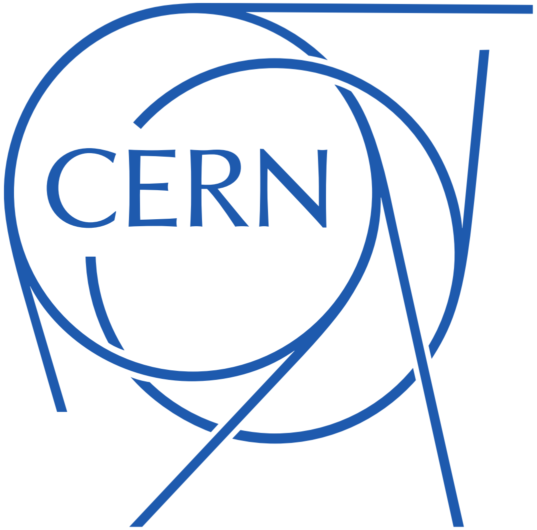

CERN

Vacuum Systems
Slot 5

V. Baglin

CERN TE-VSC, Geneva

Joint Universities Accelerator School

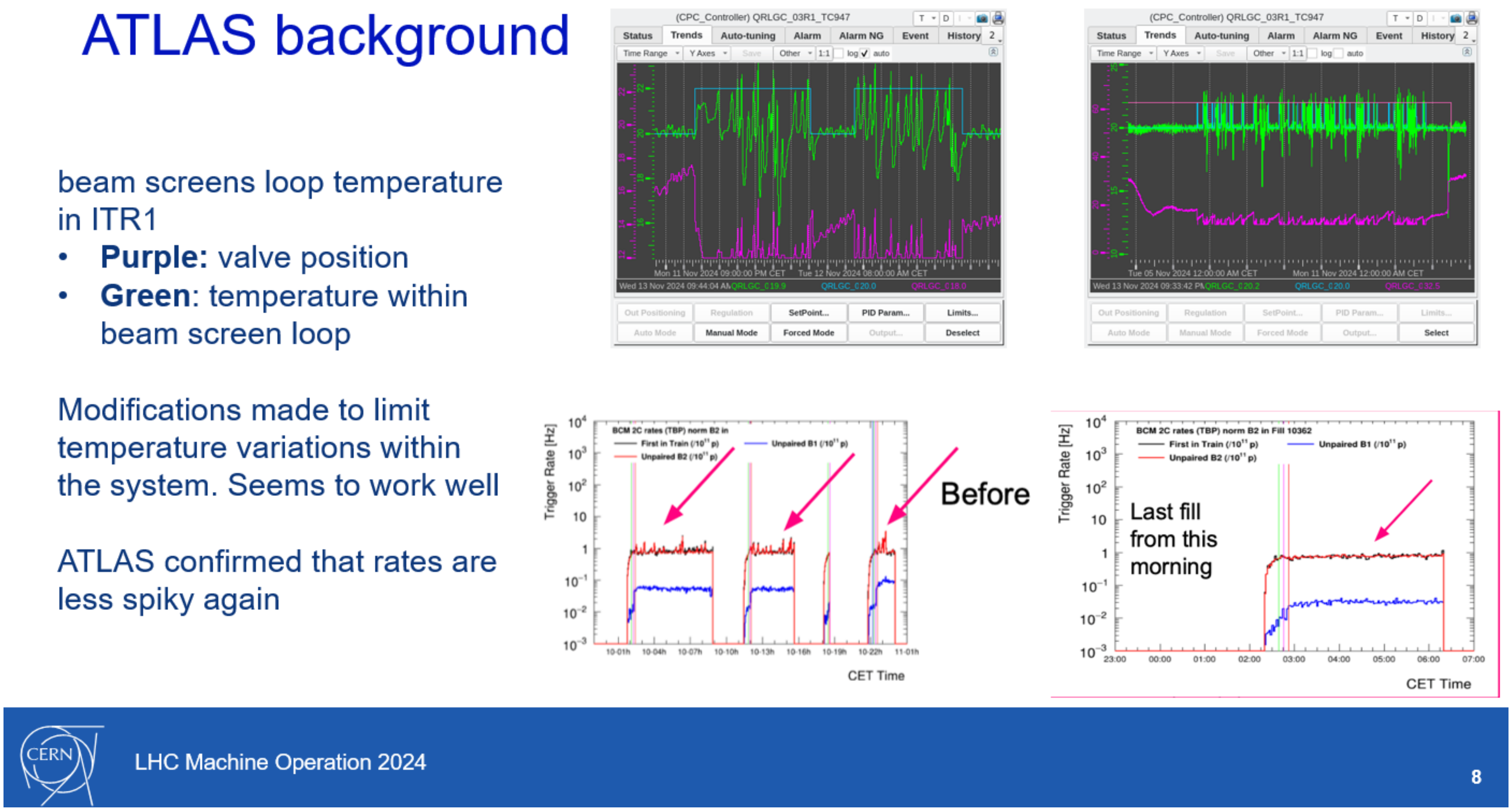
https://indico.cern.ch/event/1470062/timetable/?view=standard#day-2025-02-17

Outline

1. Cryo-pumping
2. Adsorption isotherms
3. Synchrotron radiation

Why cryo-vacuum matters?

- Explanation of beam induced background in ATLAS during November 2024 …



ATLAS background

beam screens loop temperature in ITR1
- **Purple:** valve position
- **Green**: temperature within beam screen loop

Modifications made to limit temperature variations within the system. Seems to work well

ATLAS confirmed that rates are less spiky again

Before

Last fill from this morning

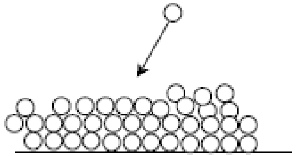
LHC Machine Operation 2024

8

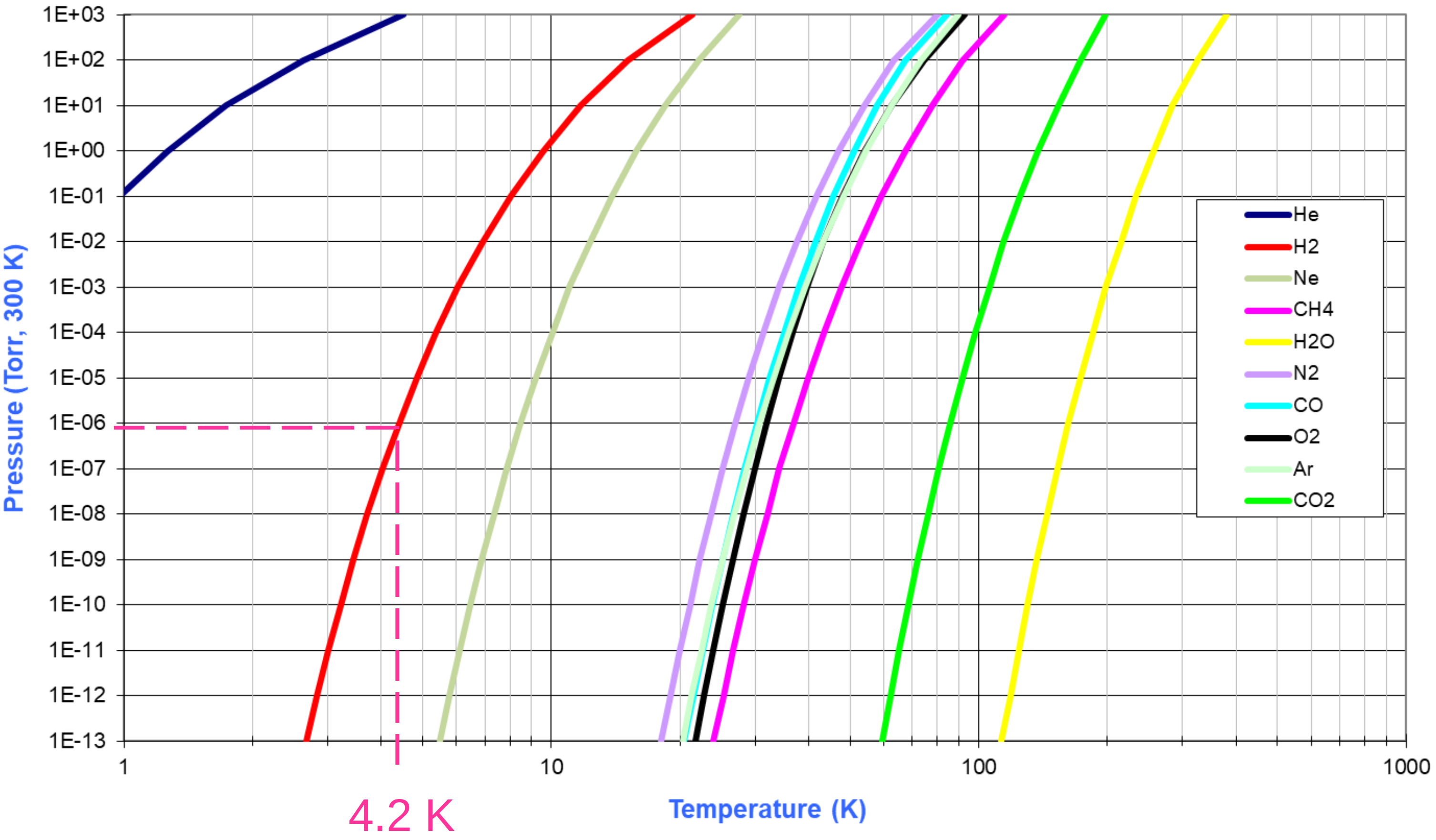
1. Cryopumping

Saturated Vapour Pressure

- Pressure over liquid or gas phase (many monolayers condensed)
- Follows the **Clausius-Clapeyron equation**: **Log P_{sat} = A – B/T**
- For a **smooth surface**:

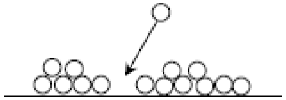


Saturated vapour pressure from Honig and Hook (1960)



Desorption probability

- The **desorption probability**, ***p***, 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 :



