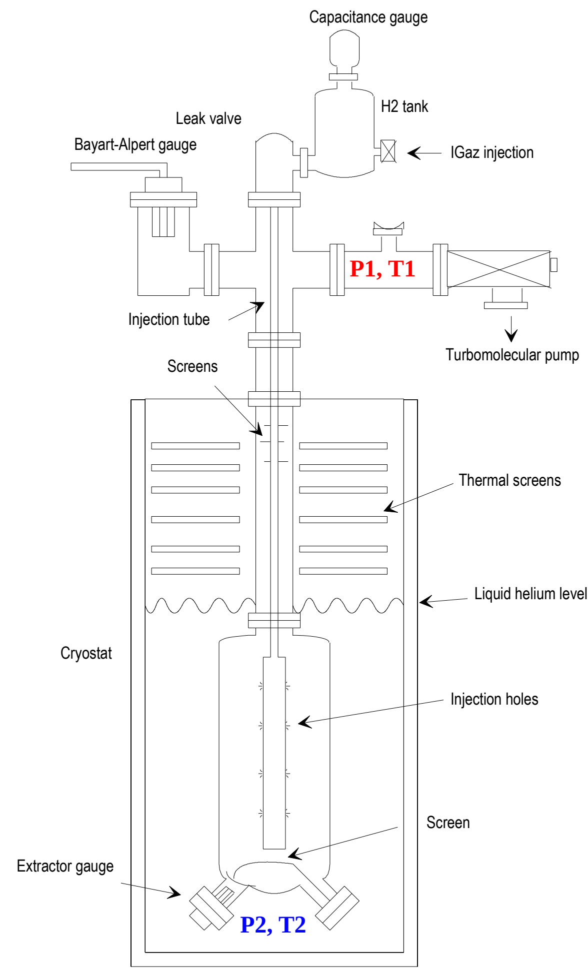
$$\nu = \frac{1}{4} n \bar{v}$$

- Since the average velocity scales like √T

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

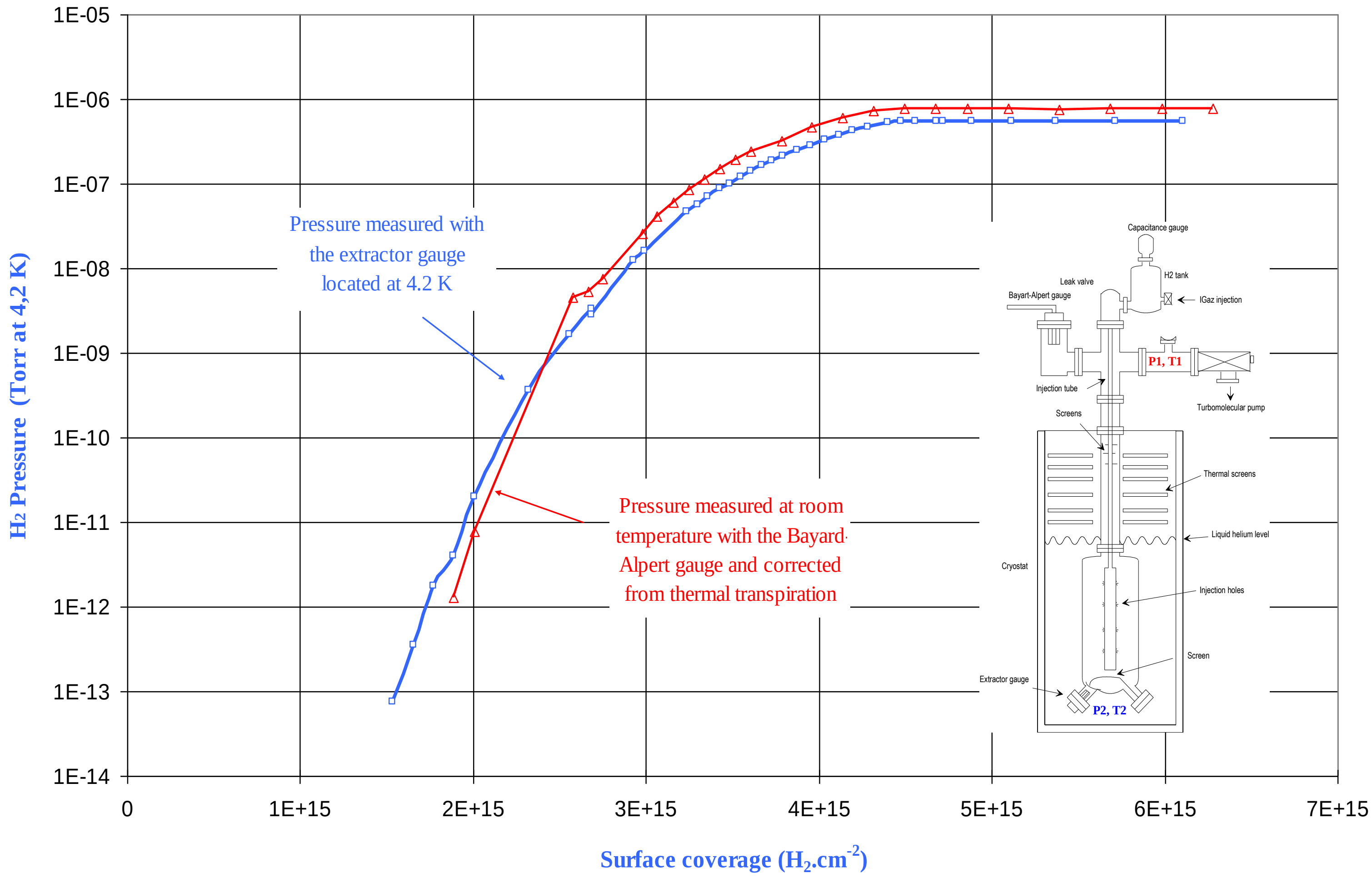
$$\frac{n_1}{n_2} = \sqrt{\frac{T_2}{T_1}}$$

T (K)	4.2	77
P_1/P_2	8	2



➔ Since the beam interacts with molecules, use gas densities rather than pressure to avoid mistakes in thermal transpiration corrections!

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

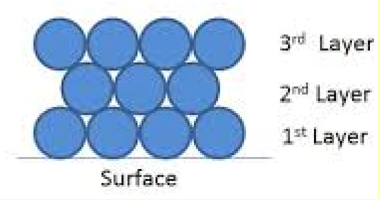
$$\theta = c\,P$$

  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

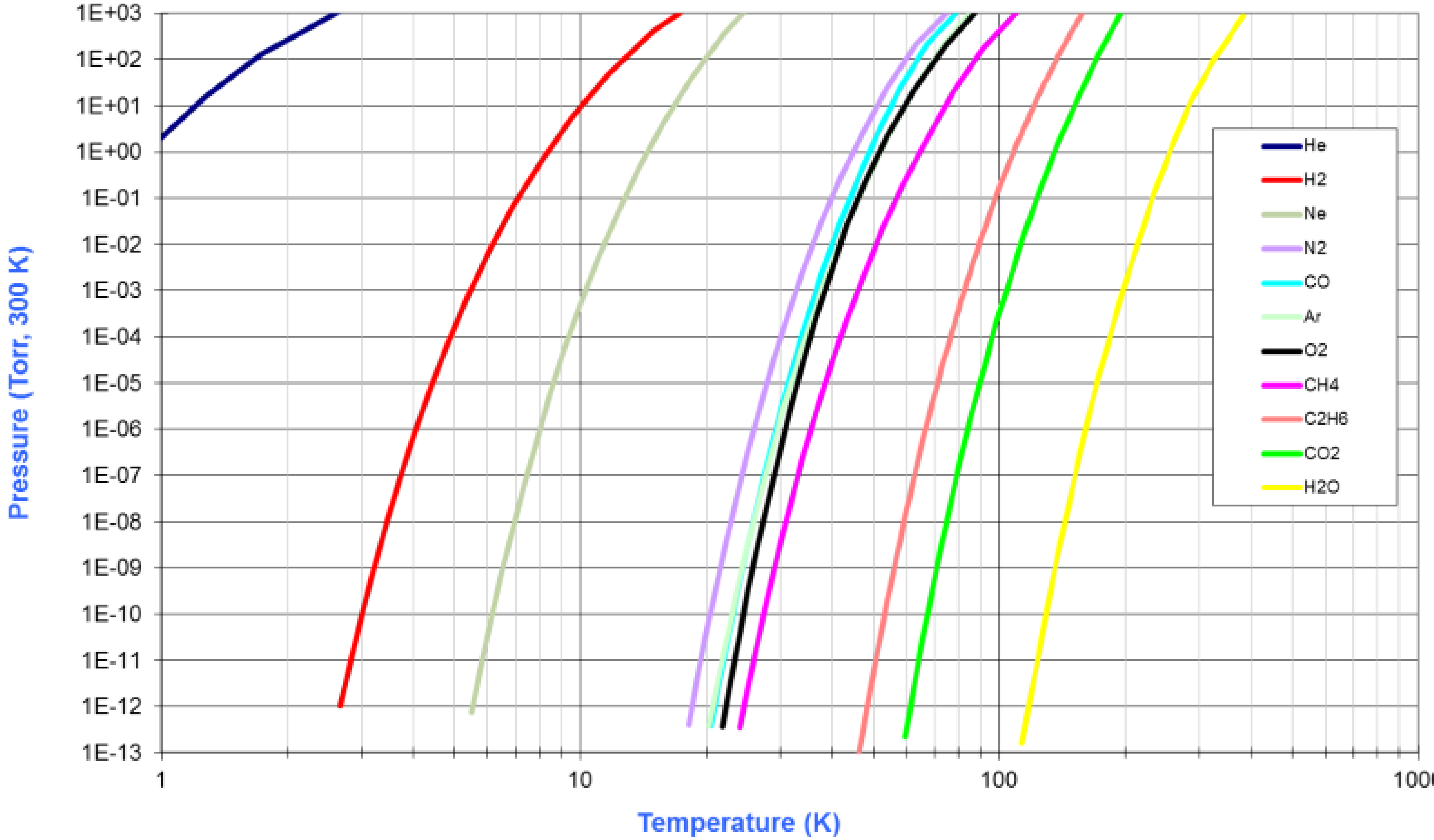
$$\frac{P}{\theta\,(P - P_{Sat})} = \frac{1}{\alpha\,\theta_m} + \frac{(\alpha - 1)}{\alpha\,\theta_m}\,\frac{P}{P_{Sat}}$$



Saturated Vapor Pressure

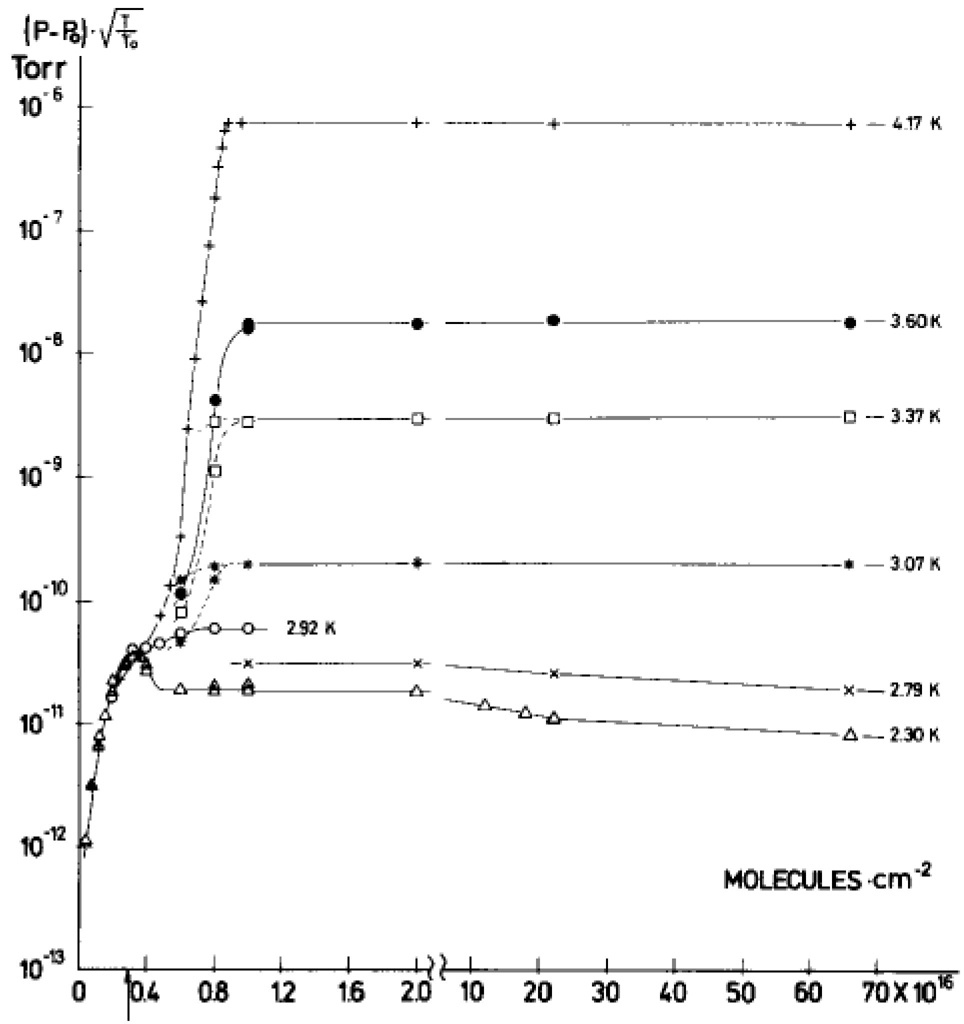
- Pressure over liquid or gas phase (many monolayers condensed)
- Follows the Clausius-Clapeyron equation: $\text{Log } P_{sat} = A - B/T$

Saturated vapour pressure from Honig and Hook (1960) (C2H6 Thibault *et al.*)



H_2 Adsorption Isotherm on Stainless Steel

- The vapor pressure increases when increasing the adsorption of gas up to a few monolayers (~ 10^{15} molecules/cm^2)
- The vapor pressure saturates when several monolayers of gas are adsorbed
- The pressure level of the saturation is a function of the temperature (Clausius-Clapeyron)



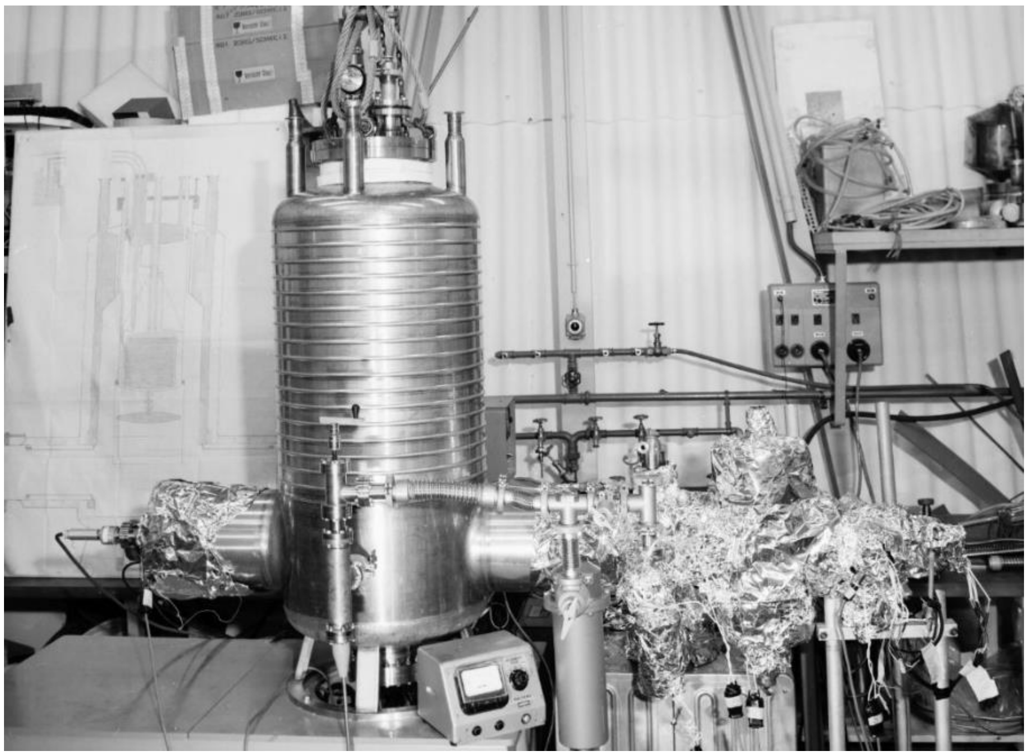
A monolayer

C. Benvenuti, R. Calder, G. Passardi
J.Vac.Sci. 13(6), Nov/Dec 1976, 1172-1182

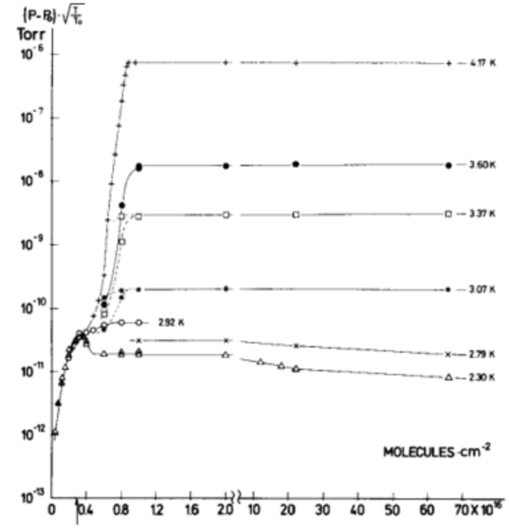
H_2 adsorption isotherm on stainless steel

- The condensation cryopumps allows to pump large quantities of H_2

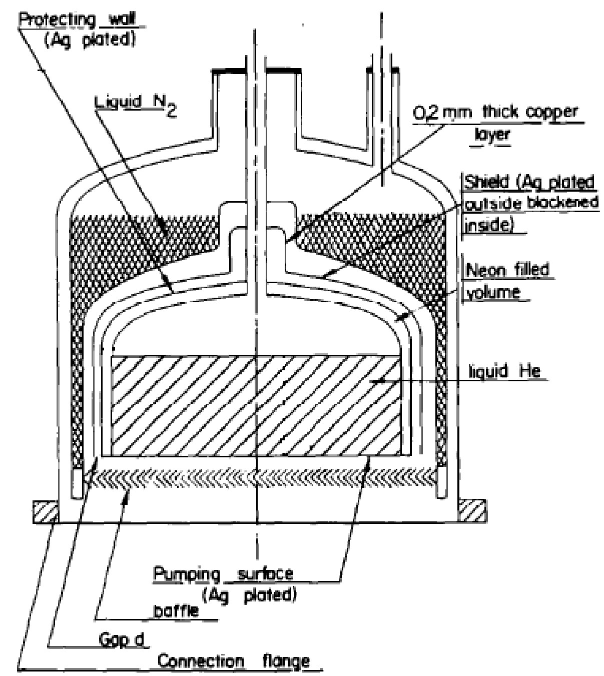
- CERN ISR condensation cryopump operated with liquid He at 2.3 K (50 Torr on the He bath)



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

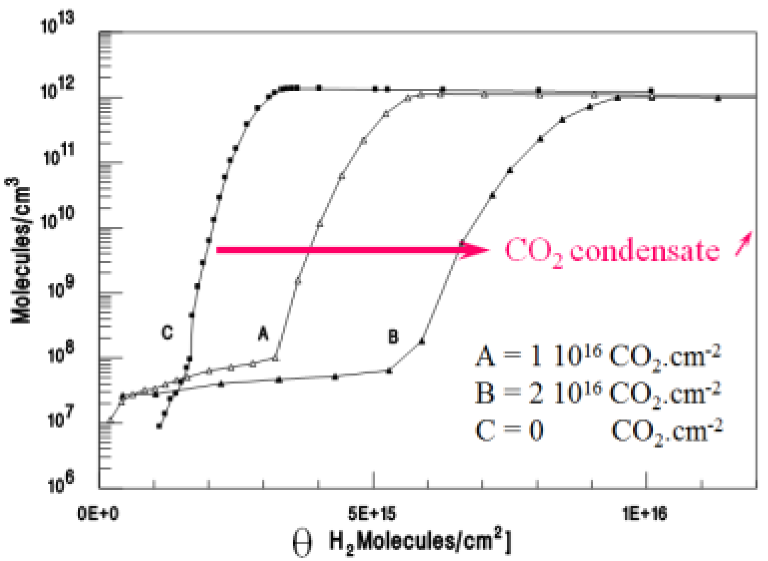


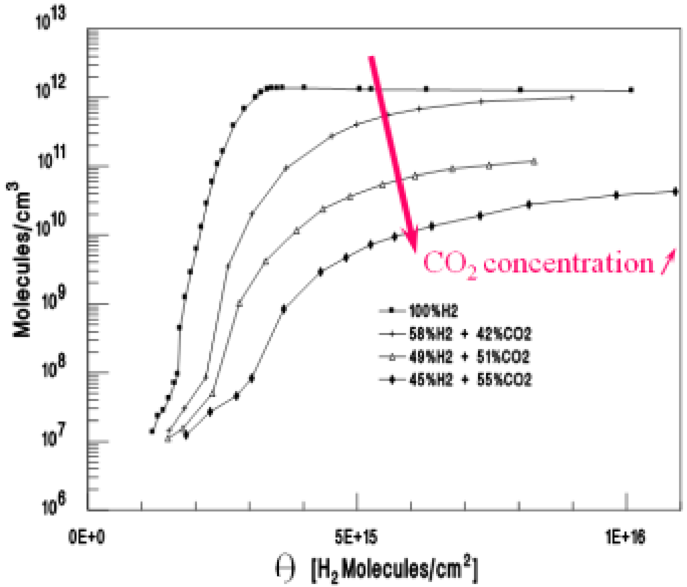
A monolayer



Vapor Pressure in a Machine

- Several types of molecules are present in machine vacuum systems
- The adsorption isotherm is affected by the presence of these molecules
- Condensed CO_2 forms a porous layer increasing the hydrogen capacity (here 0.3 H_2/CO_2)
- Co-adsorption of CH_4, CO and CO_2 reduce the vapor pressure of H_2 by cryotrapping





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

➔ Studies in real machine environments are mandatory

H_2 adsorption isotherms from 8 to 20 K

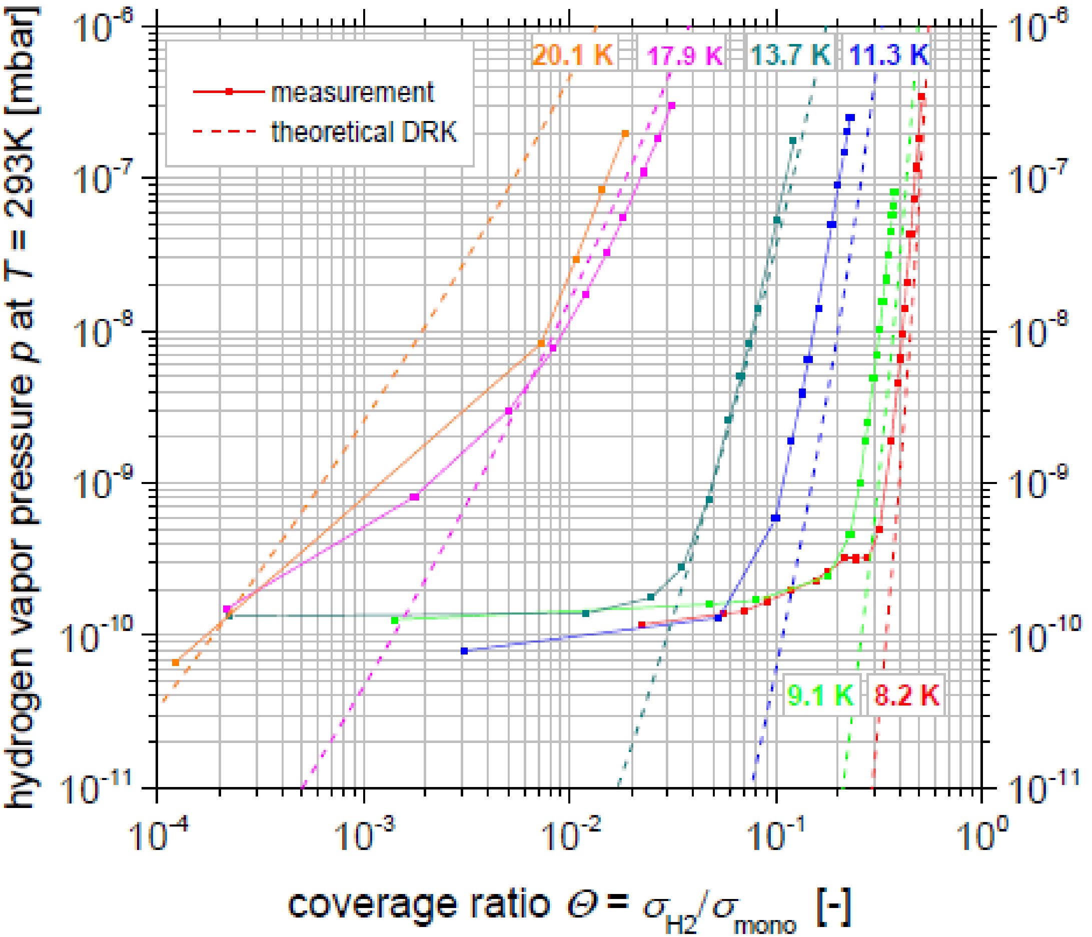
- The surface capacity strongly decreases when increasing the surface temperature

- Stainless steel

- DRK description

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

- D = 3125 eV^{-2}
- $\Theta_m = 7\ 10^{14}\ H_2/cm^2$



F. Chill *et al.* PAC'2015, Richmond, USA, 2015.

CO_2 adsorption Isotherm at 77 K

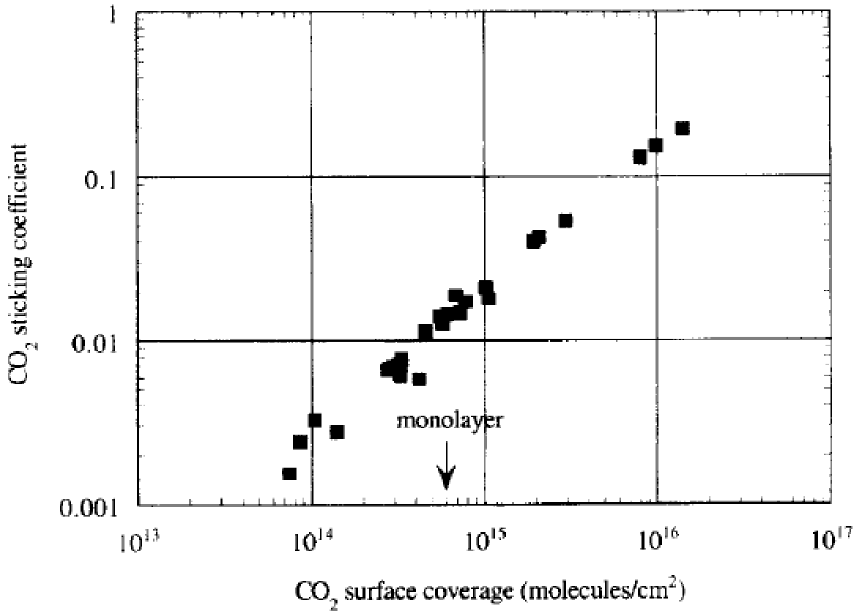


Figure 2. The sticking coefficient for CO_2 at 77 K as a function of the surface coverage.

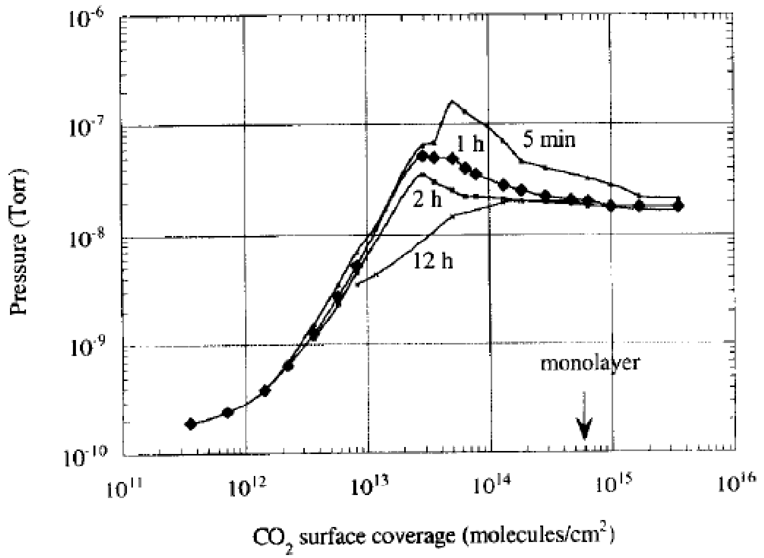


Figure 3. Adsorption isotherm for CO_2 at 77 K as a function of surface coverage. The curves refer to measurements for different waiting times for pressure stabilisation.

V.V Anashin et al, Vacuum 48 (1997) 785-788

- Metallic surface
- Below a monolayer, the equilibrium pressure of the isotherm is obtained after several hours
- Due to the low sticking coefficient and the molecular adsorption by cluster.

H_2 Isotherms for Industrial Surfaces

- Identification of two categories of adsorption sites:

    1) low energy (flat surface).

    2) high energy (pores, defects).

Table 1
Hydrogen adsorption capacity at 4.2 K

	Molecules/cm² at saturation: σ_m	Molecules/cm² at P_{sat} (10^{-6} Torr): σ_{sat}	Ratio σ_{sat}/σ_m
Smooth surfaces			
Copper film unbaked	6.07×10^{15}	1.49×10^{16}	2.45
Electrochemical buffed stainless-steel unbaked	2.36×10^{15}	4.08×10^{15}	1.73
Electrochemical buffed stainless-steel baked	2.68×10^{15}	5.22×10^{15}	1.95
TiZrV film	3.05×10^{15}	6.02×10^{15}	1.97
Porous surfaces			
Al anodised unbaked (USA)	1.23×10^{17}	—	—
Al anodised baked (USA)	1.80×10^{17}	—	—
Al anodised (KEK)	8.1×10^{16}	1.18×10^{17}	1.46

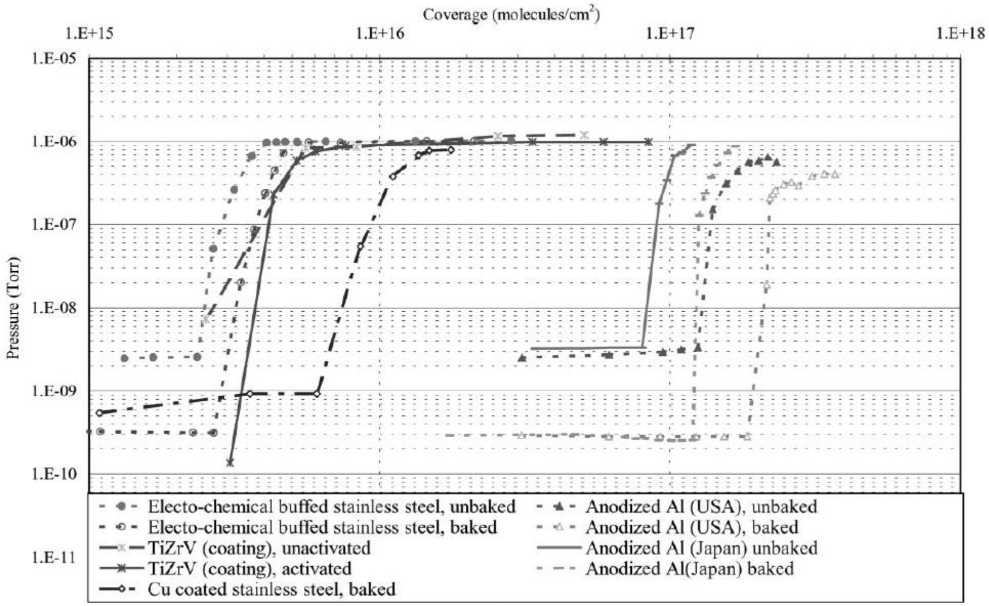
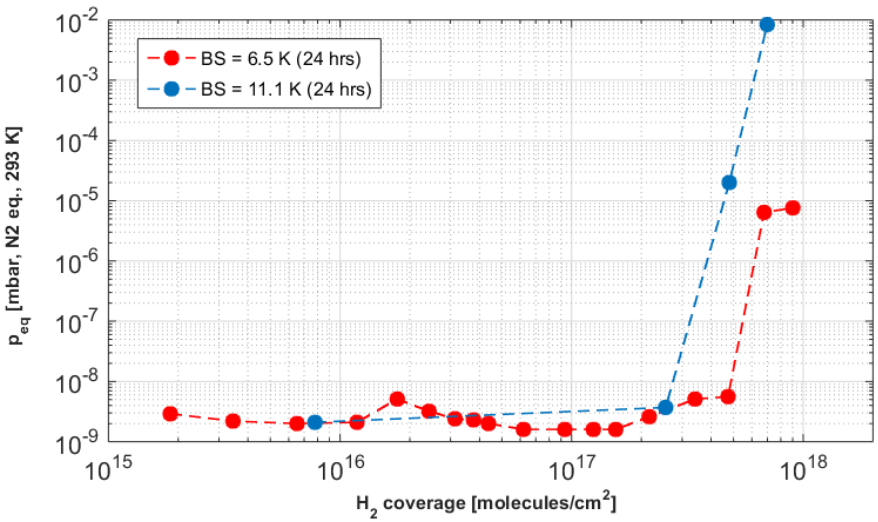


Fig. 3. Hydrogen adsorption isotherm at 4.2 K for various samples.