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

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

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

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

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

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

Sojourn time at cryogenic temperature

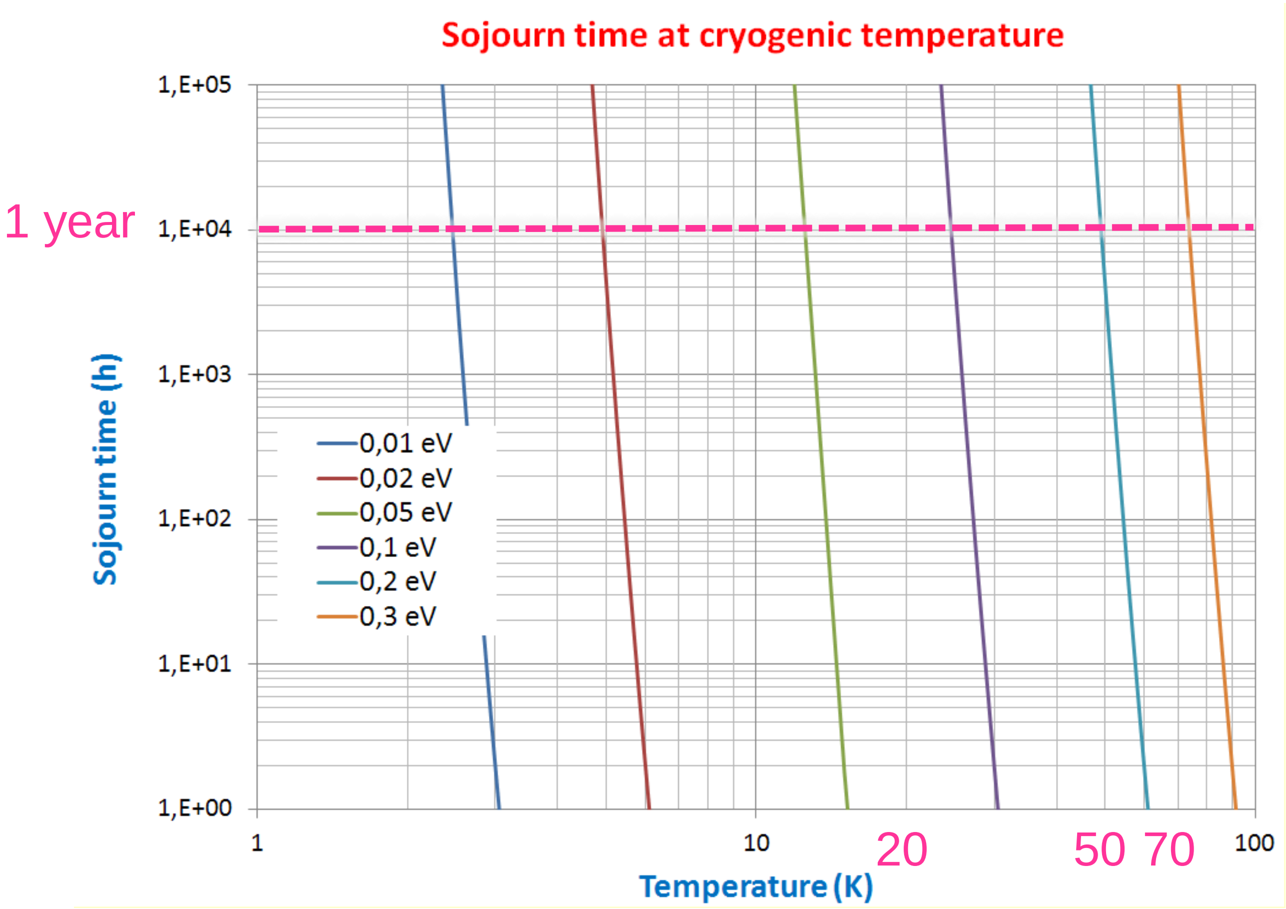
- Cryosorption occurs up to ~ 100 K

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

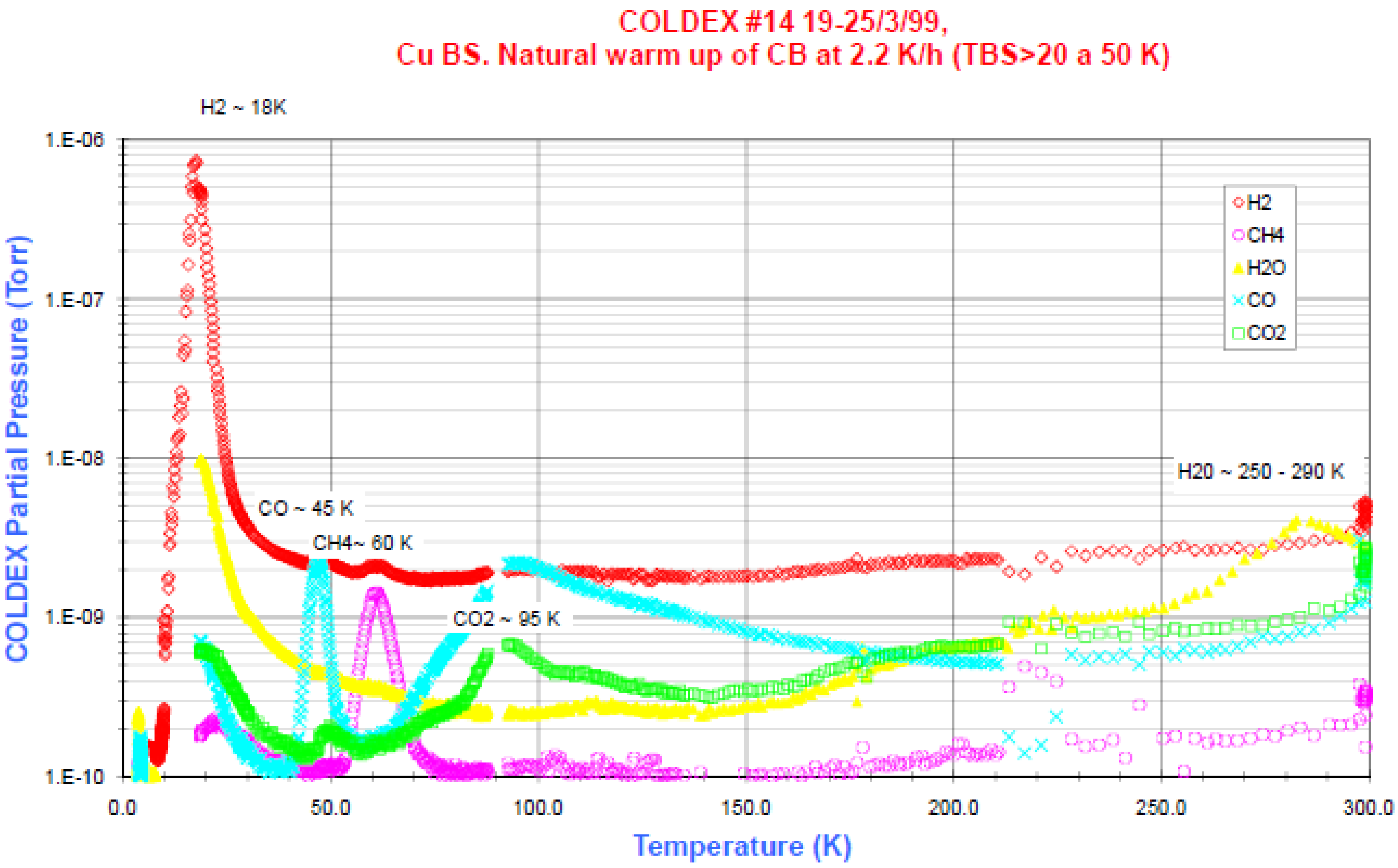
1 eV/k = 11,604.5 K	Superfluid He	Liquid He		~LN$_2$ (77K)
E(eV)	**1.9 K**	**4.2 K**	**50 K**	**70 K**
0.01	1 10^6 years	0.1 s	1 ps	0.5 ps
0.02	∞	3 10^3 years	10 ps	2 ps
0.15	∞	∞	130 s	6 ms
0.21	∞	∞	5 years	130 s
0.3	∞	∞	1 10^4 years	12 years

Sojourn time - Physisorbed molecules

- **Physisorption** occurs:
  below 23 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



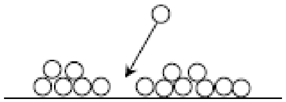
A Natural Warm Up of a St. Steel Cold Bore



Cryopumping regimes/mechanisms

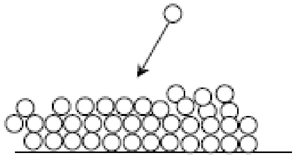
Physisorption

- 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 respectively
- 1 h sojourn time at 5.2 K and 26 K for smooth and porous materials resp.



Condensation

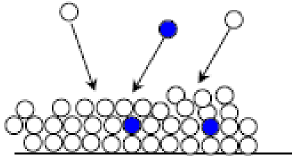
- For thick gas coverage, only forces between gas molecules
- Energy of vaporisation 9 to 175 meV for H_2 and CO_2 resp.
- 1 h sojourn time at 2.8 K and 53.4 K for H_2 and CO_2 resp.



➔ 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 an **easily condensable carrier** (*e.g.* Ar) to trap molecules with **a high vapor pressure gas** (*e.g.* He, H_2)



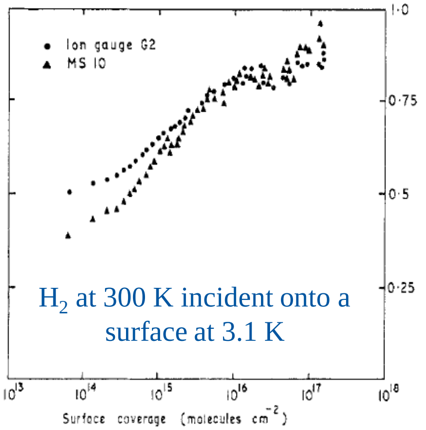
Sticking probability/coefficient

- Probability : $0 < \sigma < 1$

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

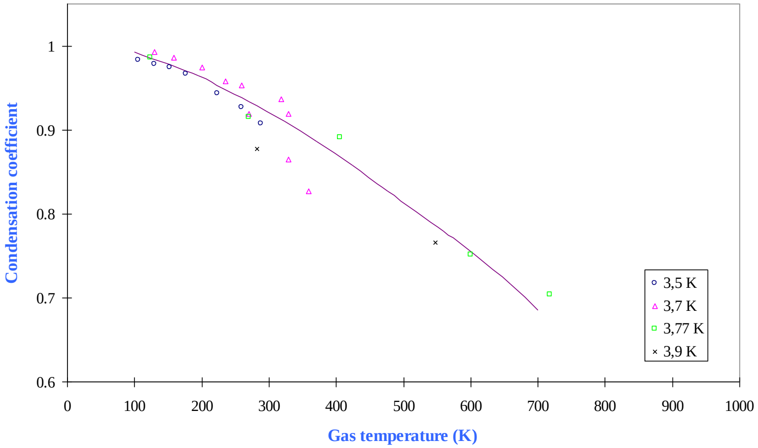
$$\boxed{\sigma = \frac{\nu_{\text{incident}} - \nu_{\text{departing}}}{\nu_{\text{incident}}} = \frac{\nu_{\text{sticking}}}{\nu_{\text{incident}}}}$$

- Function of the gas specie, surface condition, surface coverage, temperature of gas and surface



H_2 at 300 K incident onto a surface at 3.1 K

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

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

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

i.e : σ multiplied by the conductance of a surface

A = area sample (m^2); <v>=MB averag. veloc.

- H_2 and CO at 4.2 K :

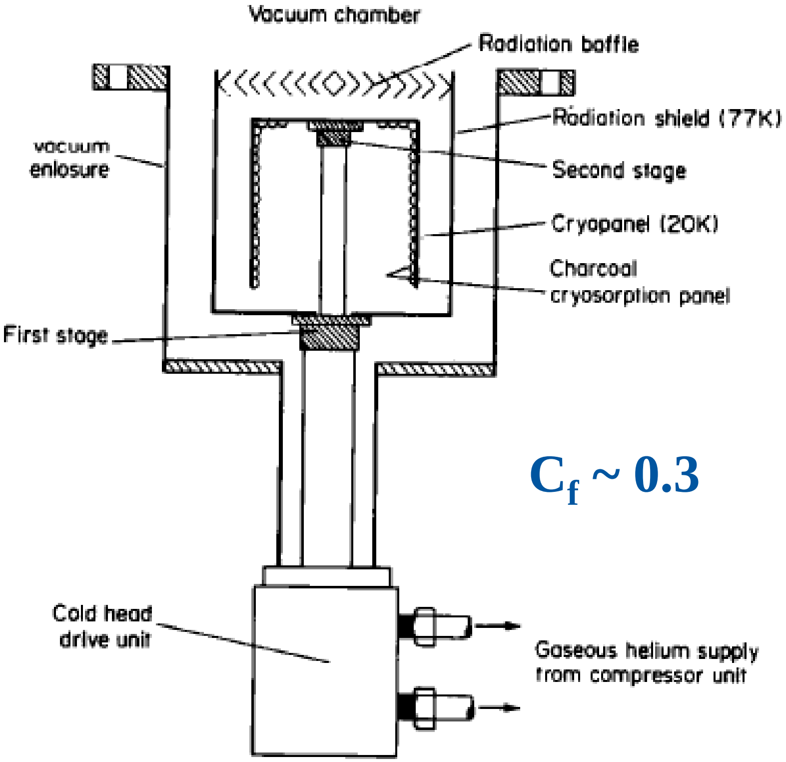
  $S_{H2} = 5.3$ ℓ.s^{-1}·cm^{-2}

  $S_{CO} = 1.4$ ℓ.s^{-1}·cm^{-2}

Capture factor, C_f

- The **capture factor** takes into account the **geometry 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

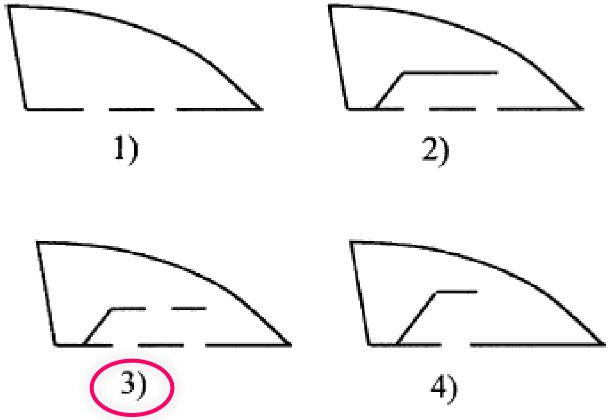


Fig. (1) Two slots in the beam screen, without electron shield, (2) two slots in the beam screen, electron shield without slot, (3) two slots in the beam screen, electron shield with slot, (4) only one slot in the beam screen, electron shield without slot.

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

LHC Beam Screen hole's Pumping Speed

- Operating temperature ~ 15 K : molecule's kinetic energy is accommodated to the vacuum chamber walls, T = 15 K

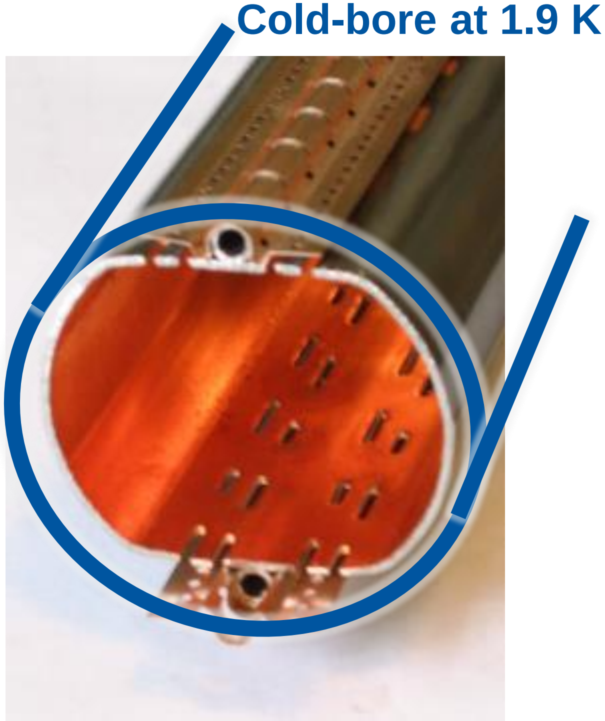
- Transparency, t=4.4%, Capture factor, C_f=0.5

- Horizontal width 4,6 cm
    - Specific surface area A = 1445 cm^2/m

$$S_{holes} = 3{,}63 \cdot A \cdot t \cdot C_f \cdot \sqrt{\frac{T}{M}}$$

	H_2	CH_4	CO	CO_2
ℓ/s/m at 15 K	316	112	84	67

Cold-bore at 1.9 K

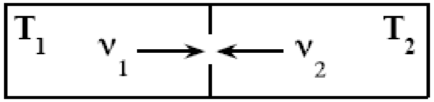


- Assume P = 2 10^{-9} mbar (10^{15} H_2/m^3) at 15 K, what is the quantity, Q, of gas pumped per m?
- 1 mbar · ℓ at 15 K ⬄ G= 6.4 · 10^{20} molecules
    -

- **<u>At LHC design pressure</u>, ~ monolayers per s per m are pumped on the cold bore**

Thermal transpiration

- **What is the pressure (gas density) in a cryogenic tube?**
  - Vacuum gauges are usually located at room temperature to reduce heat load and have more accessibility
- For small aperture, the impingment rate, ν, is conserved at the cold / warm transition



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

- Since the average velocity scales like √T

- Pressure scaling

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

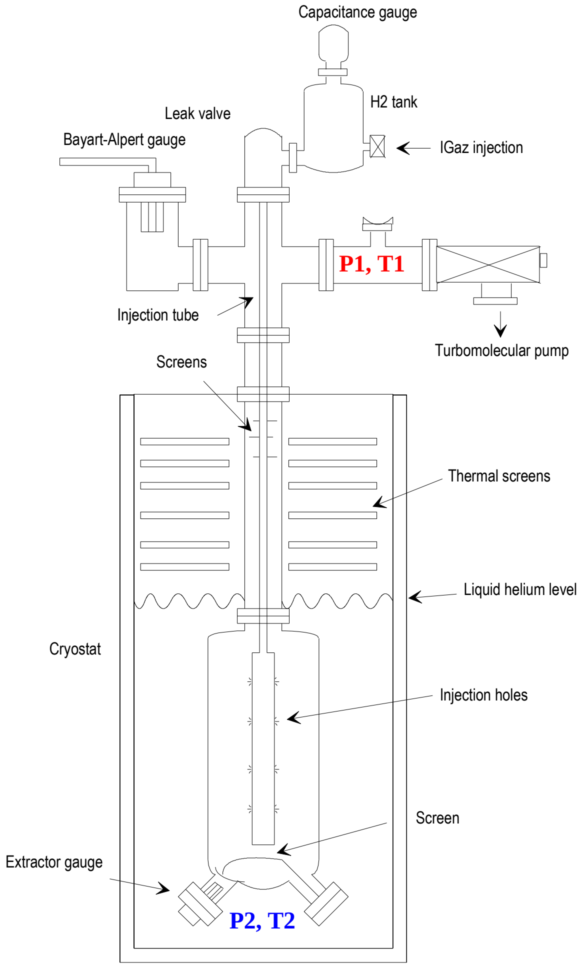
- Density scaling

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

- In practice:

T_1 (K) = 300 K

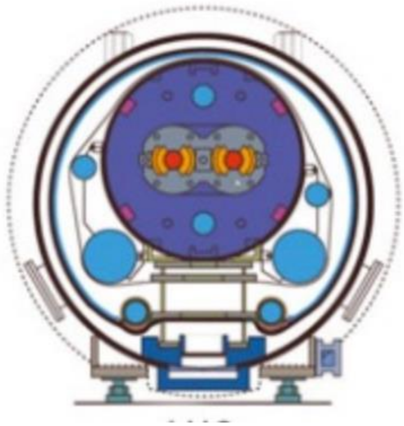
T_2 (K)	4.2	77
P_1/P_2	8	2

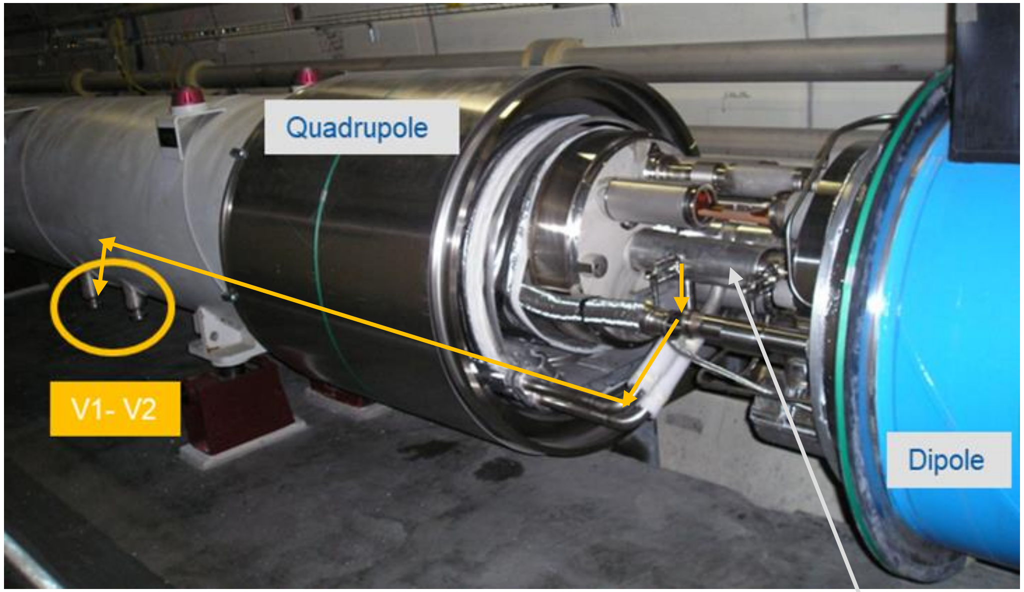


Pressure measurement in a cryogenic machine

- What and how is the pressure measured by <u>a gauge located at room temperature</u> for a given gas density in the LHC beam screen at 15 K?

$$P_{300} = n\,k\,T_{BS}\sqrt{\frac{300}{T_{BS}}}$$





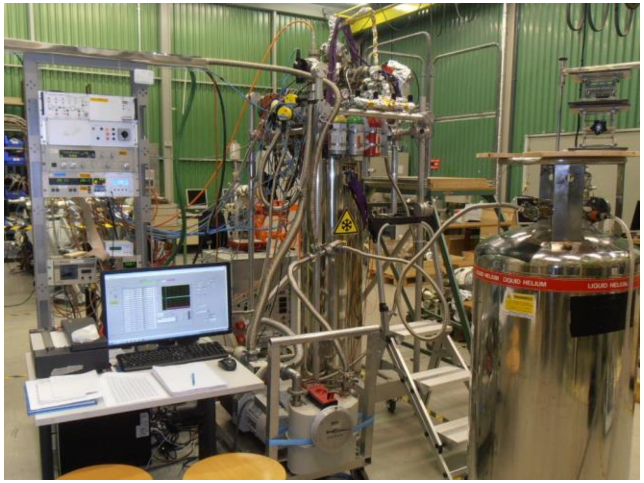
n (H_2/m^3) *(year)*	$1\ 10^{15}$ (design)	$2.25\ 10^{13}$ (2015)	$2.5\ 10^{12}$ (2018)
P at 15 K (mbar)	$2\ 10^{-9}$	$5\ 10^{-11}$	$5\ 10^{-12}$
P at RT (mbar)	$1\ 10^{-8}$	$2\ 10^{-10}$	$2\ 10^{-11}$

BS

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**

$$\theta = c\,P$$

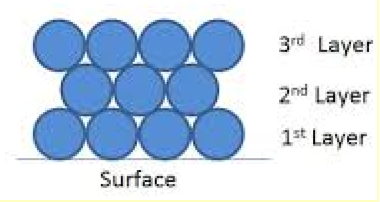
DRK (Dubinin, Radushkevich and Kaganer) for metallic, glass and porous substrate. **Valid at low pressure**. **Good prediction with temperature variation**

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

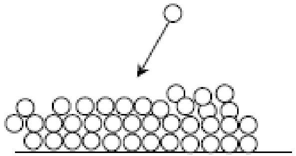
BET (Brunauer, Emmet and Teller). **Multi-monolayer description**