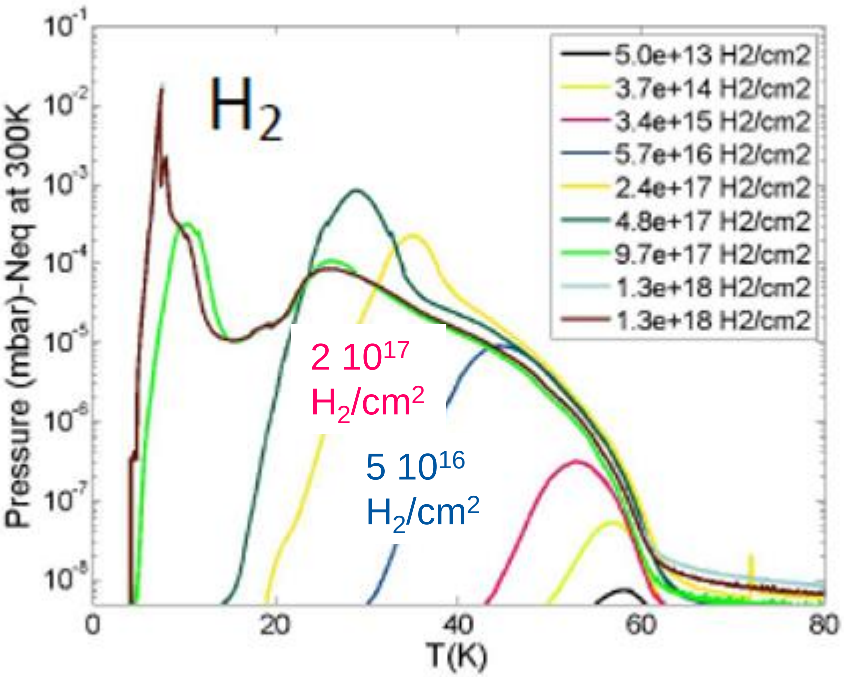
G. Moulard, B. Jenniger, Y. Saito, Vacuum 60 (2001) 43-60

Temperature Programmed Desorption

- aC coating are "porous" for electrons (anti-multipacting surface) and also for molecules:
  ➔ Roughness ~ x 100 Cu as shown by the adsorption isotherm



Courtesy R. Salemme, A-L. Lamure



- Temperature Programed Desorption (TPD) shows that the binding energies decrease when increasing the surface coverage from 0.2 to 0.01 eV (at about 20 K, the H_2 vaporisation / sublimation heat ~ 10 meV)

- When all the available sites of the coating are occupied *i.e.* above "one monolayer" (~ 10^{17} H_2/cm^2), the shape of the TPD spectra change.

B.E.T surface area – Roughness factor

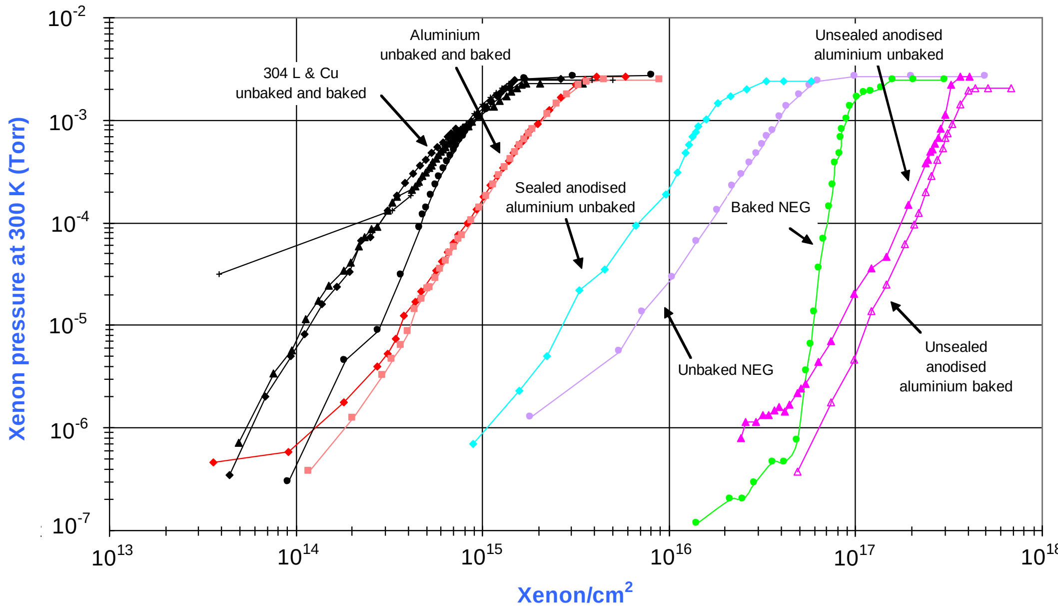
- Xe is an inert gas which can only be physisorbed on a surface
- Xe adsorption isotherms at 77 K are used to derive the roughness factor of surface using the BET multi-monolayer theory

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

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

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

A for Xenon ~ 25 Å^2



Technical surface	Unbaked	Baked at 150 °C
Copper Cu-DHP acid etched	1,4	1,9
Stainless steel 304 L vacuum fired	1,3	1,5 (at 300 °C)
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

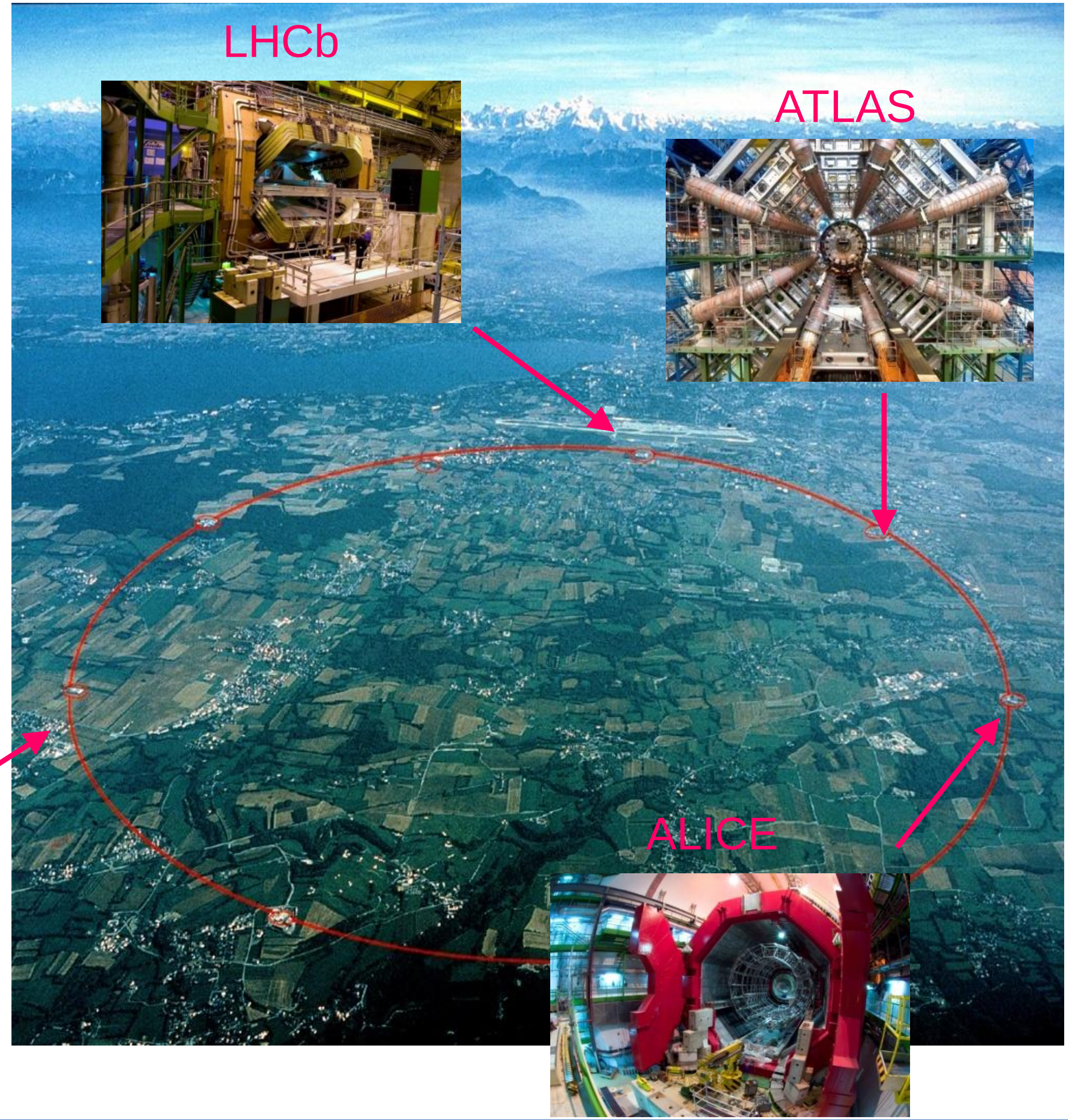
V. Baglin. CERN Vacuum Technical Note 1997

3. Cryo-vacuum Systems

A. Cryosorbers

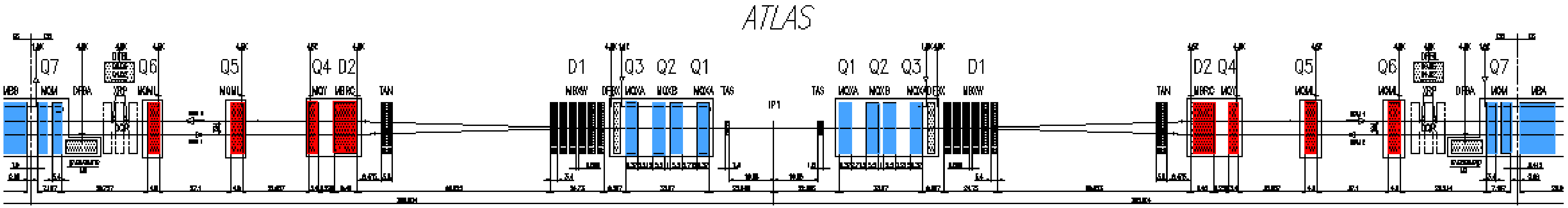
The CERN Large Hadron Collider (LHC)

- 26.7 km circumference
- 8 arcs of 2.8 km
- 8 long straight sections of 575 m
- 4 experiments
- 7 TeV / beam
- 90% of the machine is held at cryogenic temperature: 1.9-20K



CMS

LHC Long straight section vacuum system



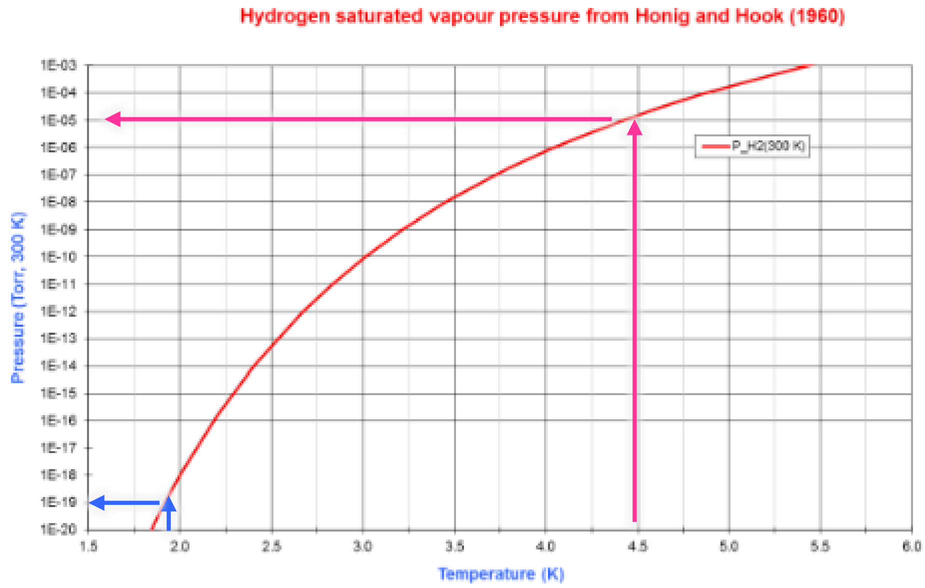
- Focusing inner triplets located around experiments operate at 1.9 K
- Matching sections operate at 4.5 K

} Perforated beam screens

- 1.9 K cold bore (~660 m, arc beam screen technology) – H_2 SVP = 10^{-19} mbar
- ~ 4.5 K cold bore (~ 740 m)

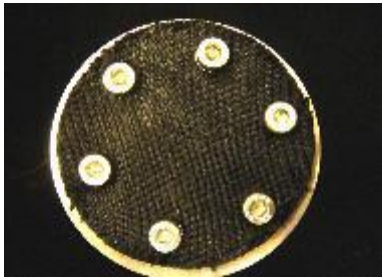
With a 4.5 K Cold Bore

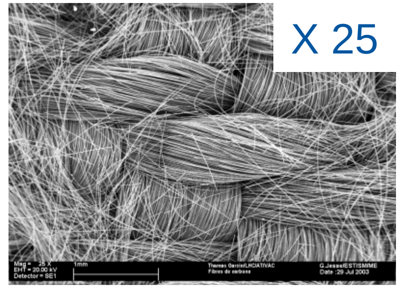
- Saturated vapour pressure equals 2 10^{-5} mbar
- Cryosorbers are needed to provide a porous surface
- Required performances:
  - Operates from 5 to 20 K, 200 cm^2/m
  - Capacity larger than 10^{18} H_2/cm^2
  - Capture coefficient larger than 15 %

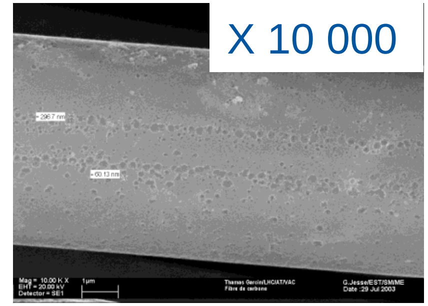


Cryosorbers performance with H_2

- Woven carbon fibers are used in LHC as cryosorbers in 4.5 K magnets
- Beam screen operates in the 5-20 K range



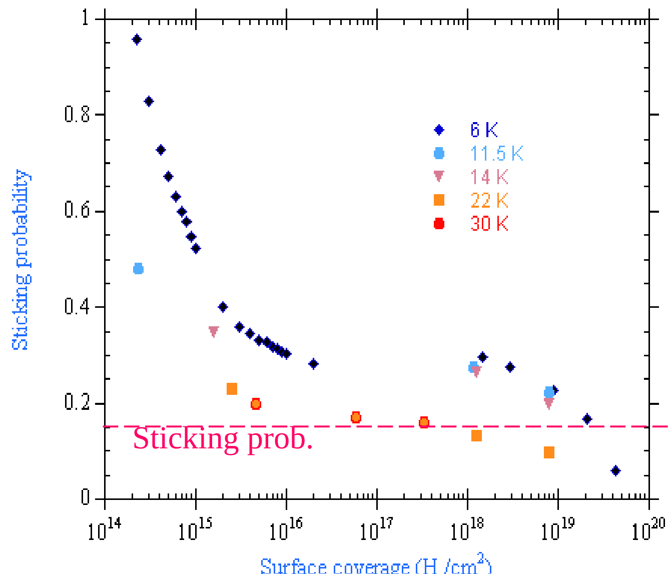


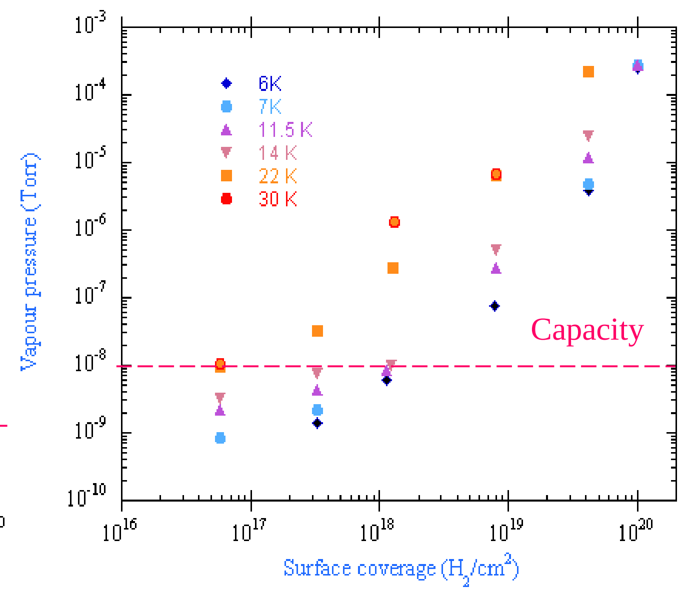


V. Anashin *et al.* Vacuum 75 (2004) 293-299

- Sticking probability at 10^{18} H_2/cm^2 :
  - 15 % at 22 K
  - > 15 % below 22 K
- Capacity at 10^{-8} mbar :
  - 10^{18} H_2/cm^2 at 6 K
  - 10^{17} H_2/cm^2 at 30 K

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

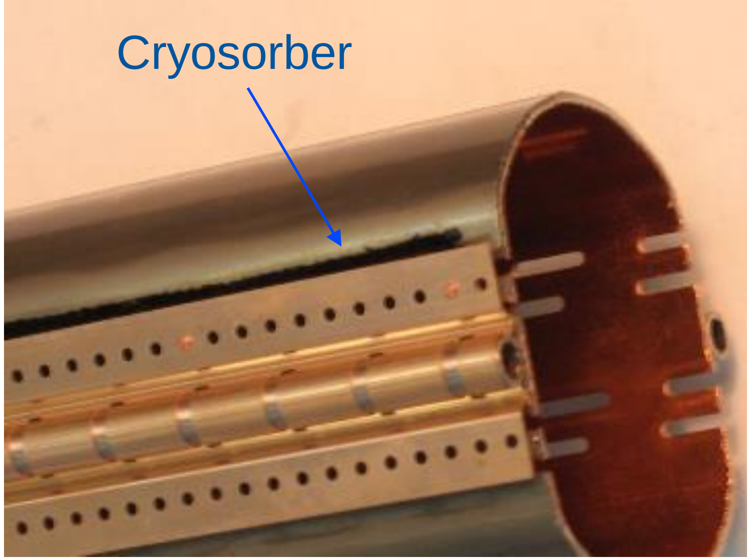


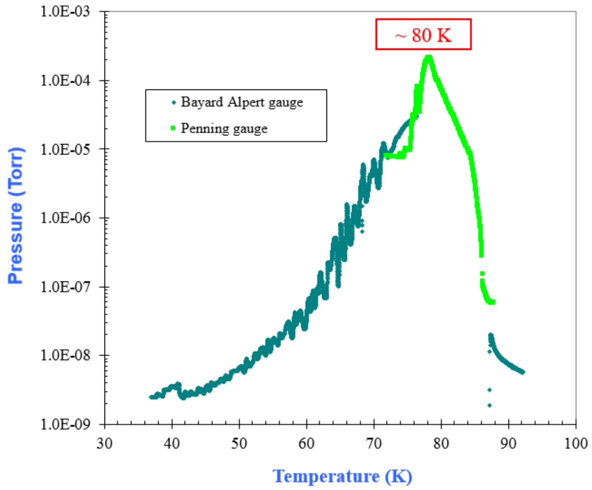


V. Baglin *et al.* EPAC'04, Luzern 2004.

Operation of cryosorbers in LHC

- 200 cm^2/m of cryosorbers are installed on the electron shield clamped on the back of the beam screen on the cooling capillary.
- The cryosorbers require a regeneration during the shutdown for removing the H_2
- The cryosorber is regenerated at ~ 80 K (activation energy = 236 meV)
- 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 liberated from the cryosorbers, it is pumped by an external pumping system.