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

$\alpha = \exp(\Delta E/kT) >> 1$

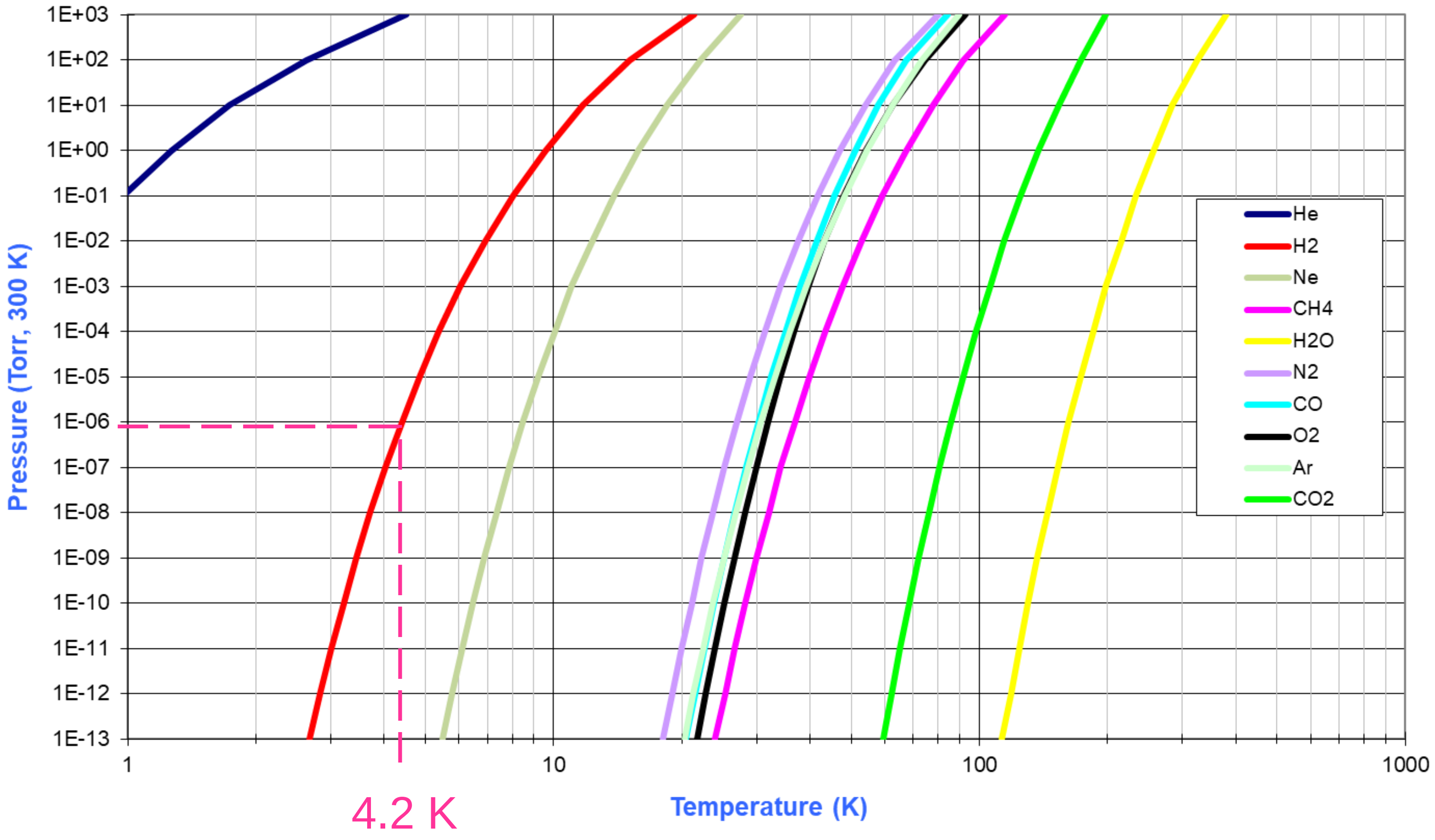


Saturated Vapor Pressure



- Pressure over liquid or gas phase (**many monolayers condensed →**)
- Follows the **Clausius-Clapeyron equation**: **$\log P_{sat} = A - B/T$**
- For a smooth surface:

Saturated vapour pressure from Honig and Hook (1960)

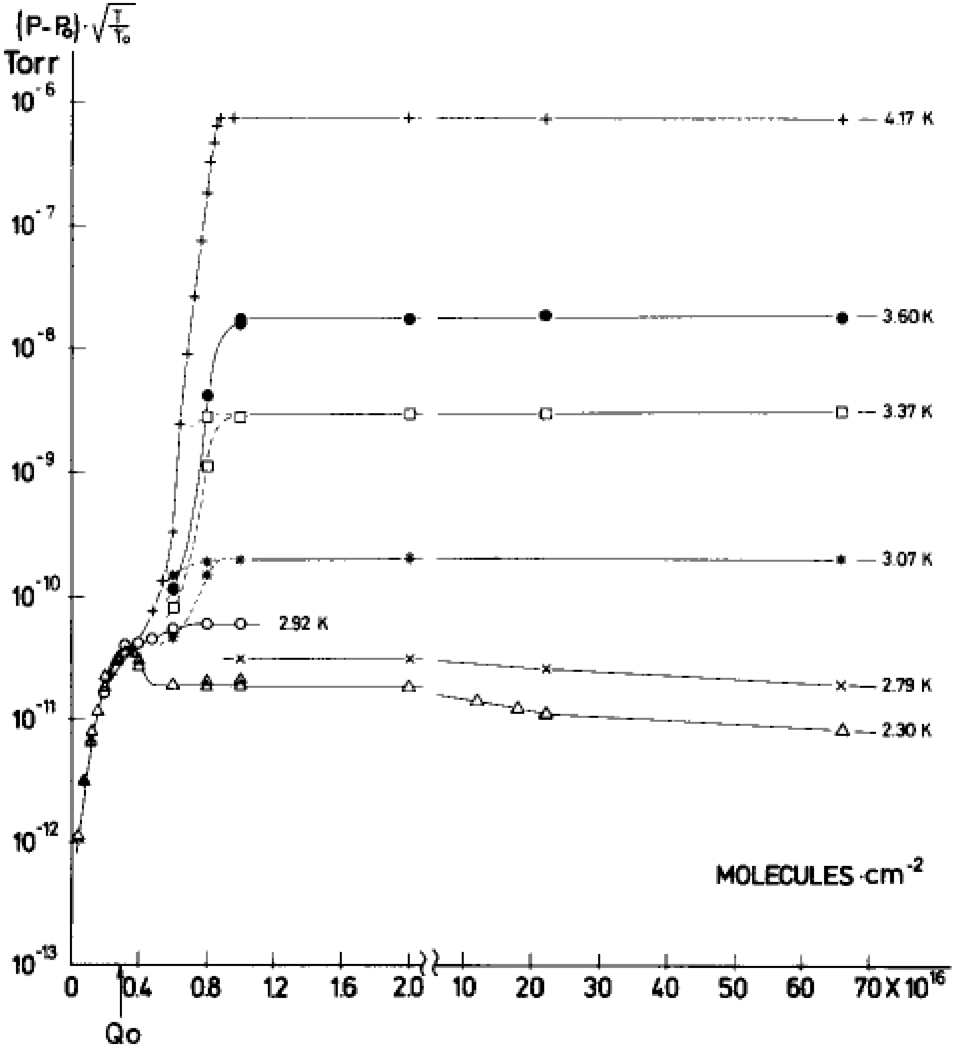


H_2 Adsorption Isotherm on Stainless Steel

- 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



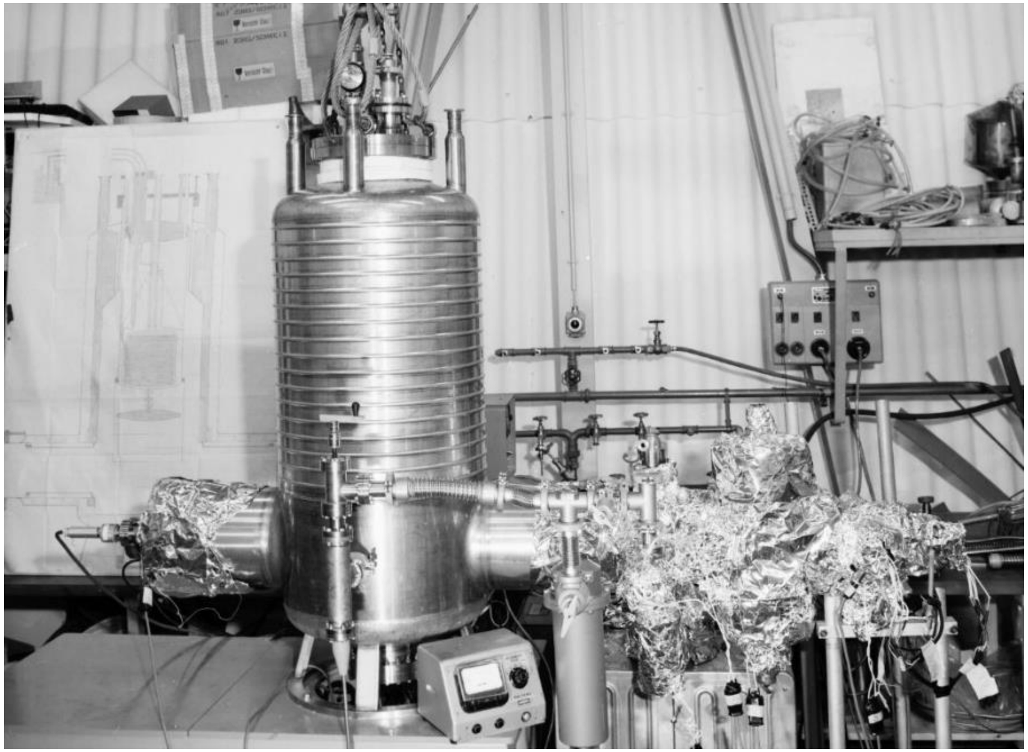
Q_o = one monolayer

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

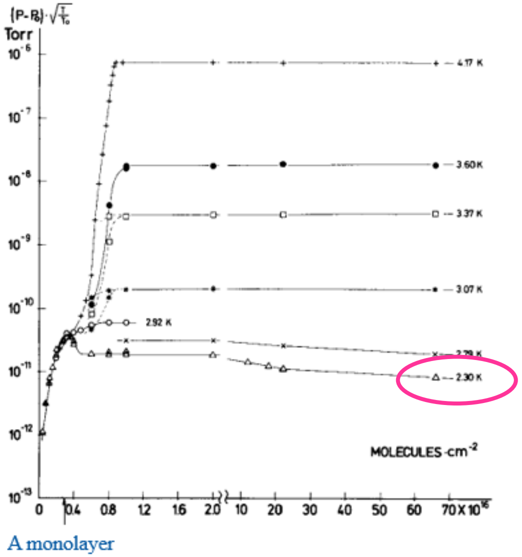
H_2 adsorption isotherm on stainless steel

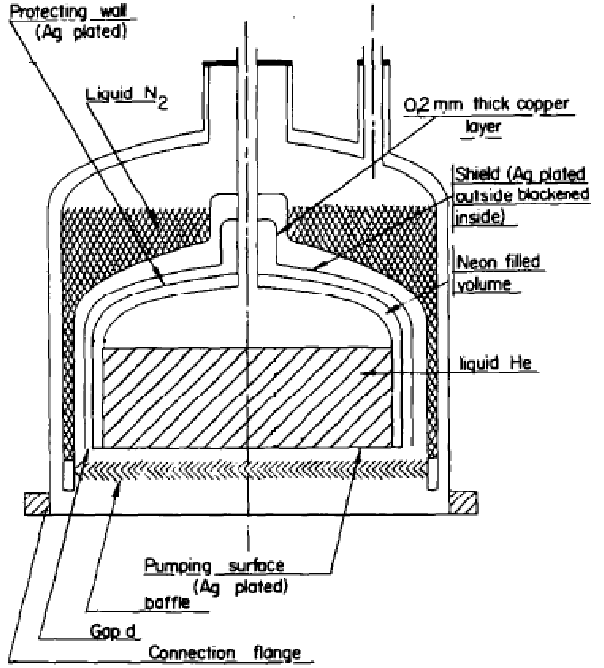
- A condensation cryopumps allows to pump large quantities of H_2 at 2.3 K.

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



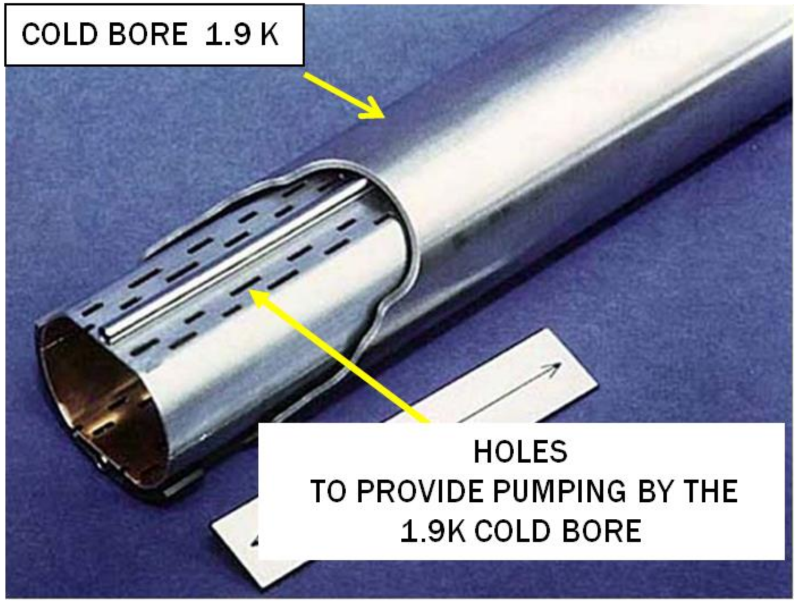
C. Benvenuti *et al*. Vacuum, 29, 11-12, (1974) 591



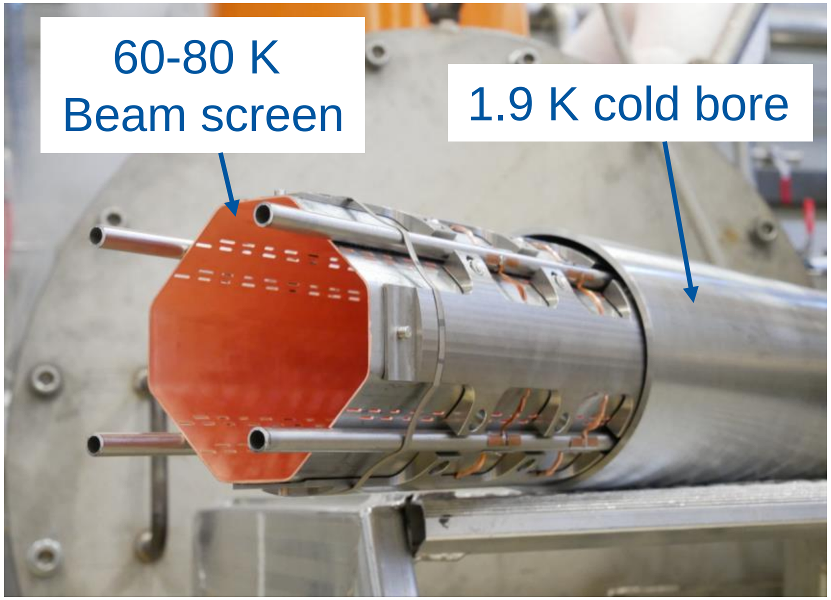


LHC and HL-LHC cold bores

- Operating at 1.9 K are modern integrated and distributed condensation cryo-pumps !!!



The Large Hadron Collider:
A marvel of Technology by L. Evans
Open Access book
Availlable at CERN Document Server



The High Luminosity
Large Hadron Collider
by O. Brüning & L. Rossi
Open Access book
https://doi.org/10.1142/13487

H_2 adsorption isotherms from 8 to 20 K

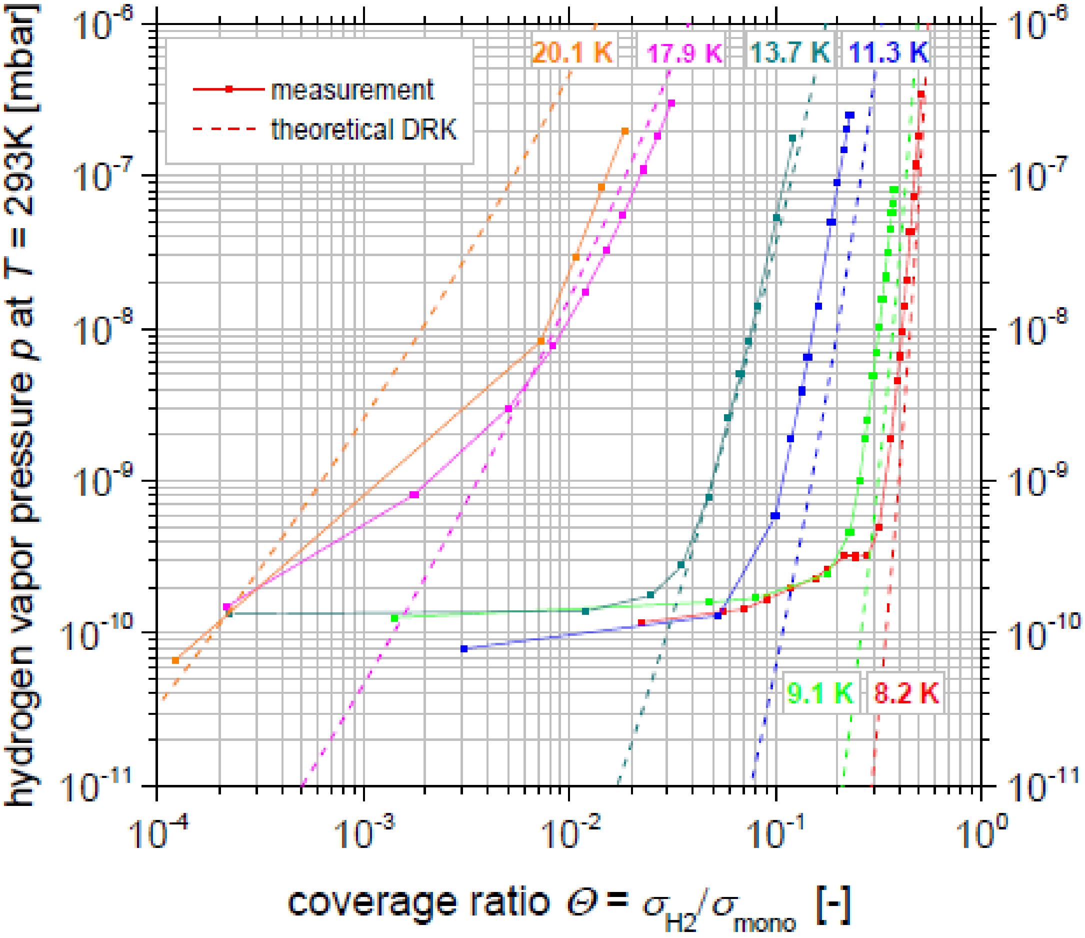
- The surface capacity strongly decreases when increasing the surface temperature

- Stainless steel

- DRK description

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

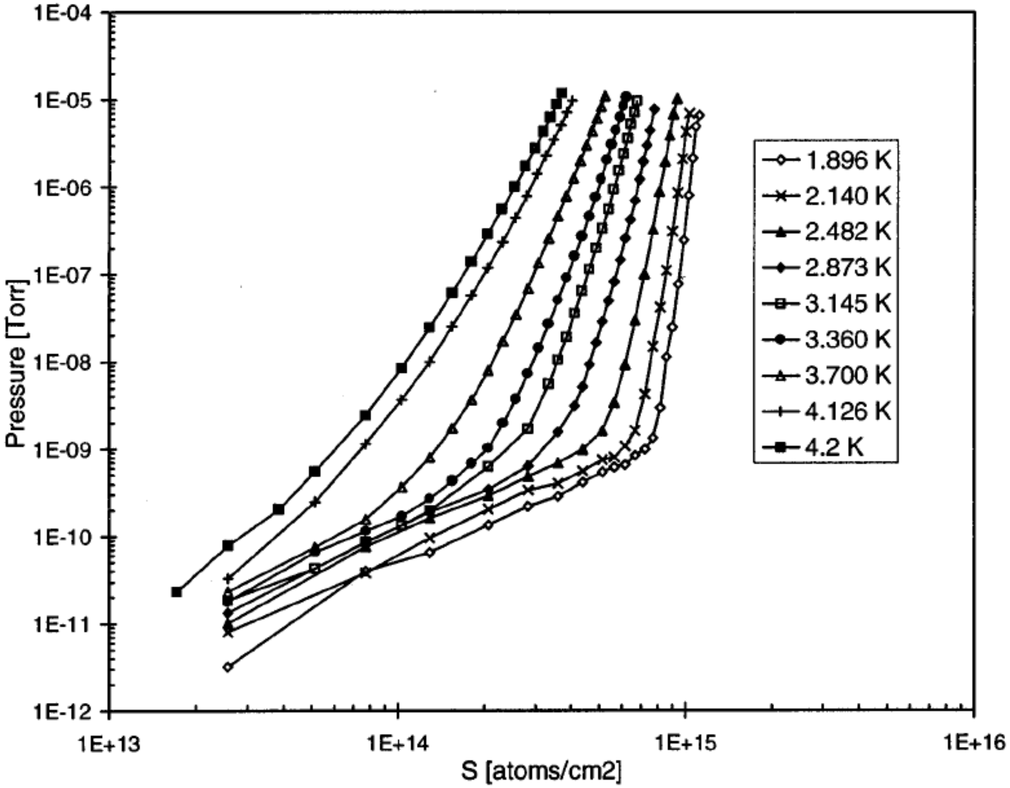
- D = 3125 eV^{-2}
- $\Theta_m = 7\ 10^{14}\ H_2/cm^2$



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

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
- $\theta_m \sim 1.3\ 10^{15}\ H_2/cm^2$
- Stainless steel



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

H_2 Isotherms for Industrial Surfaces

- Identification of two types of adsorption sites with:
  1) high energy (pores, defects)
  2) low energy (flat surface).

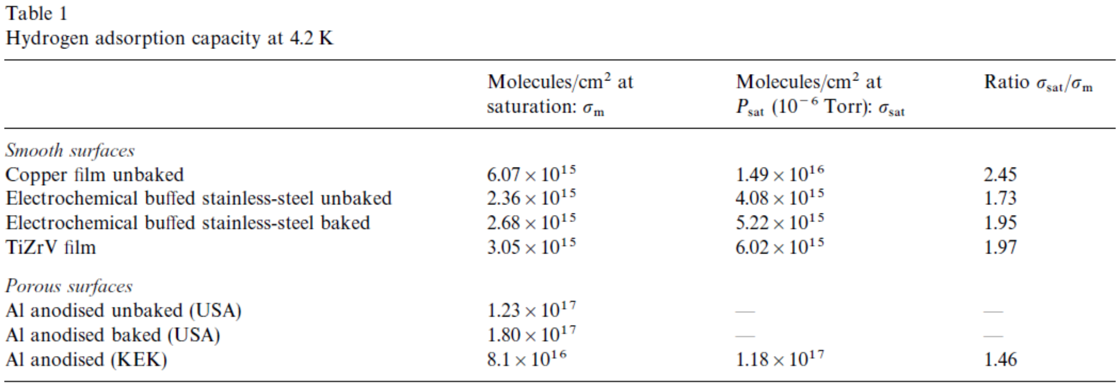


Table 1
Hydrogen adsorption capacity at 4.2 K

	Molecules/cm^2 at saturation: σ_m	Molecules/cm^2 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

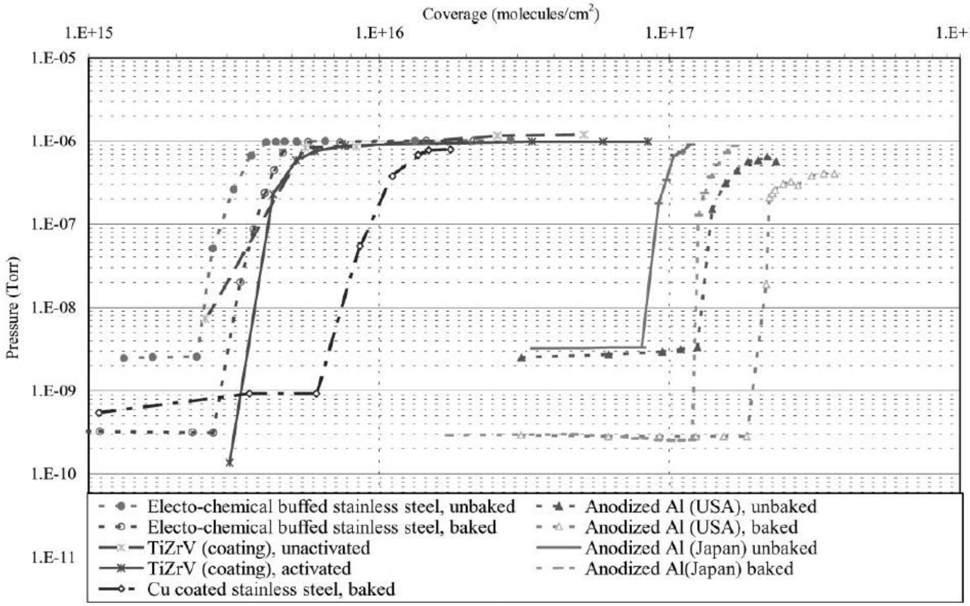


Fig. 3. Hydrogen adsorption isotherm at 4.2 K for various samples.