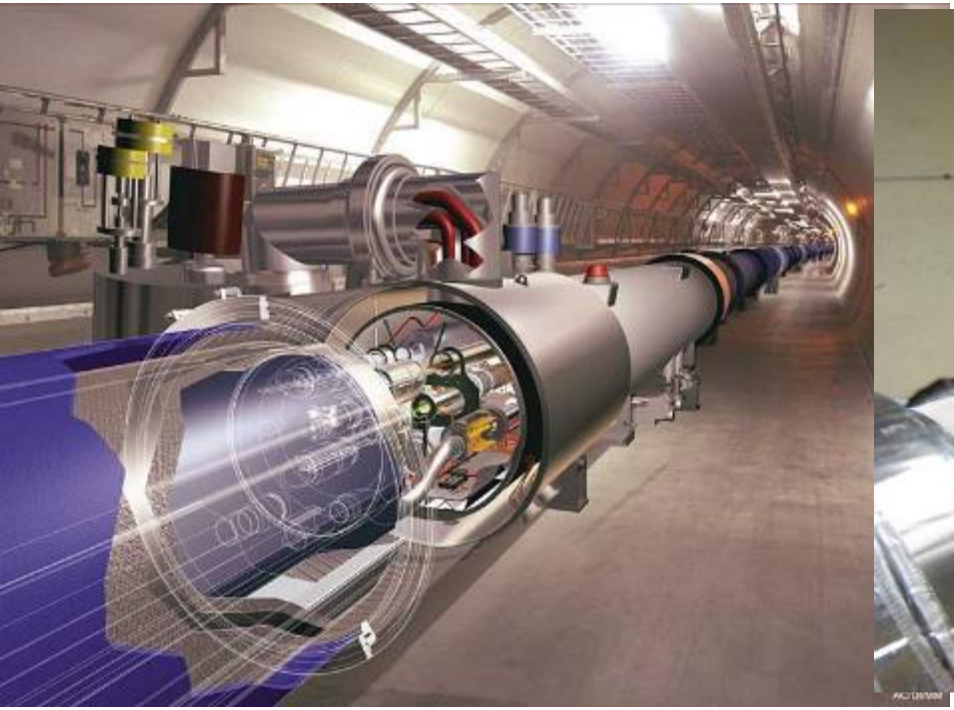


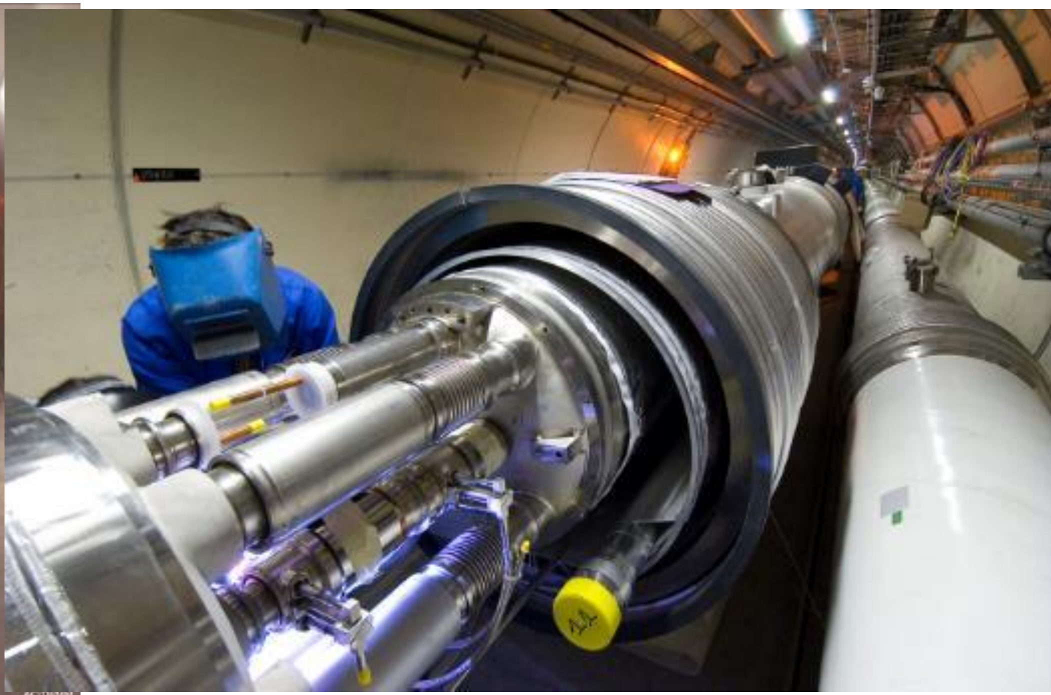


V. Baglin *et al.* EPAC'04, Luzern 2004.

B. He Leaks in Cryogenic Beam Pipes

LHC : Superconducting technology

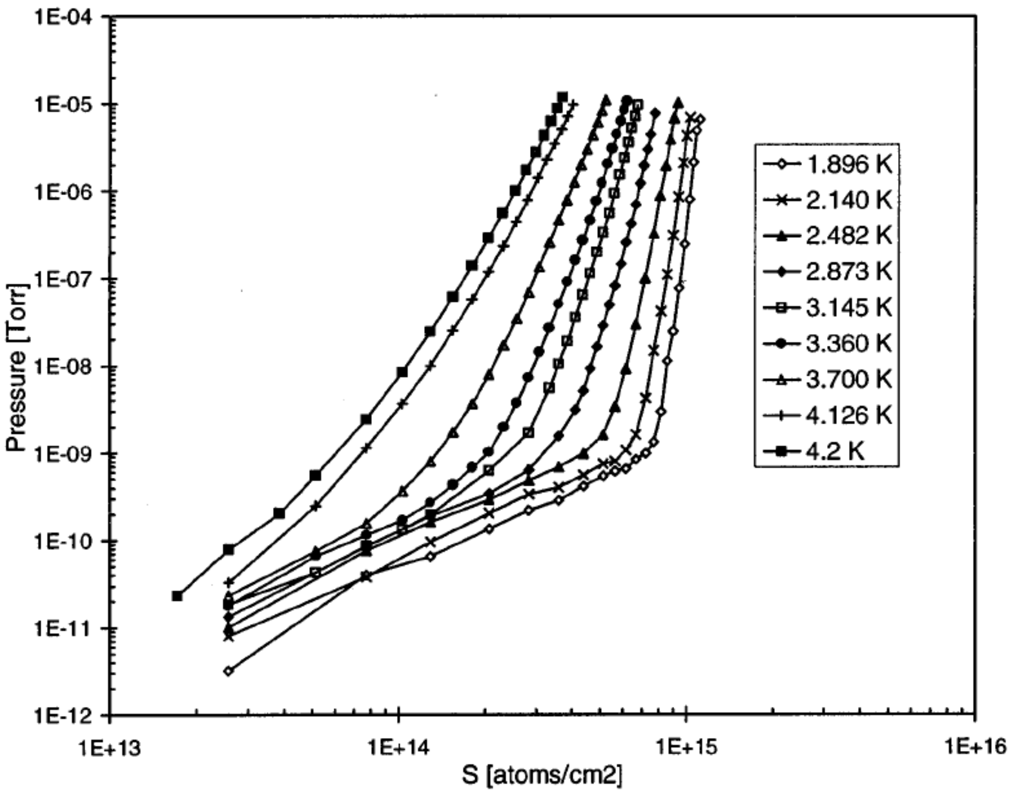




• Air leak or He leaks could appear in the beam tube during operation :
the consequences are risk of magnet quench, pressure bump and radiation dose

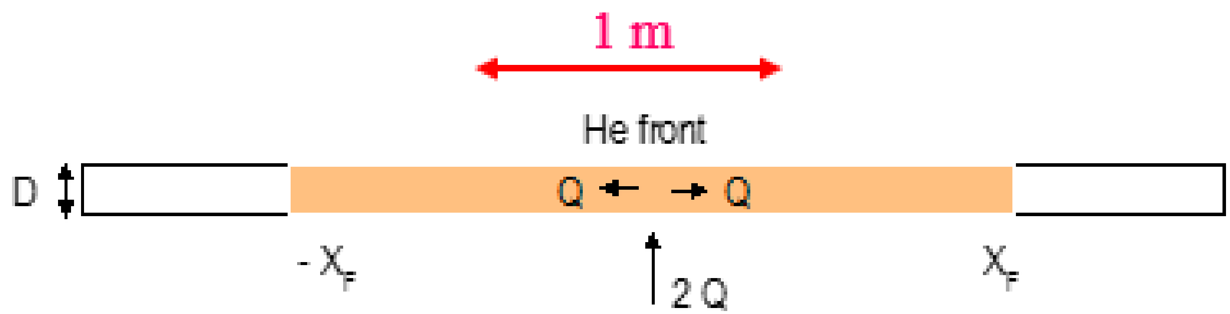
He adsorption isotherm from 1.9 to 4.2 K

- Sub-monolayer range
- Approaches Henry's law at low coverage
- The isotherms are well described by the DRK model
- $\theta_m \sim 1.3\ 10^{15}\ H_2/cm2$
- Stainless steel

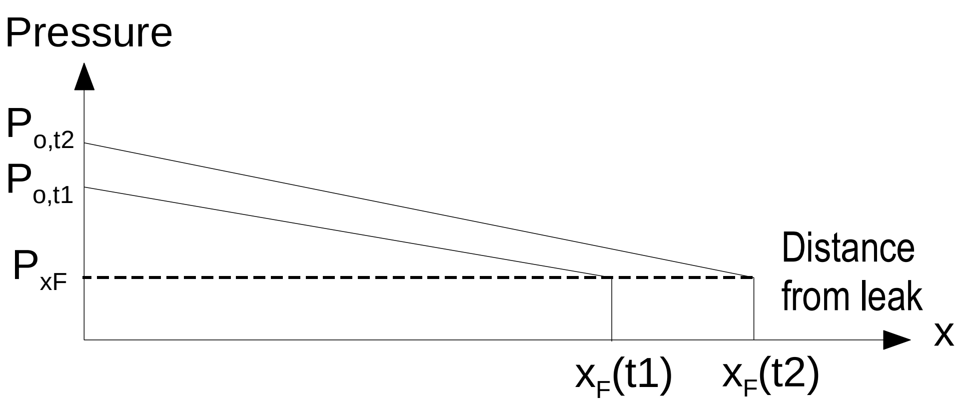


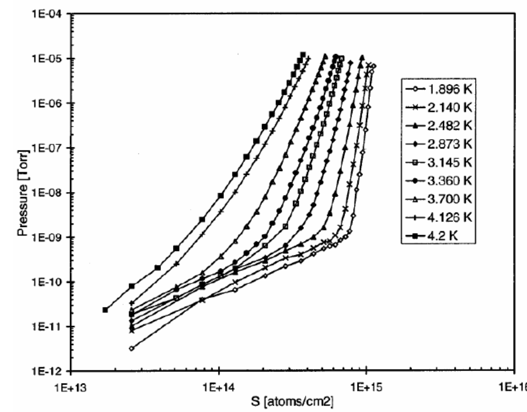
E. Wallén. J.Vac.Sci.A 15(2), Mar/Apr 1997, 265-274.

He leaks at 1.9 K



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





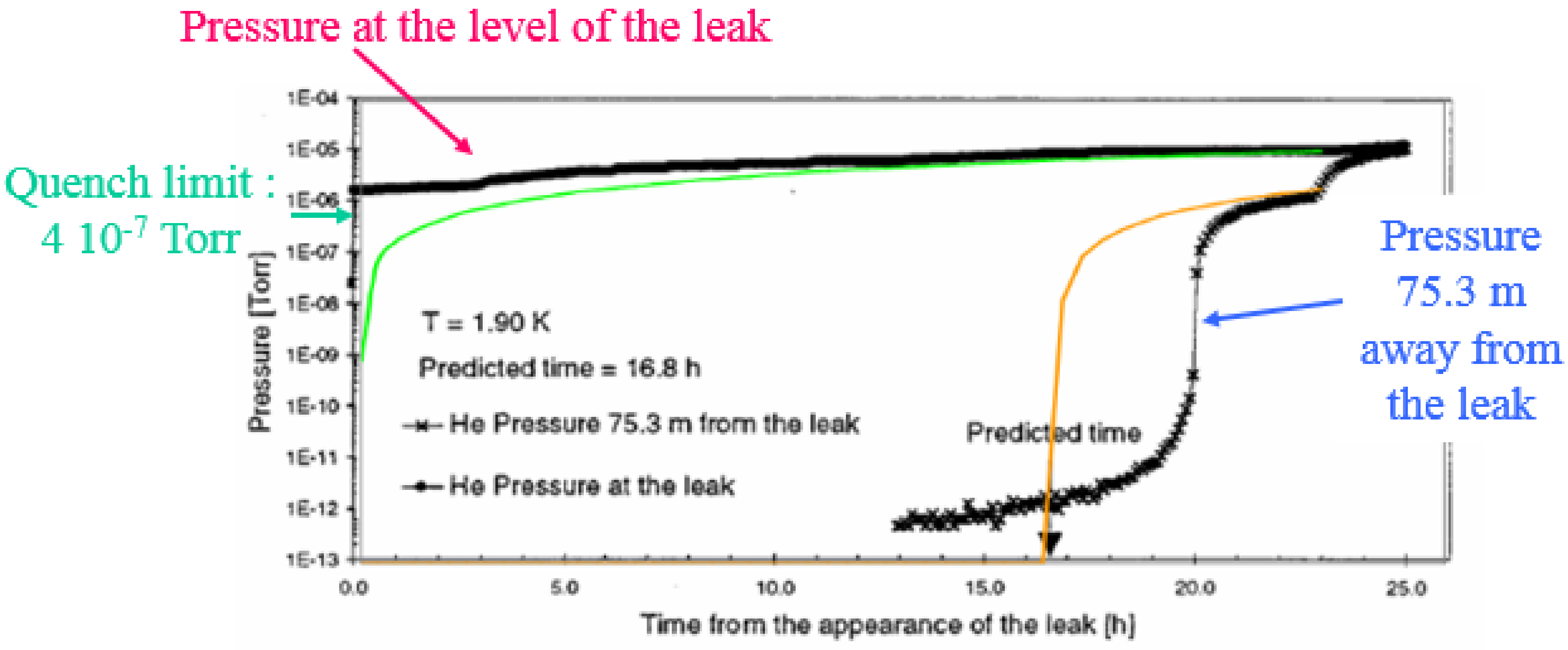
E. Wallén. J.Vac.Sci.A 15(2), Mar/Apr 1997, 265-274.

- 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

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

20h to be detected 75 m downstream!



E. Wallén, JVST A 15(6), Nov/Dec 1997

Impact on LHC design

- Appropriate cold bore & cooling capillaries material are selected (see S. Sgobba lecture)

- No cold demountable joints

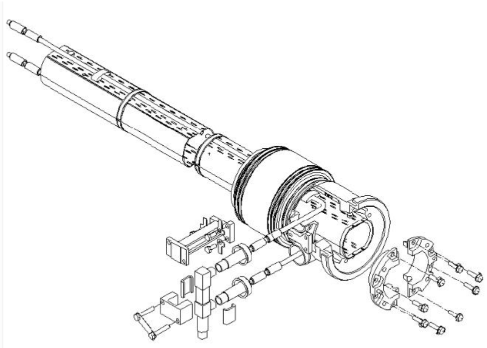
- Full penetrating welds between beam vacuum and He vessel are forbidden

- The cooling capillaries are laser spot welded to the beam screen (see S. Mathot lecture)

- All beam screen were tested at cryogenic temperature (100 K) and pressurised to 2 bars which results to a detection limit of <10^{-9} mbar.l/s when operated at 5-20 K

- The welds at the extremities of the cooling capillaries are located in the insulation vacuum

Laser welded cooling capillary



BS end finishing

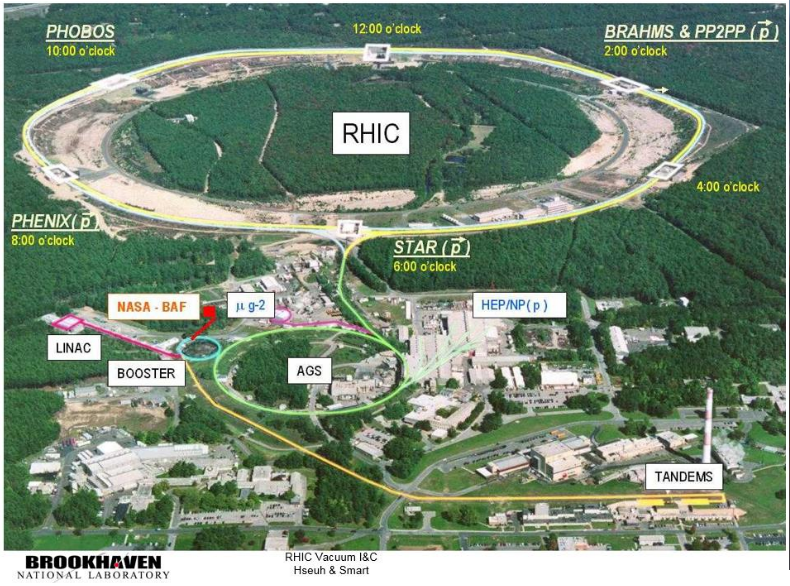
RHIC

- Ion beams collider (Au^{79+}) to study the quark-gluon plasma: 100 GeV/u + 100 GeV/u

- Two rings of 3.8 km, 84% is held at 4.5 K
- Separated cryostats

- Cold bore at 4.5 K

- Design pressure < 10^{-10} Torr.



Cryosorbing materials to mitigate leaks

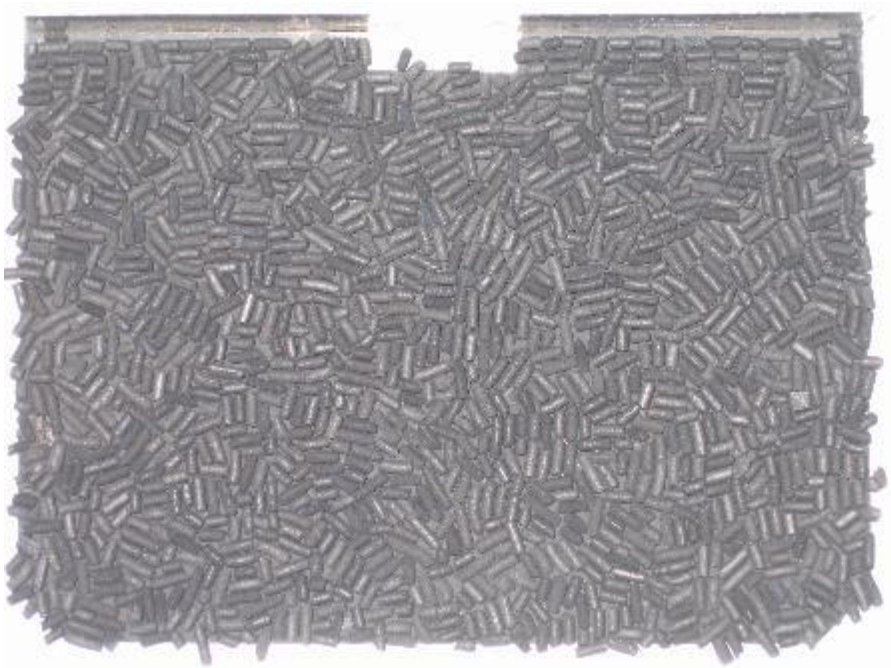
- Large capacity
- Large pumping speed
- Large temperature working range (up to ~ 30 K)

e.g. Activated Charcoal used for cryopumps

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

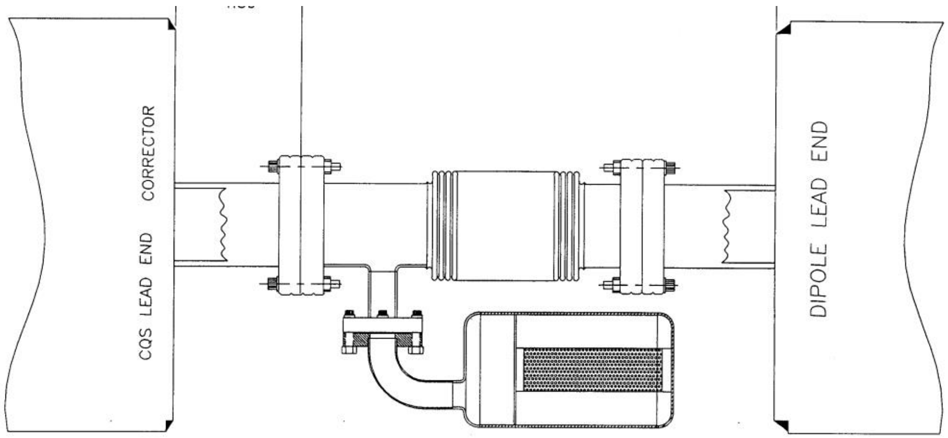


RHIC

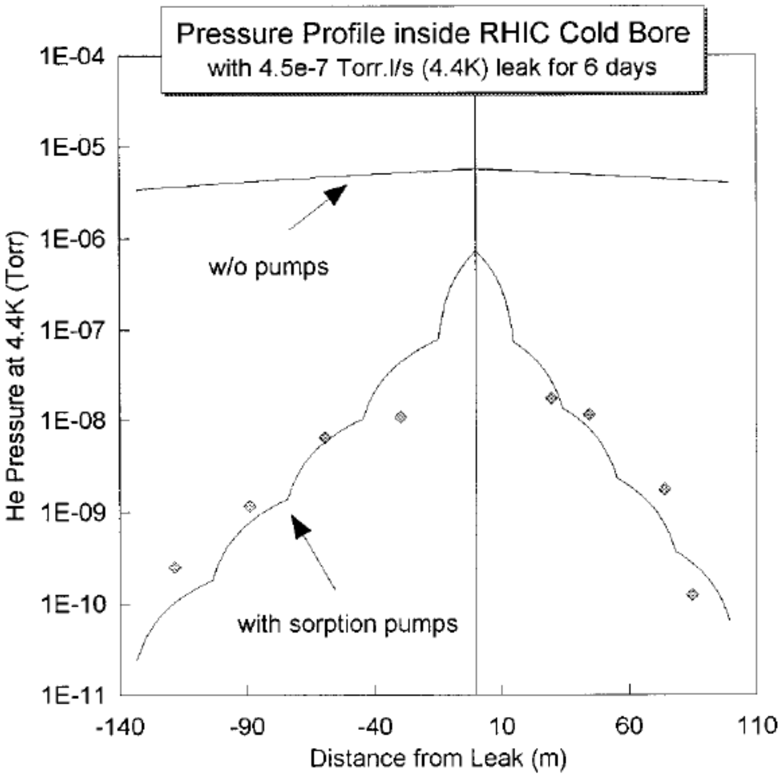
- RHIC use sorption pumps based on 300 g of activated charcoal.
- They are located every 30 m to mitigate He leaks and to pump H_2

Test in a 480 m long sector at 4.4 K

RHIC interconnect



H.C. Hseuh, Proc. PAC 1999



H.C. Hseuh, E. Wallén.
J.Vac.Sci.A 16(3), May/Jun 1998, 1145-1150.

C. Design of Cryogenic Beam Pipes

Present and future machines

- Designing the cryogenic vacuum system is really challenging!

FCC-pp collider parameters

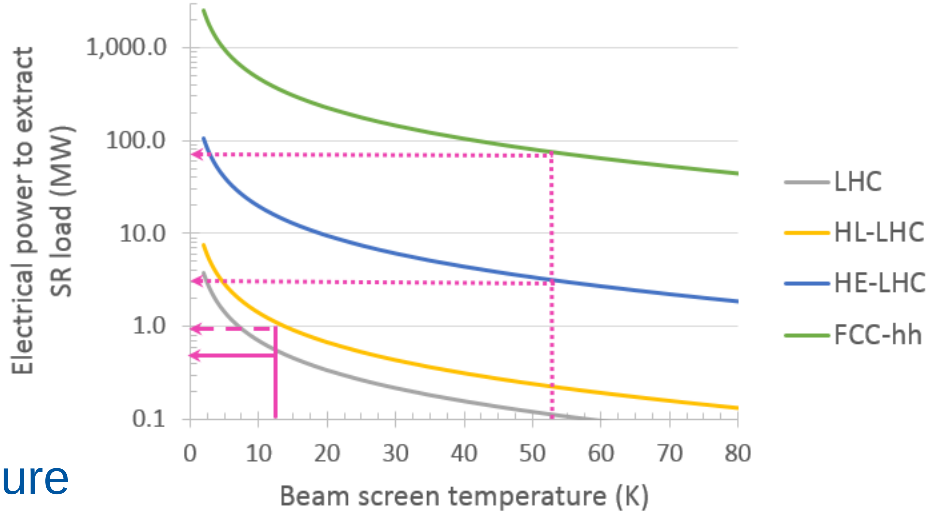
parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [µm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	25	5	1
events/bunch crossing	170	1k (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

Courtesy M. Benedikt

A design driven by heat load, Objective: lower cost and low energy consumption

- A LHC without beam screen would require ~7 MW of electrical power to maintain 1.9 K.
  ➔ A 5-20 K BS was needed to intercept the Sync. rad. heat at the electrical cost of 0.6 MW!

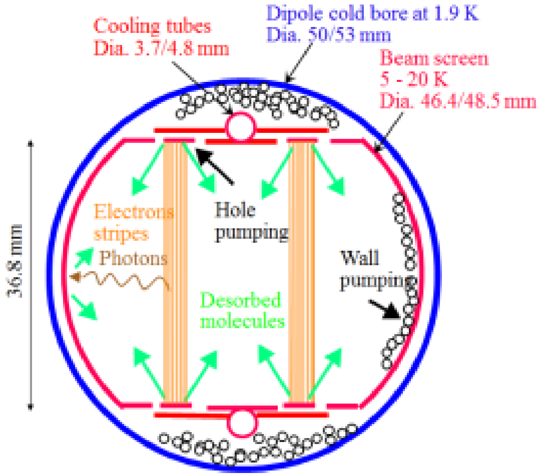
- Modern machines such as HE-LHC and FCC-hh currently under study are even more demanding … up to 75 MW of electrical power !!!

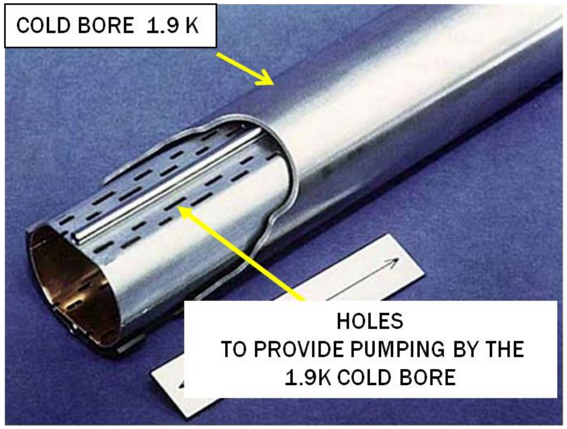


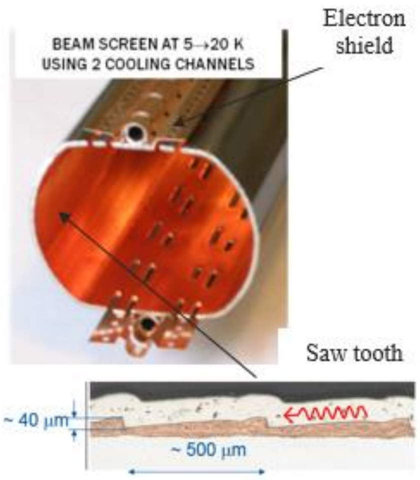
- See S. Claudet lecture

Machine	LHC	HL-LHC	HE-LHC	FCC-hh
BS temperature (K)	5-20		45-60	
Synch. rad. (kW)	7	15	202	4 800
Electrical power (MW)	**0.6**	1	3	75

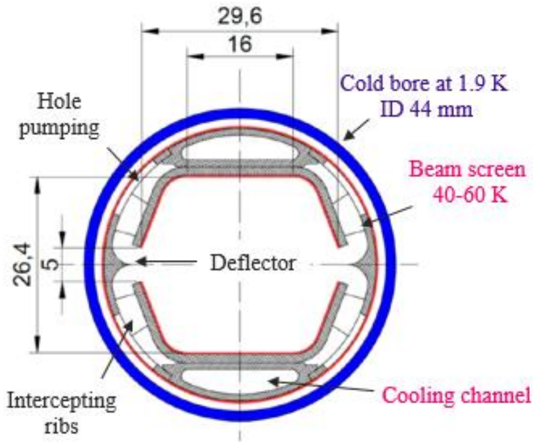
Beam screens design

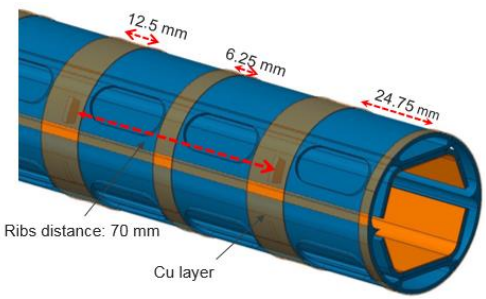






LHC





FCC-hh

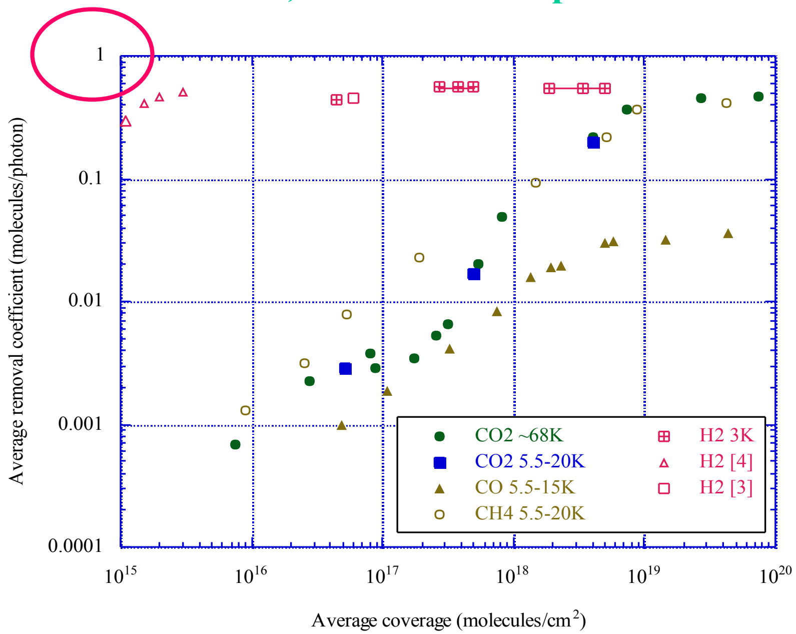
- Further details with J.M. Jimenez lecture

Photodesorption of Physisorbed Gases

- The synchrotron radiation stimulates the desorption of strongly bounded molecules
  ➔ yield 10^{-4} -10^{-2} molecules/photon

- The photodesorption yield of weakly bounded physisorbed molecules can be very large.

Stainless steel, 250-300 eV. Perpendicular incidence



V. Anashin *et al.*, Vacuum 53 (1-2), 269, (1999)

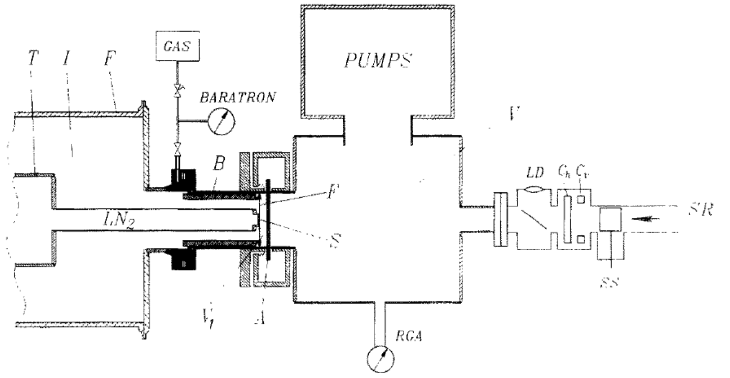


Fig. 1. The "open" geometry experimental setup. S is a substrate, F is the foil, A is an all-metal valve, B is a room temperature tube (see text), V is the experimental volume and V_1 is 0.112 litres, RGA is a quadrupole residual gas analyzer, LD is a phosphoroscent screen, C_v and C_h are vertical and horizontal collimators, SS is a safety shutter, F is the cryostat frame, I is the insulation vacuum and T is a LN_2 tank.