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

Cryosorbing materials

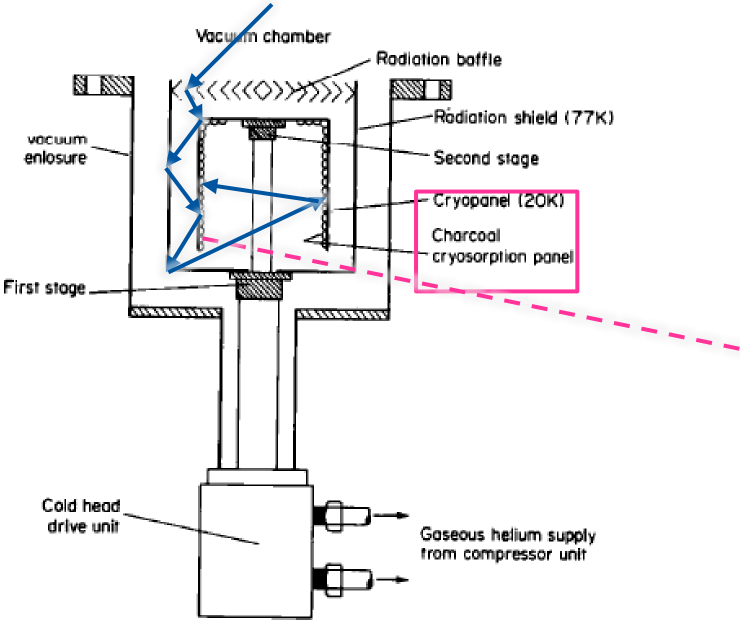
- Large capacity
- Large pumping speed
- Large temperature working range (up to ~ 30 K)

e.g. **activated charcoal** used for cryopumps

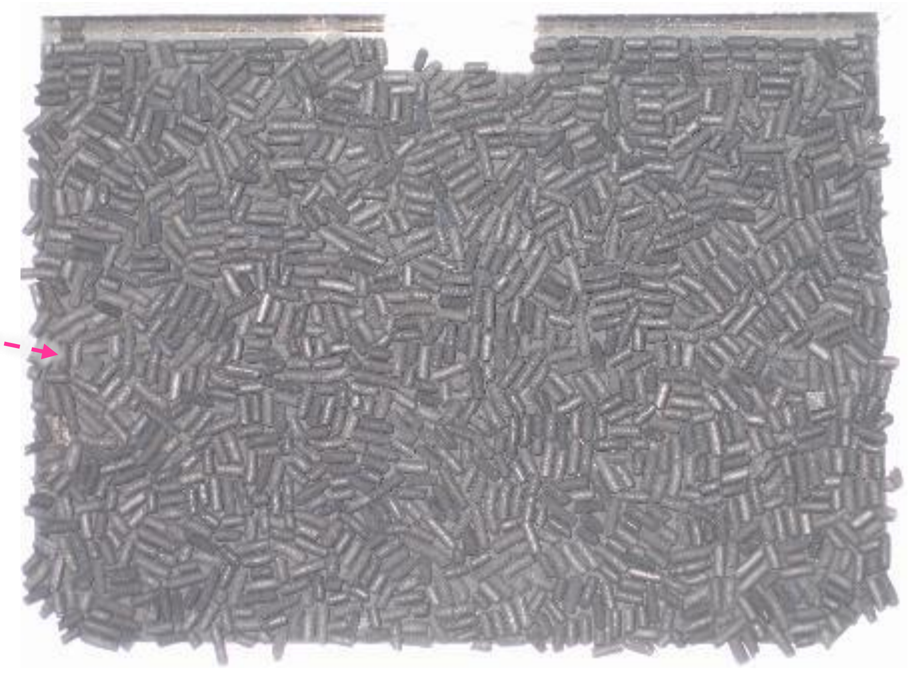
Capacity **~ 10^{22} H_2/g** i.e. **10^{21} monolayers** (P. Redhead, Physical basis of UHV,1968)

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

used for cryopanels held at **20 K**



COMMERCIAL CRYOPUMP

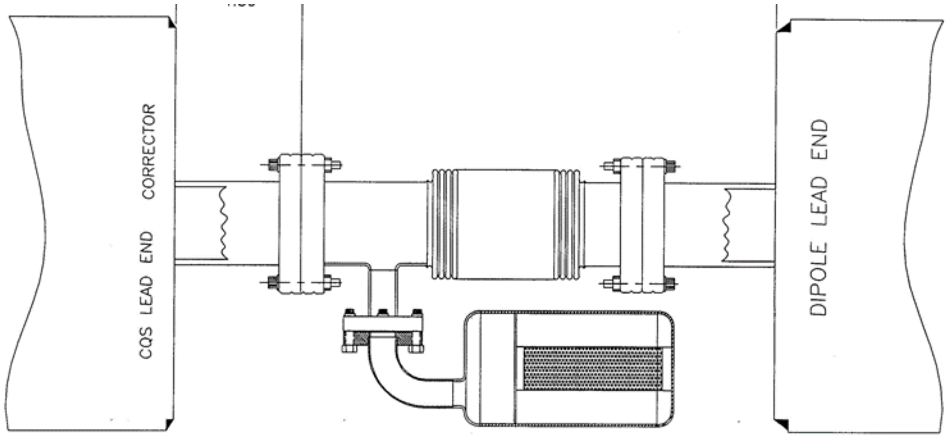


RHIC, Brookhaven, USA

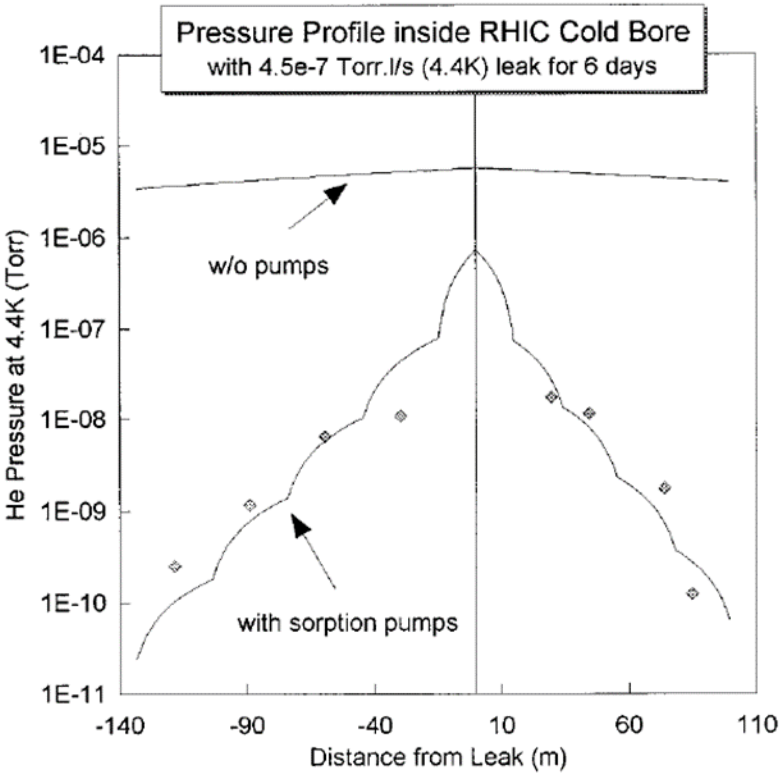
- RHIC's solution: anticipate leaks !!
- RHIC use sorption pumps based on 300 g of activated charcoal.
- They are located every 30 m to mitigate He leaks and to pump H_2

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.

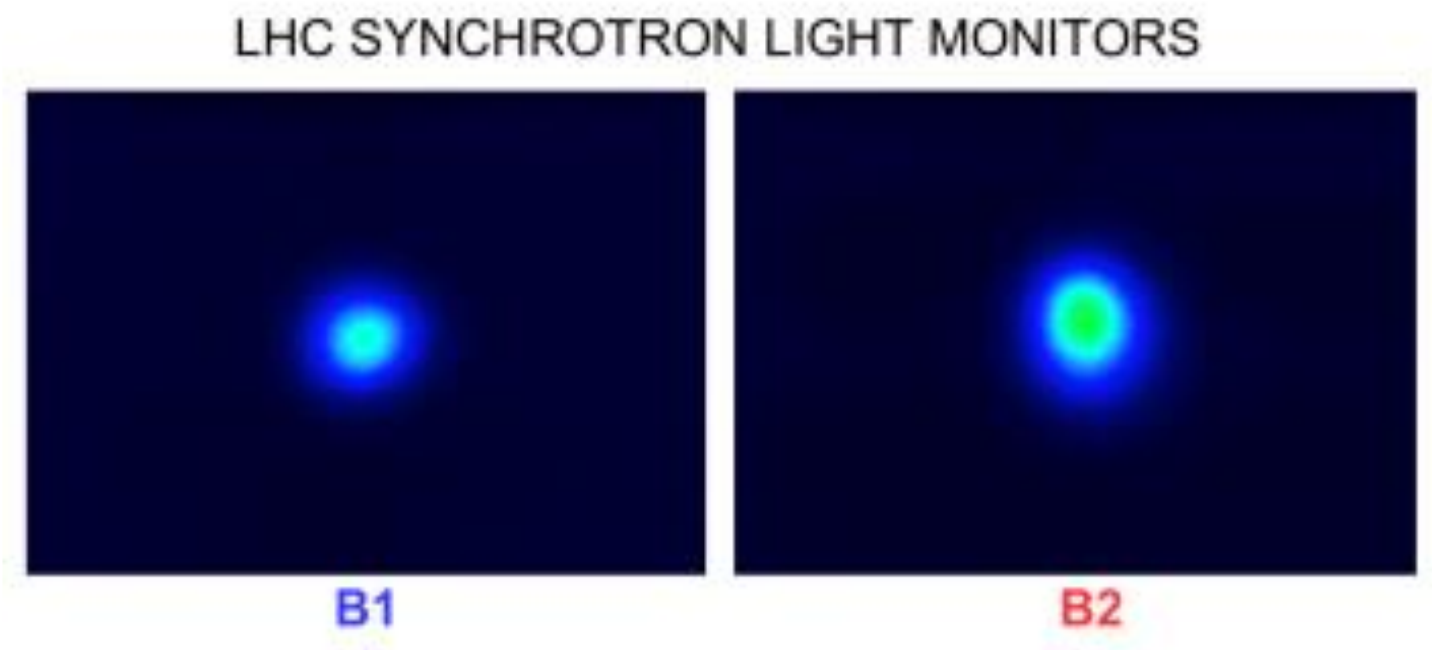
Cryo-vacuum: Summary

- Gas can be physisorbed for very long period on **cryogenic surfaces**
- The sticking coefficient characterises the pumping speed of a surface
- The capture coefficient characterises 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 depend very much on the conditions
- Some material can be porous so to adsorb many monolayers of gas without reaching the saturated vapour pressure: cryosorbers

3. Synchrotron radiation

Synchrotron radiation: visible light

- In a synchrotron, charged particles can radiate light by synchrotron radiation
- This effect can be used for diagnostics purposes



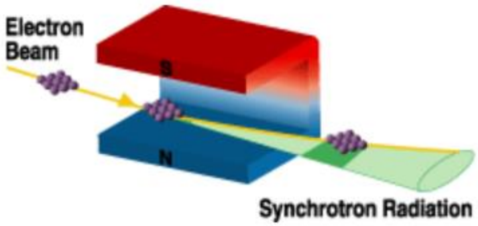
CERN Control Centre LHC beams SR displays

- Particles lose energy by synchrotron radiation ➔ should be compensated by RF system
- Beam emittance shrinks upon emission of synchrotron radiation (*damping wigglers*)

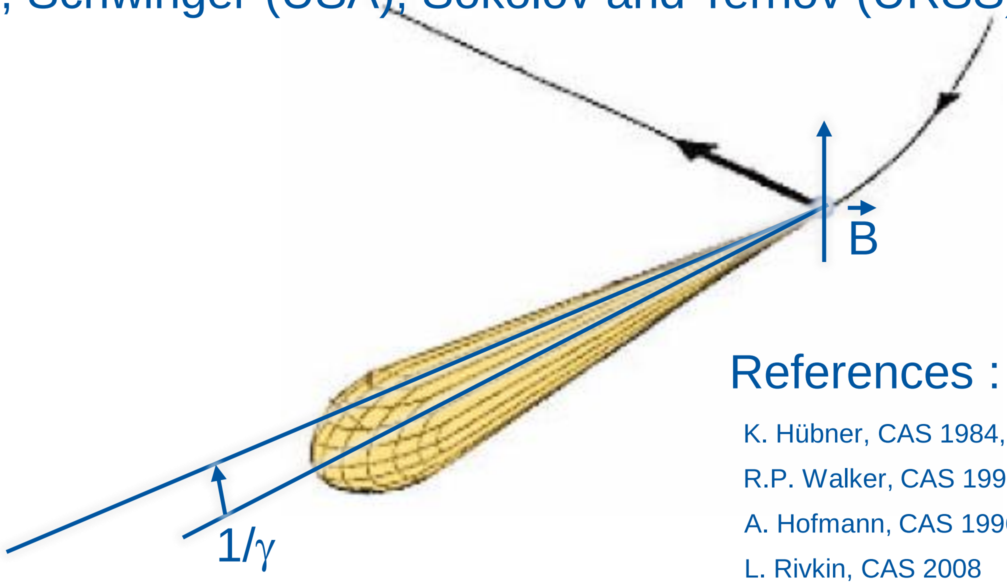
- Power is dissipated on the machine elements: **power density** , W/mm^2, can be extremely HIGH!
- **Molecules are desorbed from the vacuum chamber wall due to synchrotron radiation**