- Further details with O. Malyshev lecture

Recycling of molecules must be taken into account in models

Gas density & surface coverage equations

V.V. Anashin *et al.* J. Vac. Sci.Technol. A. 12(5) , Sep/Oct 194

$$V\frac{\partial n}{\partial t} = \eta\dot{\Gamma} + \eta'\dot{\Gamma} + \frac{A\Theta}{\tau} - \sigma S n - C n + A_c D\frac{\partial^2 n}{\partial z^2}$$

Photodesorption ($\eta\dot{\Gamma}$), Recycling ($\eta'\dot{\Gamma}$), Vapour pressure ($\frac{A\Theta}{\tau}$), Wall pumping ($\sigma S n$), Holes pumping ($C n$), Diffusion ($A_c D\frac{\partial^2 n}{\partial z^2}$)

$$A\frac{\partial \Theta}{\partial t} = \sigma S n - \eta'\dot{\Gamma} - \frac{A\,\Theta}{\tau}$$

- with:

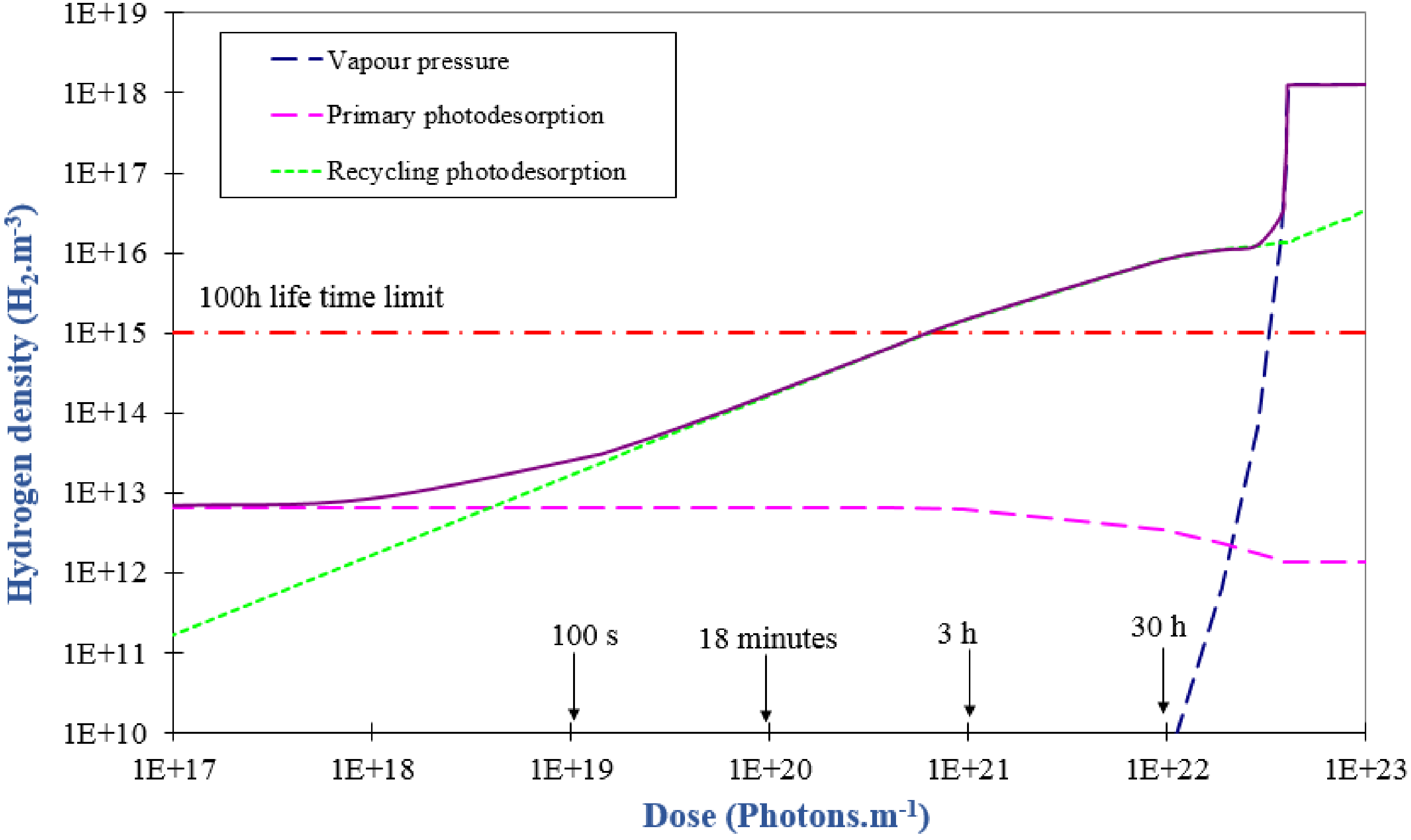
n gas density, s surface coverage, V volume per unit length, A surface per unit length, $A_c D$ axial diffusion term of molecules, σ sticking probability, S ideal speed per unit length, C beam screen holes pumping speed per unit length, τ sojourn time of physisorbed molecule, η desorption yield of chemisorbed molecules, η' recycling desorption yield of physisorbed molecules,

Cryosorbing tube without holes

- Infinitely long tube ($A_cD=0$), without beam screen (C=0) and quasi static conditions:

➔Three terms adds: primary, recycling desorption and vapour pressure

$$n = \frac{\eta\dot{\Gamma}}{\sigma S} + \frac{\eta'\dot{\Gamma}}{\sigma S} + \frac{1}{\sigma S}\frac{A\Theta}{\tau}$$

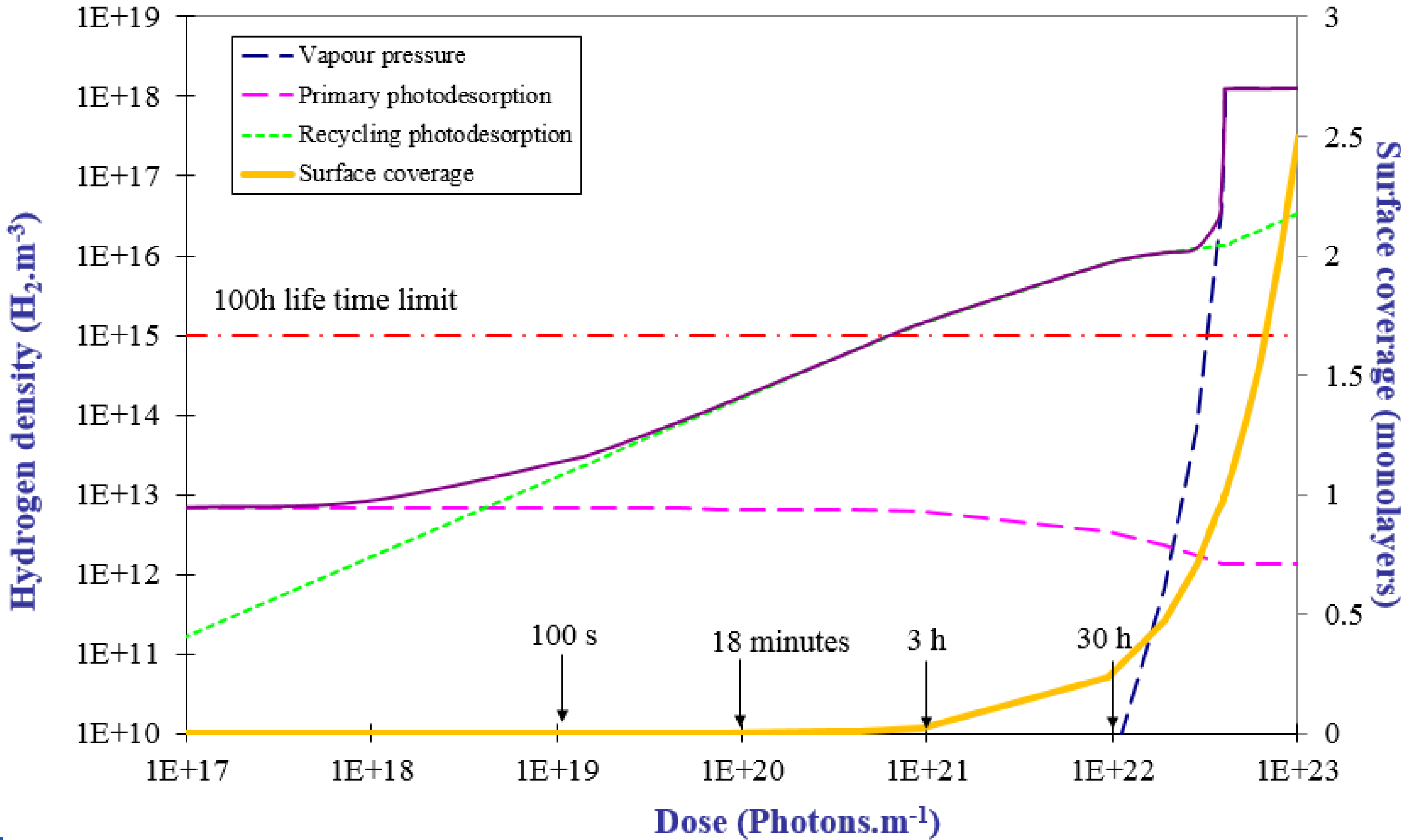


Cryosorbing tube without holes

$$n = \frac{\eta\dot{\Gamma}}{\sigma S} + \frac{\eta'(\Theta)\dot{\Gamma}}{\sigma S} + \frac{1}{\sigma S}\frac{A\Theta}{\tau}$$

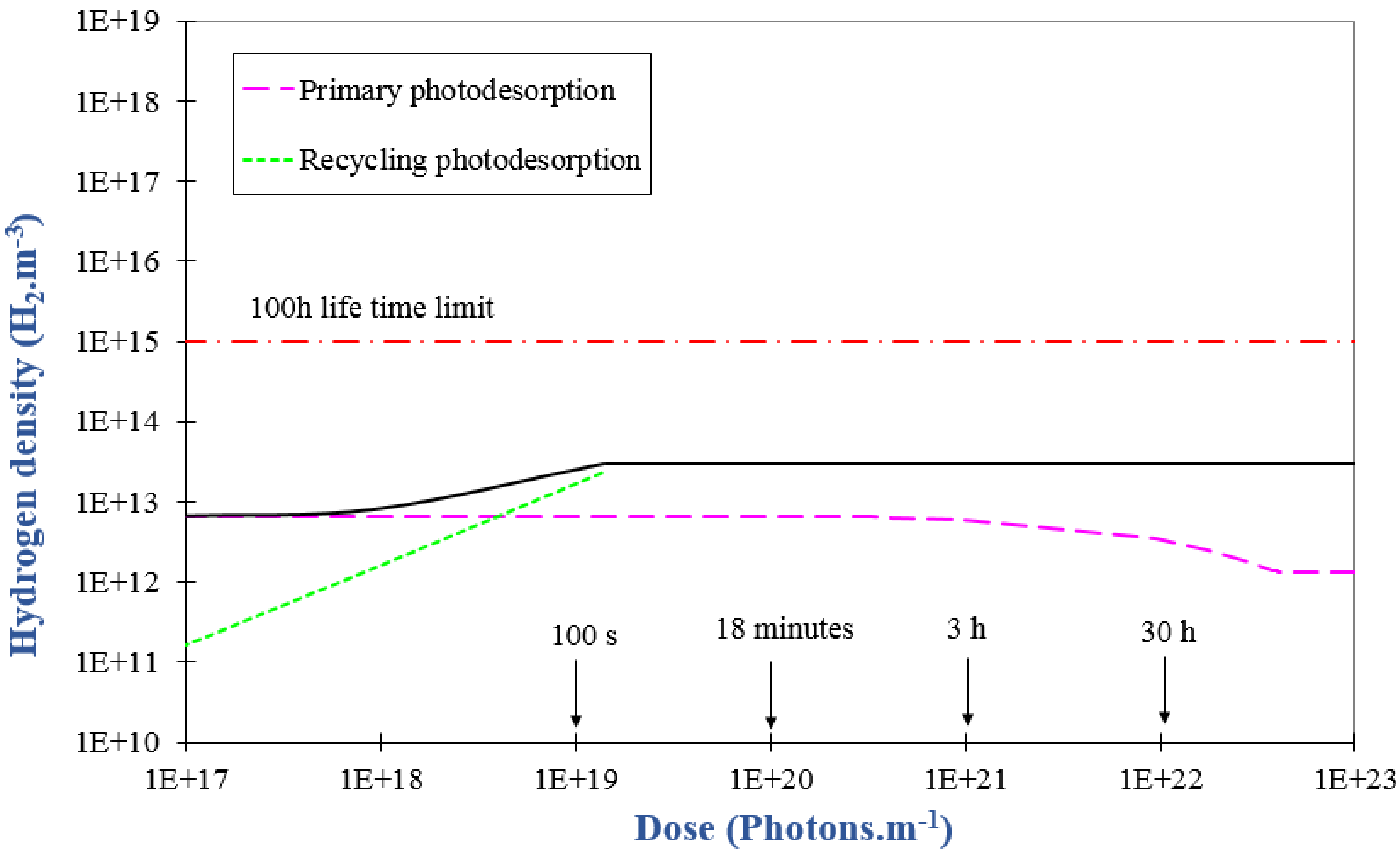
Increase with the surface coverage, Θ

$$\Theta = \frac{1}{A}\int_0^{\Gamma} \eta d\Gamma$$



Perforated beam screen

- Infinitely long tube ($A_cD=0$), with a beam screen (C=0) and quasi static conditions:
  - The equilibrium pressure n_{eq} is defined by the perforation conductance

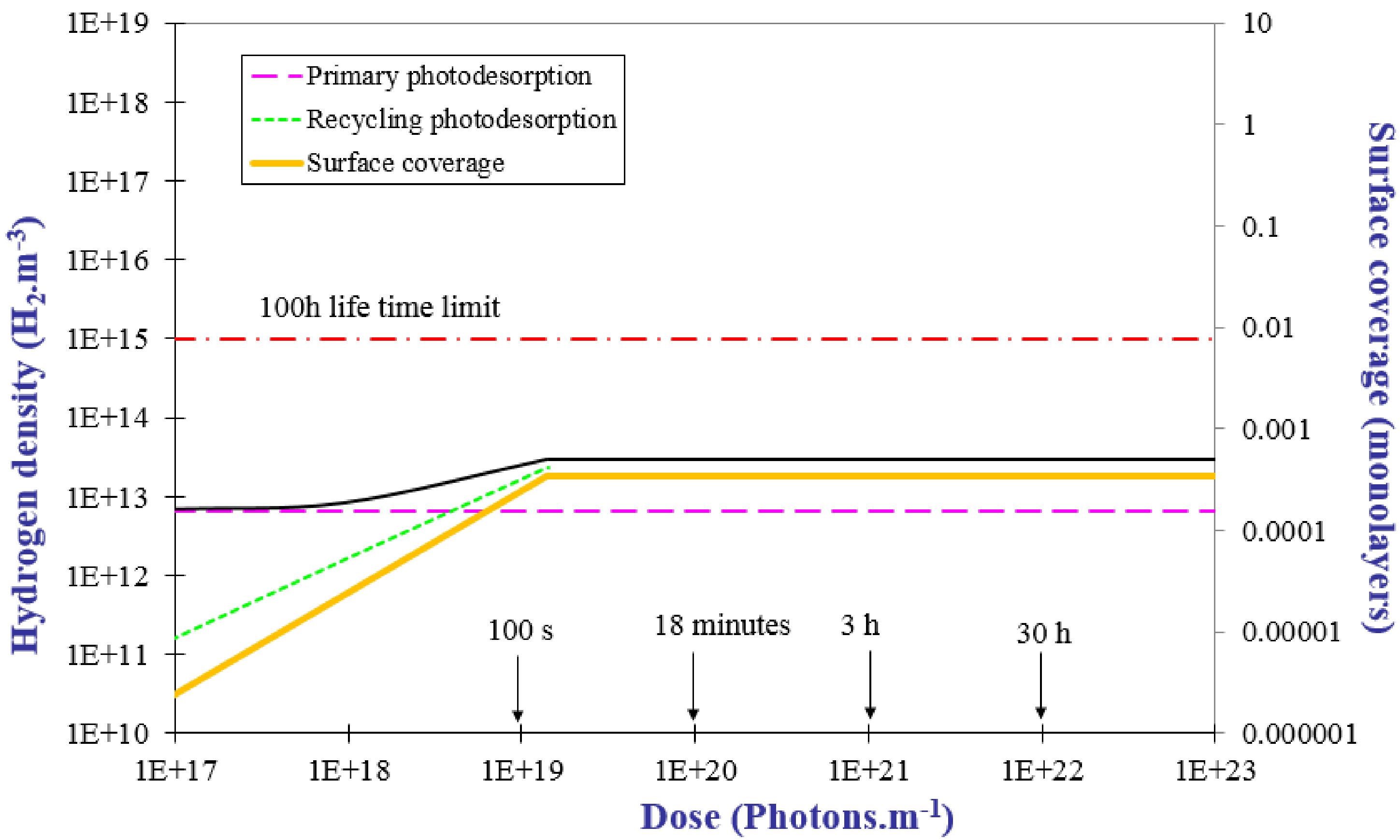


$$n_{eq} = \frac{\eta\dot{\Gamma}}{C}$$

A **perforated** beam screen allows to control the gas density

Perforated beam screen

- Infinitely long tube ($A_cD=0$), with a beam screen (C=0) and quasi static conditions:
  - The equilibrium coverage is a fraction of a monolayer



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

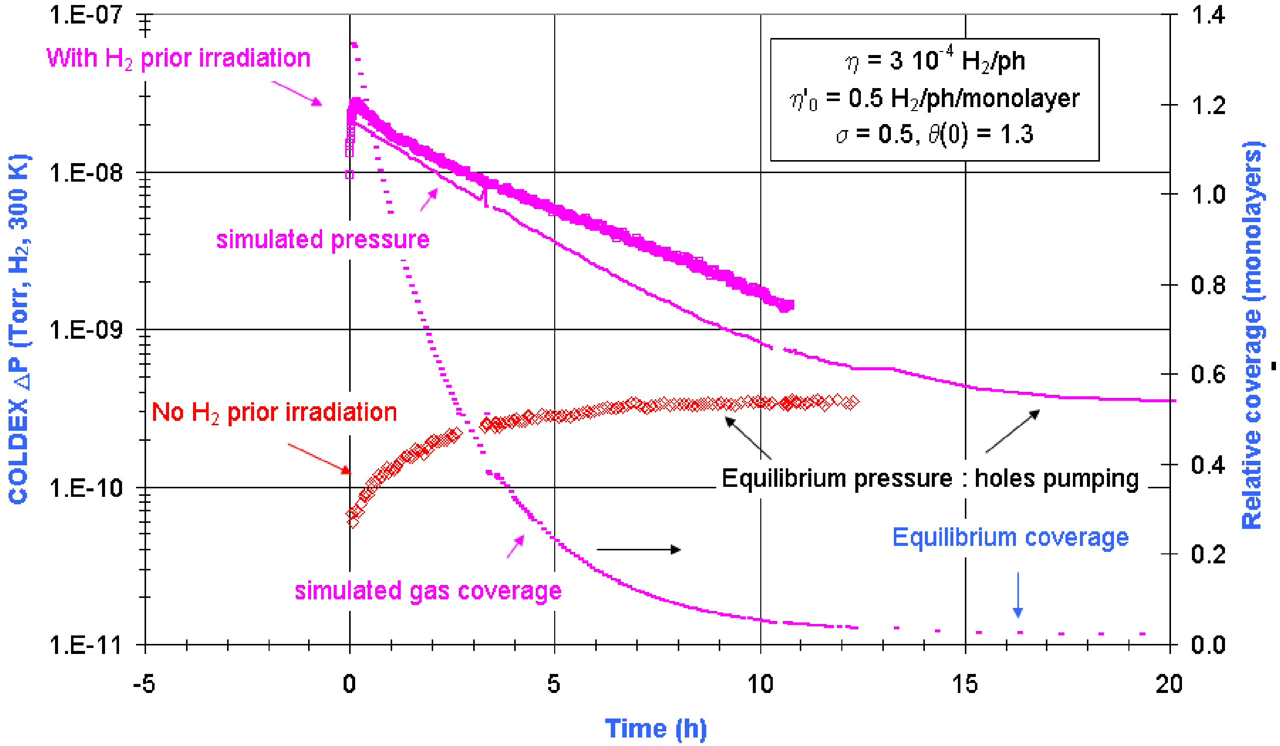
A **perforated** beam screen allows to control the surface coverage

D. Operation with Cryo-vacuum Machines: LHC, SIS100, RHIC, ISR LEP2, HIE-Isolde

Vacuum transients

- Vacuum transients appears for an excessive gas coverage onto the beam screen.

- Example: LHC at 1/3 of nominal current



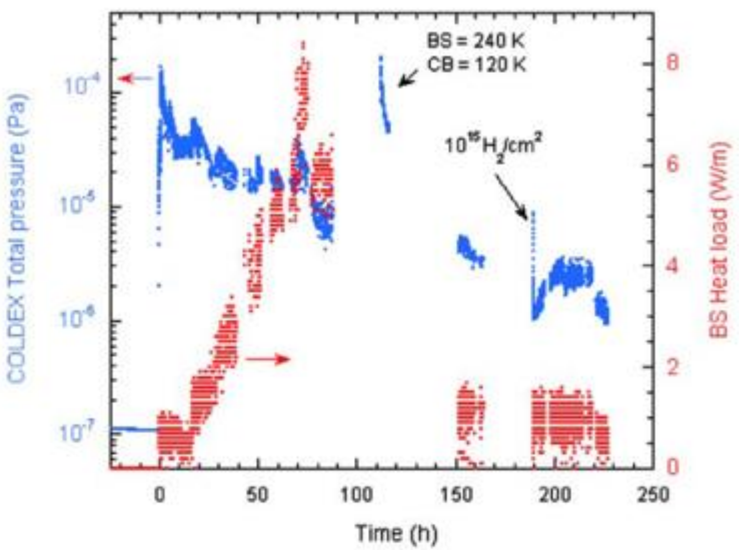
V. Baglin, Proc. of LHC Project Workshop 2004, Chamonix, France

➔ The surface coverage must be minimised

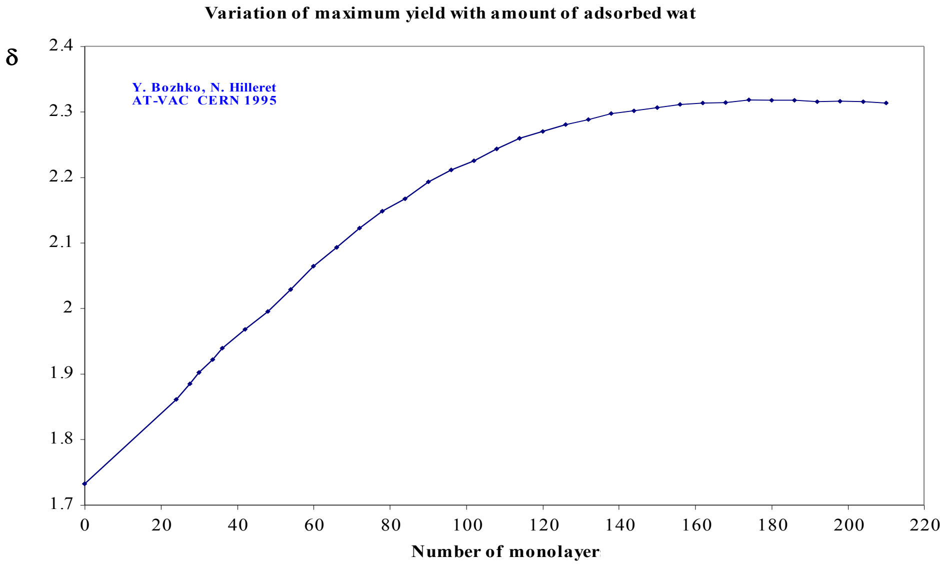
Heat load due to multipacting

- 8 W/m heat load onto the cryogenic system when the SPS machine is filled by only 24 % with LHC nominal beams !

- Origin of the heat load is attributed to H_2O condensation onto the beam screen



V. Baglin *et al.*, Vacuum 73 (2004) 201-206



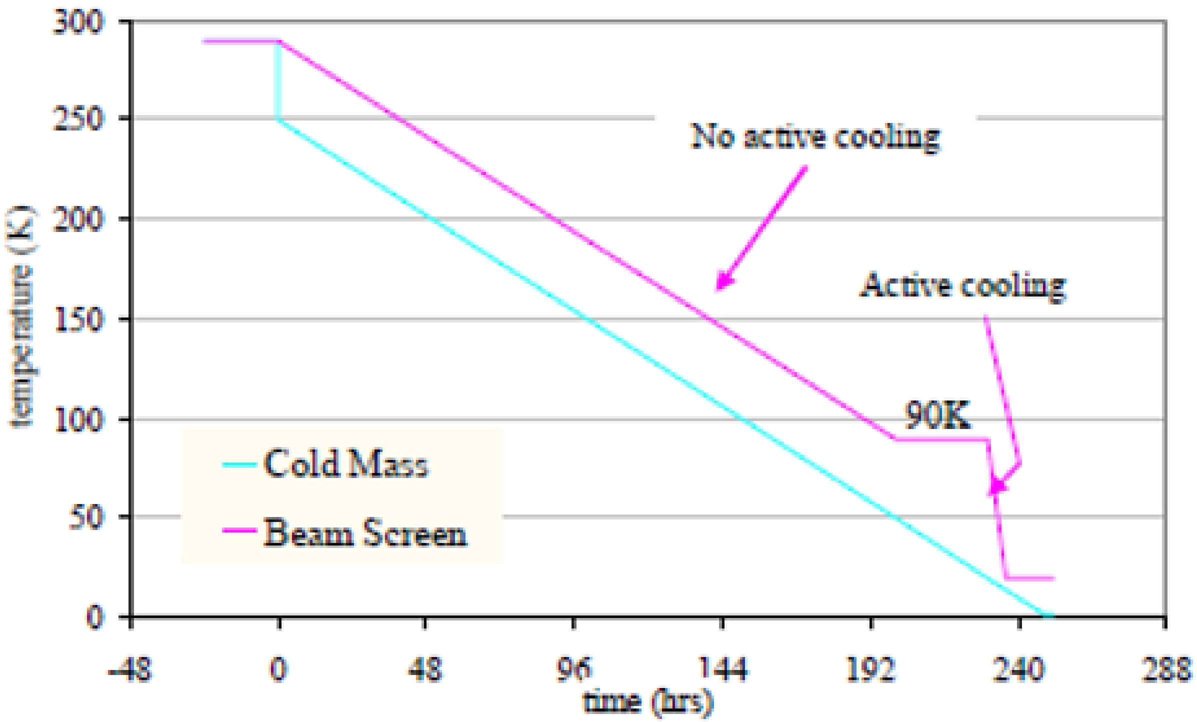
N. Hilleret *et. al.* Chamonix 2000

- Further details with R. Cimino lecture

➔ The surface coverage must be minimised

LHC Pump Down & Cool Down

- Specific scenario to minimise the surface coverage:
  - Evacuation at room temperature for at least 5 weeks before cool down
  - Cold bore (CB) cool down first to condense gas onto it
  - Beam screen cool down with plateau at > 90 K to minimise condensation until CB < 20 K
  - BS final cool down

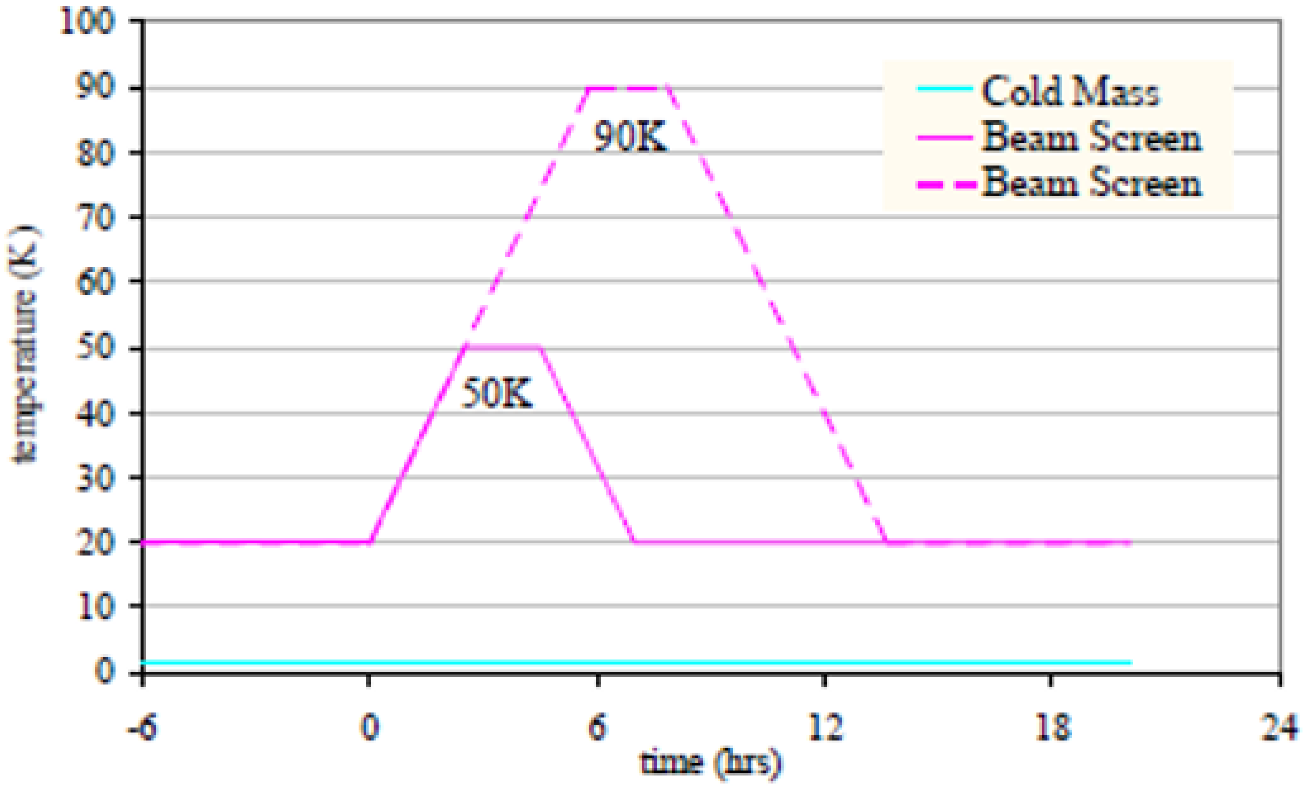


A. Rossi, Proc. of LHC Project Workshop 2003, Chamonix, France

Beam screen regeneration

- In case the surface coverage grows above the equilibrium value following *e.g.* a magnet quench, a mechanism is needed to regenerate the BS surface.

- The LHC beam screens can be warmed up to ~ 90 K to flush the gas towards the cold bore held at 1.9 K.



A. Rossi, Proc. of LHC Project Workshop 2003, Chamonix, France

SIS 100 under construction at GSI

- The machine will accelerate and deliver radioactive pulses up to 35 GeV/u

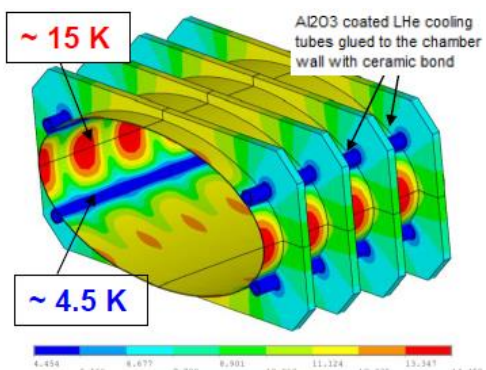
- About 82% of the 1083.6 m long machine operates at 5-15K :

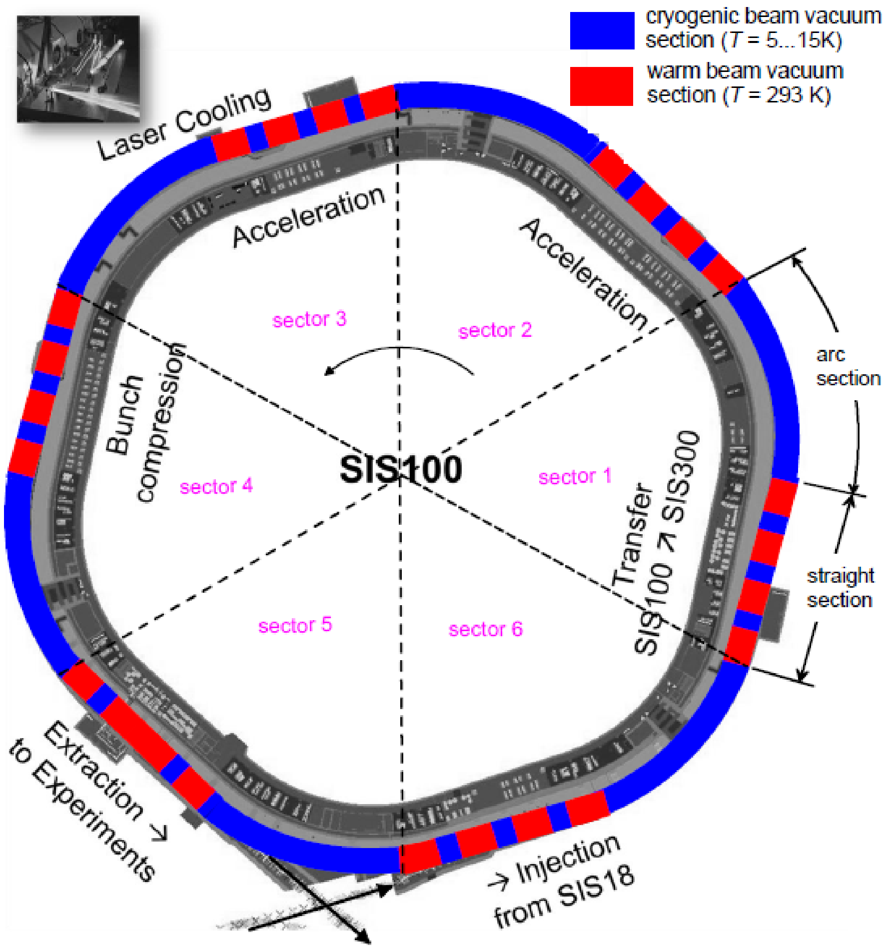
  $n < 8\ 10^{11}\ H_2/m^3$

- Due to charge exchange, circulating ions can be lost stimulating gas desorption

- The dipole field is ramped with 4 T/s at 1 Hz which induced heat load due to eddy current :

  ➔ during operation, the temperature profile of the vacuum chamber wall is non uniform and non constant





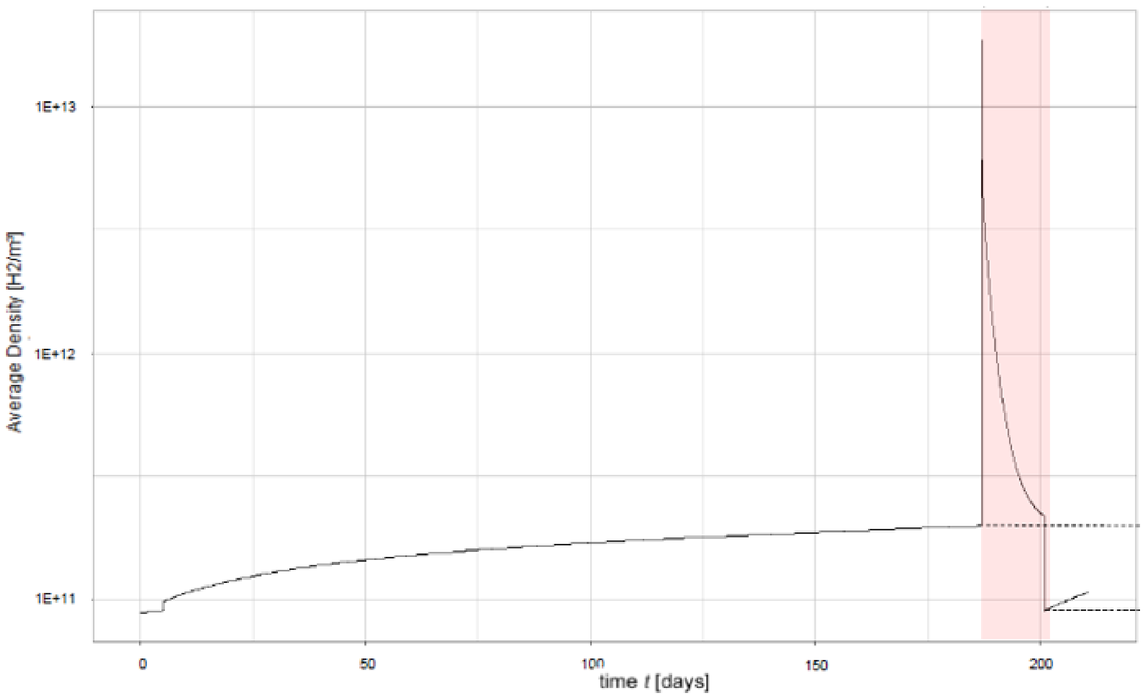
S. Wilfert *et al*, EVC 2016, Portoroz

SIS 100: impact of gas load

- Using adsorption isotherms as inputs, the volume density and gas surface equations have been solved and the gas density profiles vs time computed.