Synchrotron Radiation

- A charged particle which is accelerated generate radiation (*magnetic bremsstrahlung*)
- The power of the centripetal radiation is larger than the longitudinal radiation (factor γ^2)
- For a relativistic particle, the radiation is highly peaked (opening angle ~ $1/\gamma$)
- **The radiation energy range from infrared to gamma rays: from meV to MeV**
- The SR theory dated from 1950, Schwinger (USA), Sokolov and Ternov (URSS)



γ=relativistic factor



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K. Hübner, CAS 1984, CERN 85-19

R.P. Walker, CAS 1992, CERN 94-01

A. Hofmann, CAS 1996, CERN 98-04

L. Rivkin, CAS 2008

Critical energy

- The critical energy split the power spectrum in two equals parts

$$\boxed{\varepsilon_c = \frac{3}{2}\frac{\mathrm{hc}}{2\pi}\frac{\gamma^3}{\rho}}$$

$$\text{Electrons: } \varepsilon_c[\mathrm{eV}] = 2.218 \times 10^3 \frac{\mathrm{E[GeV]}^3}{\rho[\mathrm{m}]}$$

$$\text{Protons: } \varepsilon_c[\mathrm{eV}] = 3.5835 \times 10^{-7} \frac{\mathrm{E[GeV]}^3}{\rho[\mathrm{m}]}$$

- ~ 88 % of the emitted photons have an energy lower than the critical energy

- Magnetic rigidity:

$$\mathrm{B}\,\rho = \frac{p}{\mathrm{e}} \approx \frac{\mathrm{E}}{\mathrm{e\,c}} \qquad \frac{1}{\rho} \approx \frac{3}{10}\frac{\mathrm{B[T]}}{\mathrm{E[GeV]}} \qquad \boxed{\varepsilon_c \propto \frac{\mathrm{E}^3}{\rho} \propto \mathrm{B\,E}^2}$$

Dissipated power

- The average power emitted by the beam **per unit of length** is

$$P_0\,[\mathrm{W/m}] = \frac{e}{3\varepsilon_0 \left(m_0 c^2\right)^4} \frac{E^4}{2\pi\rho^2} I$$

- Electrons :

$$P_0\,[\mathrm{W/m}] = 88.57 \frac{E[\mathrm{GeV}]^4}{2\pi\,\rho[\mathrm{m}]^2} I[\mathrm{mA}]$$

- Protons:

$$P_0\,[\mathrm{W/m}] = 7.79\;10^{-12} \frac{E[\mathrm{GeV}]^4}{2\pi\,\rho[\mathrm{m}]^2} I[\mathrm{mA}]$$

- For the total dipole radiation power dissipated around the ring, **multiply by 2πρ**

- **Protons generate a lot less SR compared to electrons** because there is a $1/m_0^4$ dependency in the formula for the radiated power, where m_0 is the mass of the radiating particle. Protons are 1836 times heavier than electrons, so the reduction factor is $\sim 8.8 \cdot 10^{-14}$

$$\frac{88.57}{7.79 \times 10^{-12}} = (1836)^4$$

1836 = ratio of proton to electron mass

Linear photon flux

- The **photon flux per unit of length** is given by :

$$\dot{\Gamma} = \frac{15\sqrt{3}}{8}\,\frac{P_0}{\varepsilon_c} = \frac{5\sqrt{3}e}{12\,h\,\varepsilon_0 c}\,\frac{\gamma}{\rho}\,I$$

$$\boxed{\dot{\Gamma} \propto \frac{E}{\rho}\,I \propto B\,I}$$

- Electrons :

$$\boxed{\dot{\Gamma}[\text{photons.m}^{-1}.\text{s}^{-1}] = 1.28810^{17}\,\frac{E[\text{GeV}]}{\rho[\text{m}]}\,I[\text{mA}]}$$

- Protons:

$$\boxed{\dot{\Gamma}[\text{photons.m}^{-1}.\text{s}^{-1}] = 7.01710^{13}\,\frac{E[\text{GeV}]}{\rho[\text{m}]}\,I[\text{mA}]}$$

- **Example 1:**

ESRF-1 (Grenoble):
(high-energy
light source)

ρ = 23.366 m

I = 200 mA

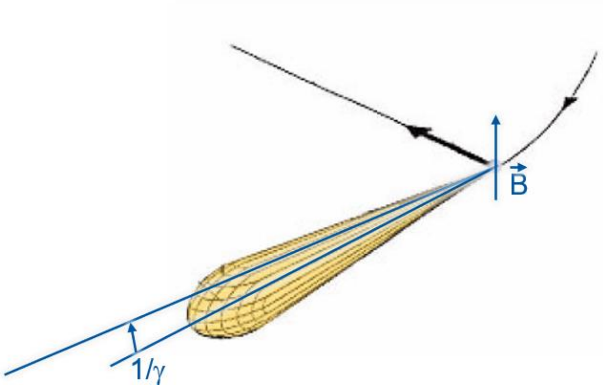
E = 6 GeV

ε_c = 20.503 keV

F = 6.604 10^{18} ph/s/m

P = 6.692 kW/m

$1/\gamma$ = 82.5 µrad → **0.82 mm @10 m**



- **Example 2:**

LHC (CERN):
(high-energy proton storage ring)

ρ = 2784 m

I = 584 mA

E = 7 000 GeV

ε_c = 44 eV

F = 1 10^{17} ph/s/m

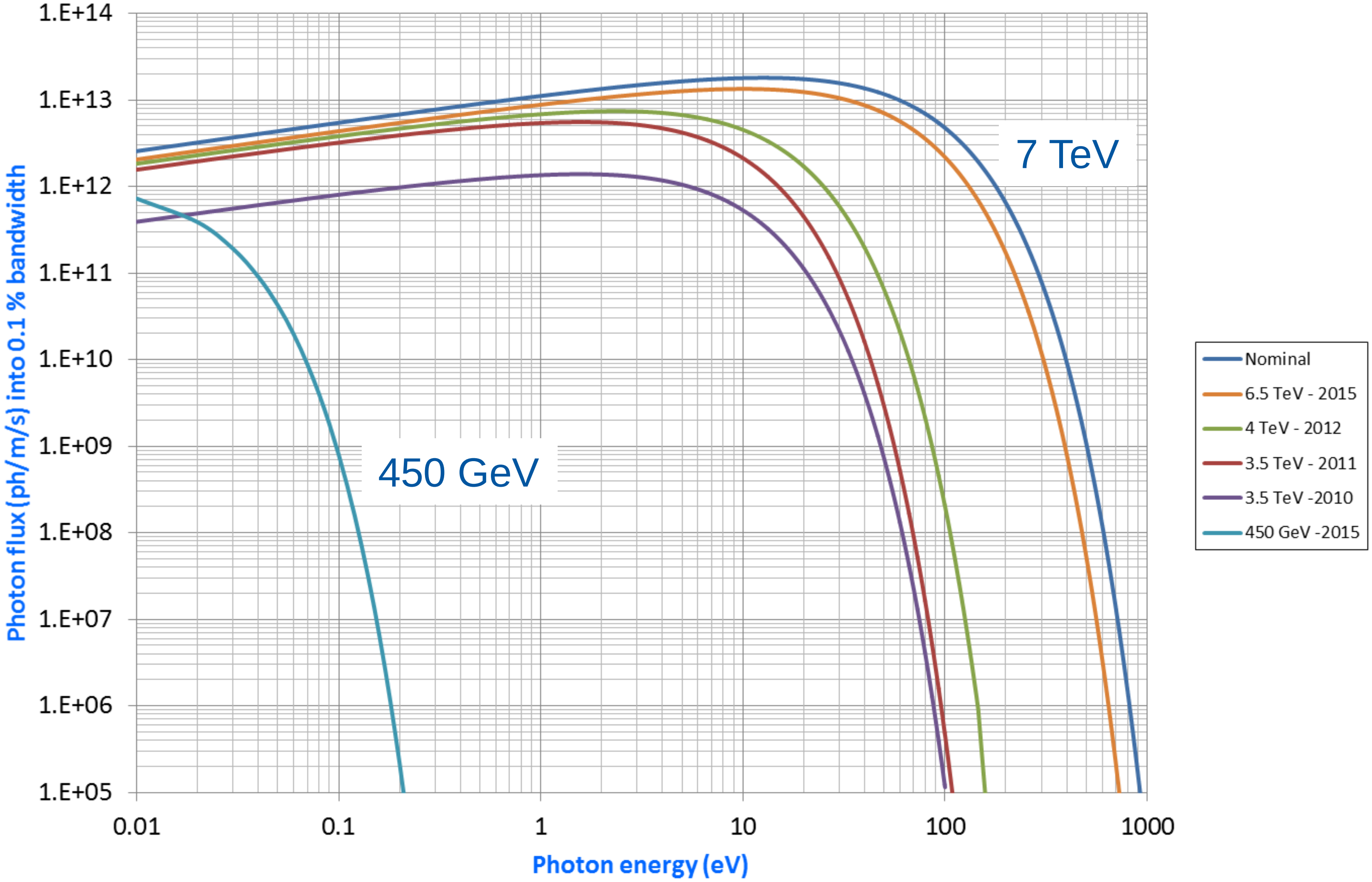
P = 0.2 W/m

$1/\gamma$ = 134 µrad → **1.34 mm @10 m**

LHC SR Spectrum : from IR to UV

- With nominal parameters : 7 TeV and 585 mA
- 2010, 2011, 2012 and 2015 spectra

Key parameter: photodesorption yield



LEP SR spectrum: harder spectrum, X-rays & gamma rays

- LEP: electron-positron collider; was installed in the (now) LHC tunnel before LHC; same circumference (26.8 km)

- **Example 3:**

LEP (CERN): (high-energy COLLIDER)