- After ~ 180 days of operation, the gas density limit is reached.

Warm-up period
to ~20 K to release hydrogen



S. Wilfert *et al*, EVC 2016, Portoroz

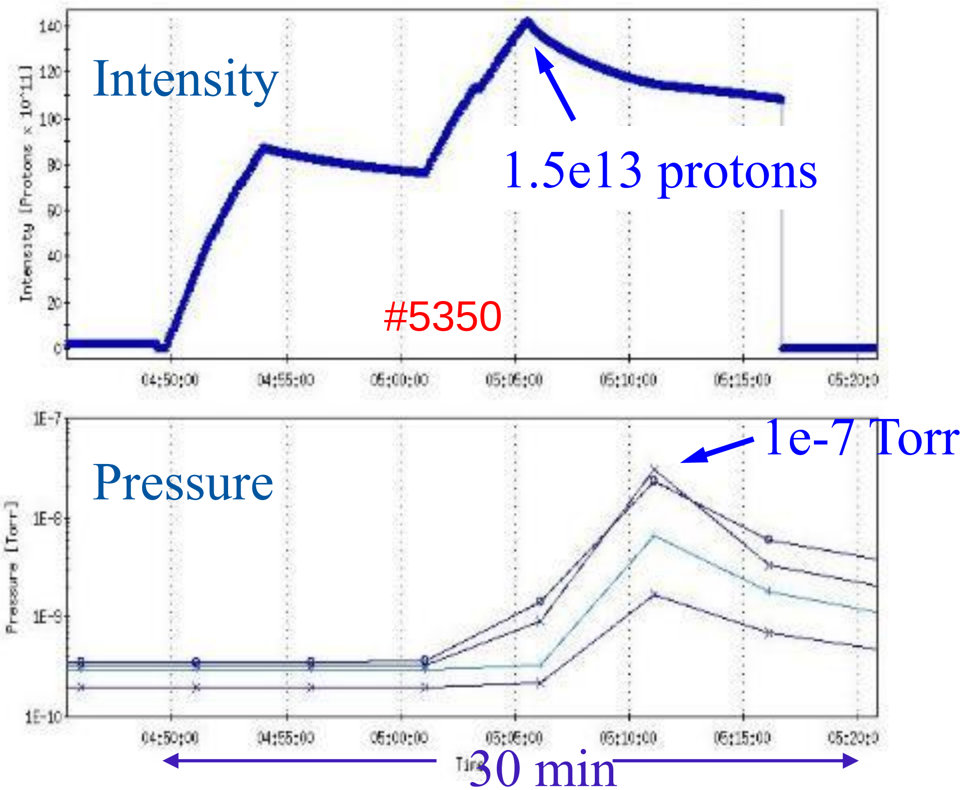
- Warming up to evacuate the condensed gas towards the external pumping system is part of the base line

RHIC cold bore pressure rise

- In 2004-2005, observation of large pressure rise (up to 10^{-7} mbar) in the arcs & triplets
- Due to ion and / or electron bombardment
- Mitigation:

  reduce pressure to <10^{-3} mbar before cool down to minimise amount of physisorbed gas

Courtesy H.C. Hseuh



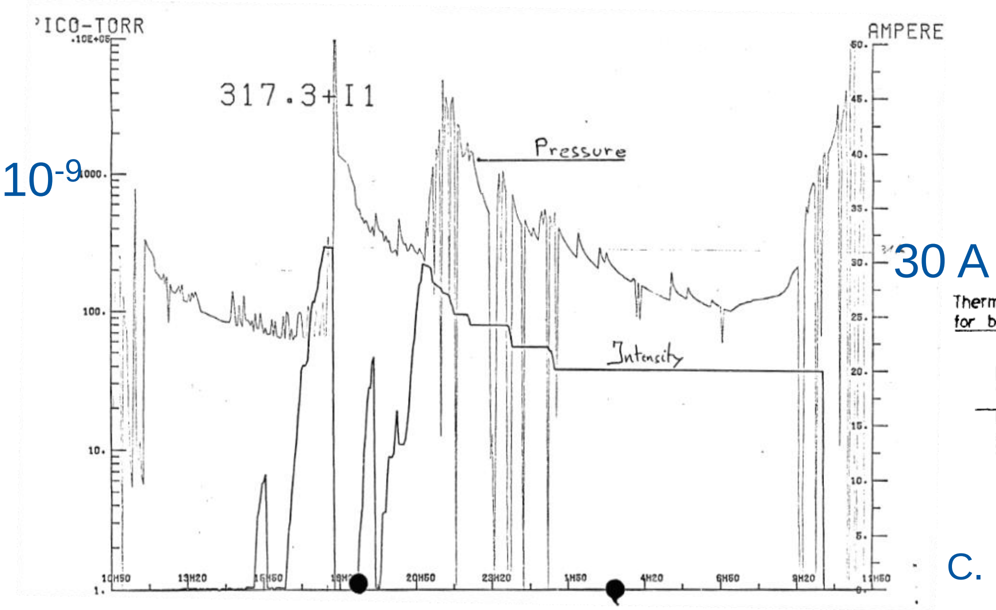
W. Fischer et al, Proc. of PAC 2007, Albuquerque, USA

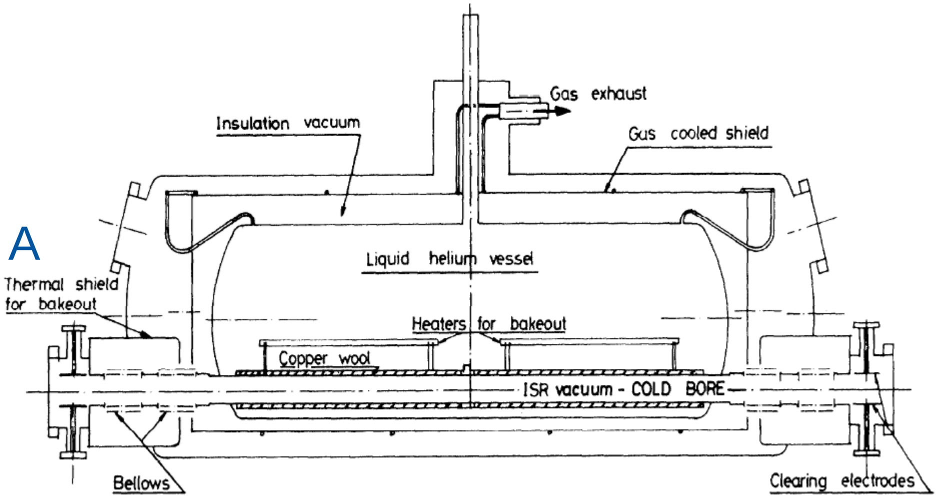
➔ The issue disappeared

ISR cold bore

- In the ISR, two cold bore were operated during ~ 5 years in order to prepare the use of superconducting magnets for the future !
    - Vacuum stability
    - Condensation of gas
    - …
- With ~ 100 monolayers of N_2 condensed (air leak), pressure spikes up to ~ 10^{-8} mbar were recorded

- The suspected origin is breakdown in the N_2 film which leads to gas desorption





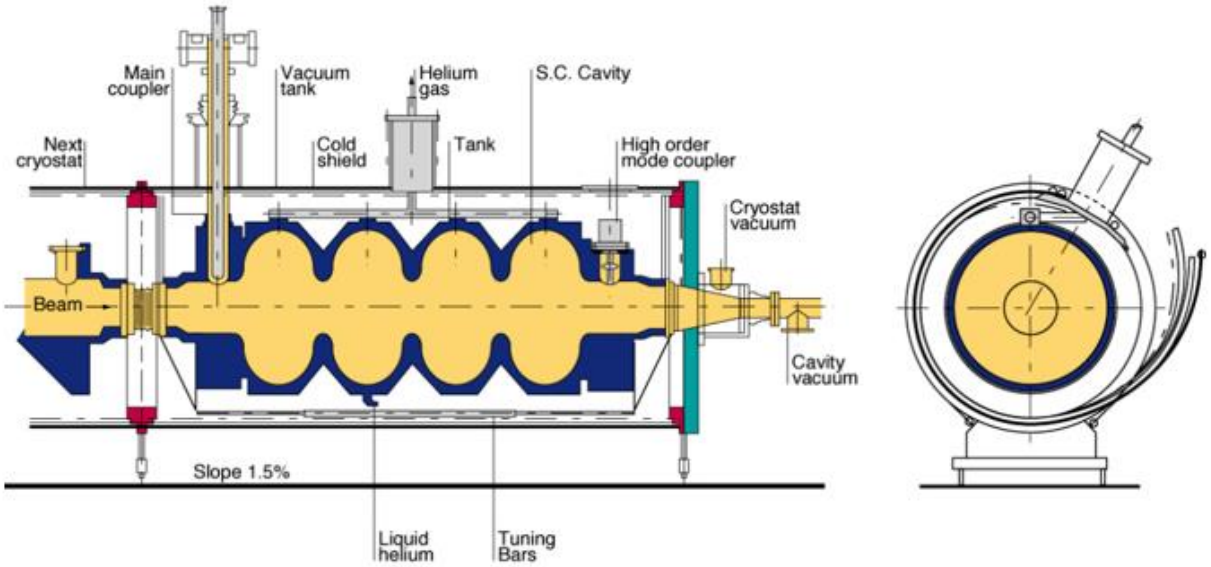
C. Benvenuti, N. Hilleret, IEE Trans. Nucl. Sci. June 1979

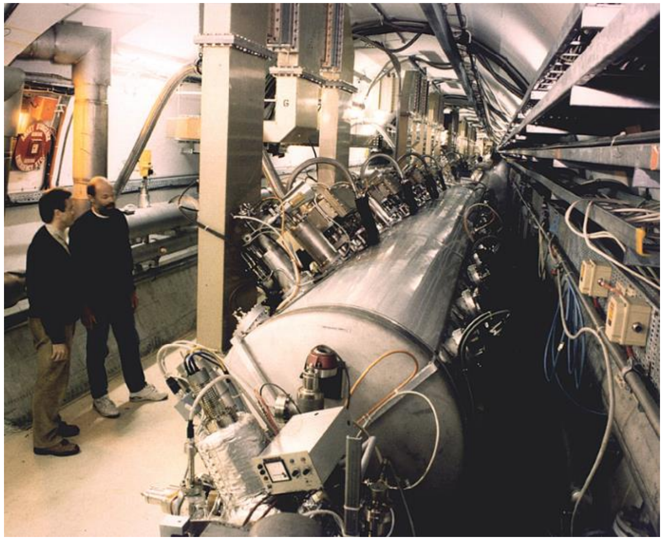
➔ Air leaks in cold systems are not acceptable

LEP2

- 95 – 100 GeV
- Electron / positron beams
- 5+5 mA, 6 bunches/beam

- Pill-box cavity
- Elliptical cavity shape
- Nb coated at 4.5 K
- 6 MV/m field, 352.2 MHz





LEP2 coupler: impact of gas condensation

- During the construction of the cavities deconditioning of the coupler surface was observed.

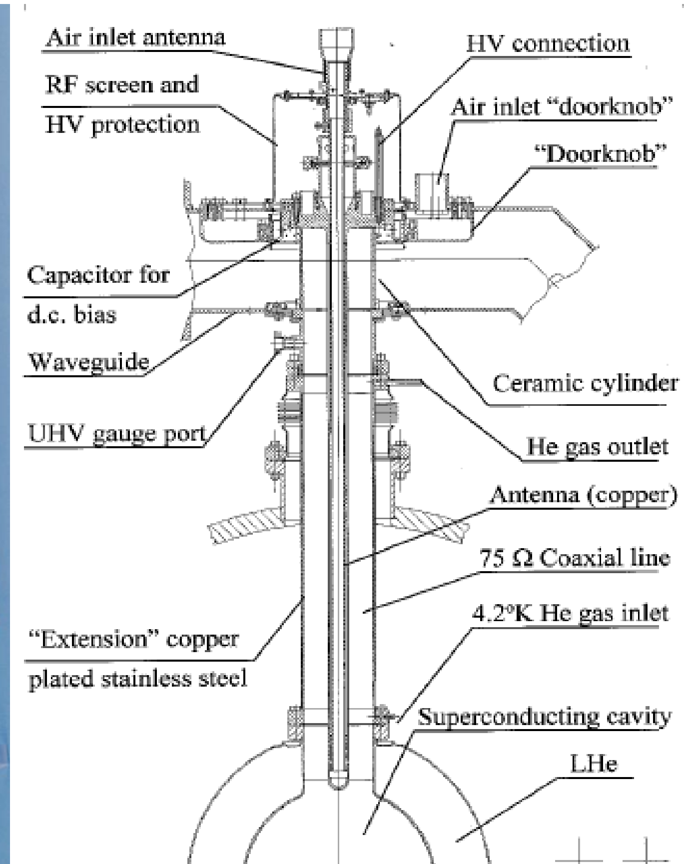
- Water was condensed on the outer surface of the coupler and produced multipacting at cryogenic temperature stimulating even more the thermal desorption of water by RF heating

- 200 kW coupling power

➔ the coupler including its porous window was baked *in-situ* at 200ºC before cooling down

➔ when needed, a negative bias of -2.5 kV was applied on the centre conductor to modify the electron kinetics

➔ The surface coverage must be minimised



J. Tückmantel , Applied Superconductivity Conference, Desert Springs Resort, CA, USA, 1998

HIE-Isolde

- Nuclear physics studies
- Acceleration of radionucleides: from mass 6 to 224
- 10 MeV/u available by 2018

5 cavities in a cryomodule

2 cryomodules in the beam line

HIE-Isolde cavity: recovering from multipacting

- Cavity conditioning is started at ~ 200 K, when conditioned, the cavity is cool down to 4.2K for operation.

- In the case of multipacting after cool-down, a recipe consist in warming up to 20-30 K the cavity to redistribute and pump away the gas (courtesy W. Venturini).

- Quarter wave resonator: lambda/4 cavity

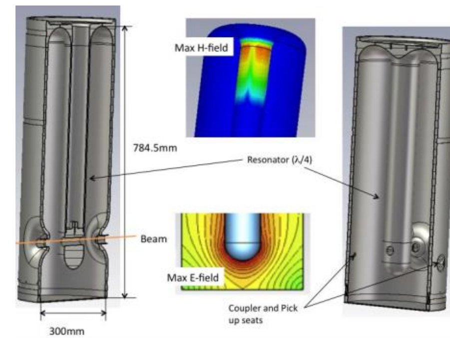
- Cylindrical shape, Nb coated

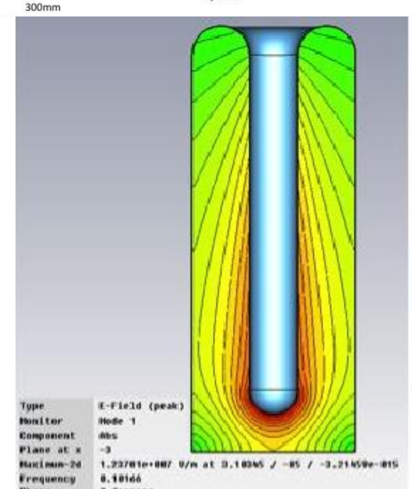
- 4.5 K

- 6 MV/m field

- 101.28 MHz

A. D’elia *et al.* Proc. SRF 09, Berlin, 2009





➔ The surface coverage must be minimised

Conclusion

- Gas can be physisorbed for very long period on cryogenic surface
- The sticking coefficient characterise the pumping speed of a surface
- The capture coefficient characterise the pumping speed of a device
- At cryogenic temperature, thermal transpiration correction shall be applied
- The vapour pressure is the equilibrium pressure as a function of gas coverage
- When saturated (many monolayers), the vapour pressure follows the Clausius Clapeyron law
- Adsorption isotherms vary very much with the conditions

Conclusion

- Some material can be porous so to adsorb many monolayers of gas without reaching the saturated vapour pressure: cryosorbers

- He leak can be difficult to detected at cryogenic temperature except by the beam itself!

- Molecular physisorption and condensation can be strongly detrimental for the operation of vacuum system held at cryogenic temperature. For this reason, appropriate design, surface treatments and minimisation of the sources of gas is required.

Some References

- Cern Accelerator School, Vacuum technology, CERN 99-05

- Cern Accelerator School, Vacuum in accelerators, CERN 2007-03

- US Particle Accelerator School, Vacuum science and technology for accelerators

- The physical basis of ultra-high vacuum, P.A. Redhead, J.P. Hobson, E.V. Kornelsen. AVS.

- Capture pumping technology, K. Welch, North Holland.

- Cryopumping, theory and practice, R. Haefer, R. Clarendon press

Some Journals Related to Vacuum Technology

- Journal of vacuum science and technology

- Vacuum

Thank you for your attention !!!