ρ = 2963 m

I = 4 mA

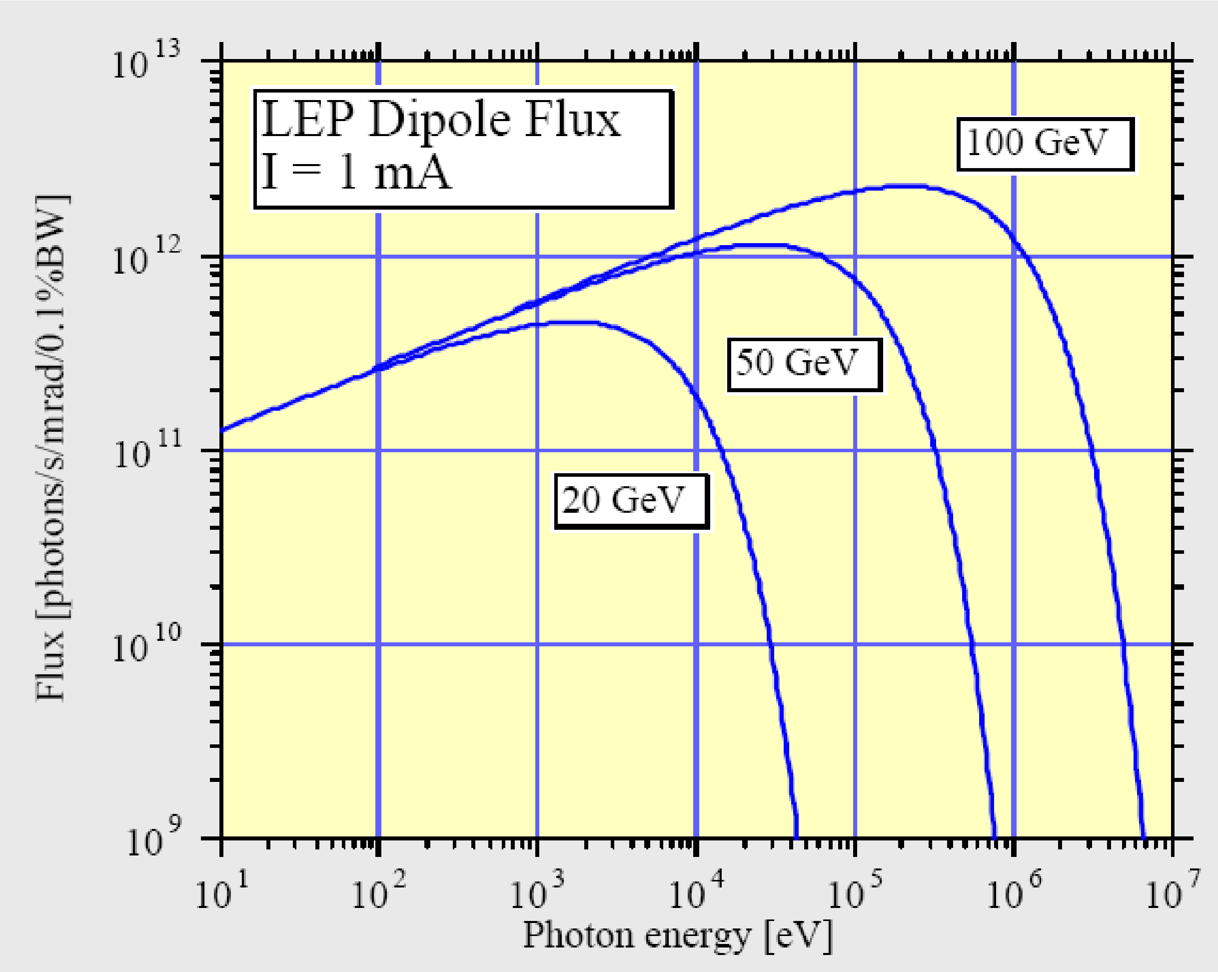
E = 100 GeV (up to 104)

ε_c = 748.6 keV ←

F = $1.736 \cdot 10^{16}$ ph/s/m

P = 0.642 kW/m

$1/\gamma$ = 5.11 μrad → **0.511 mm <u>@100 m</u>**



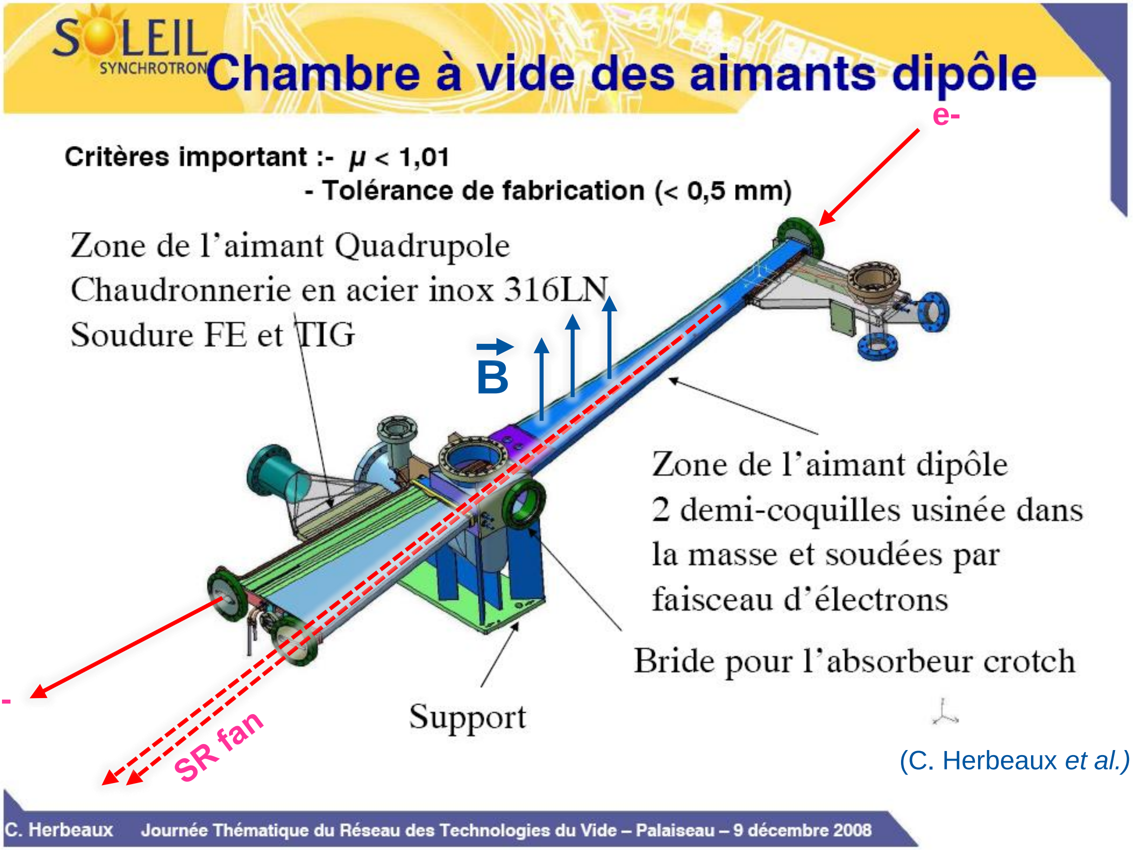
SR impact on different type of machines …

		Soleil	KEK-B		LEP			LHC	
			LER	HER	Inj.	1	2	Inj.	Col.
Particle		e^-	e^+	e^-	e^-	e^-	e^-	p	p
Beam current	mA	500	2600	1100	3	3	7	584	584
Energy	GeV	2.75	3.5	8	20	50	96	450	7000
Bending radius	m	5.36	16.31	104.46	2962.96			2784.302	
Power	W/m	14 030	20 675	5 820	0.8	30	955	0	0.2
Critical energy	eV	8 600	5 800	11 000	6 000	94 000	660 000	0	44
Photon flux	photons/m/s	$3\ 10^{19}$	$7\ 10^{19}$	$1\ 10^{19}$	$3\ 10^{15}$	$7\ 10^{15}$	$3\ 10^{16}$	$7\ 10^{15}$	$1\ 10^{17}$
Dose at 3000 h	photons/m	$4\ 10^{26}$	$8\ 10^{26}$	$1\ 10^{26}$	$3\ 10^{22}$	$7\ 10^{22}$	$3\ 10^{23}$	$7\ 10^{22}$	$1\ 10^{24}$

- In LEP, and all synchrotron light sources, the evacuation of the **power is an issue**
- The LHC operates at 7 TeV with ~ 0.6 A. **Power evacuation is an issue for the cryogenic system (1 kW/arc), due to the low Carnot efficiency at low temperature**
- The critical energy varies from a few 10 eV to 660 keV. **Strongly bound molecules can be desorbed**
- The photon flux is large, so large gas load. **Adequate dimensioning of the effective pumping** speed is required
- The annual integrated photon dose is large. **Implications on gas reduction and radiation (next lecture)**

… heavy consequences on design

- Stainless steel
- NEG coated, in-situ baked to 180ºC



SOLEIL SYNCHROTRON

Chambre à vide des aimants dipôle

Critères important :- $\mu < 1{,}01$
- Tolérance de fabrication (< 0,5 mm)

Zone de l'aimant Quadrupole
Chaudronnerie en acier inox 316LN
Soudure FE et TIG

Zone de l'aimant dipôle
2 demi-coquilles usinée dans la masse et soudées par faisceau d'électrons

Bride pour l'absorbeur crotch

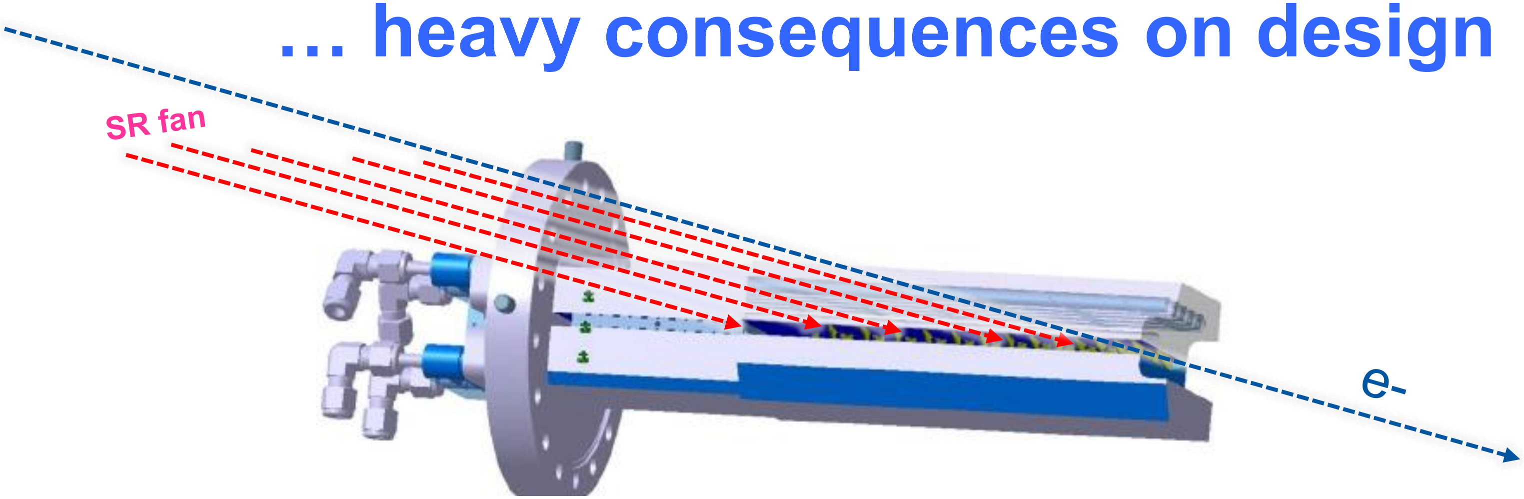
Support

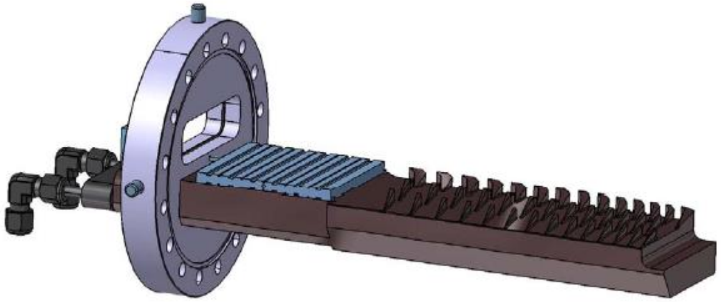
C. Herbeaux Journée Thématique du Réseau des Technologies du Vide – Palaiseau – 9 décembre 2008

(C. Herbeaux *et al.)*

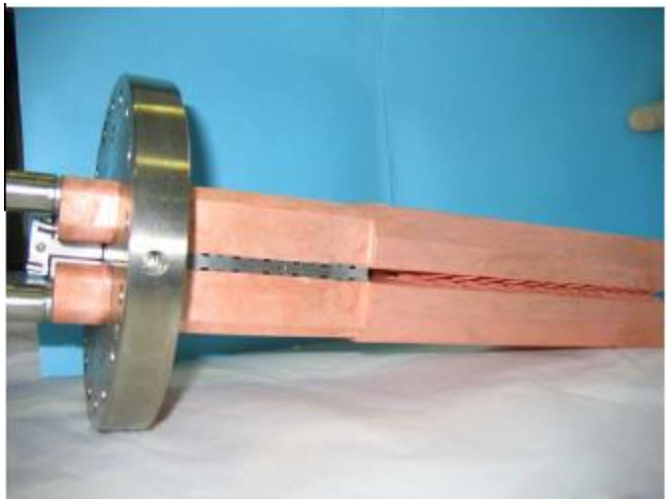
- A complex vacuum chamber design with a light extraction path, pumping and instrumentation ports and power absorbers (crotch)

… heavy consequences on design





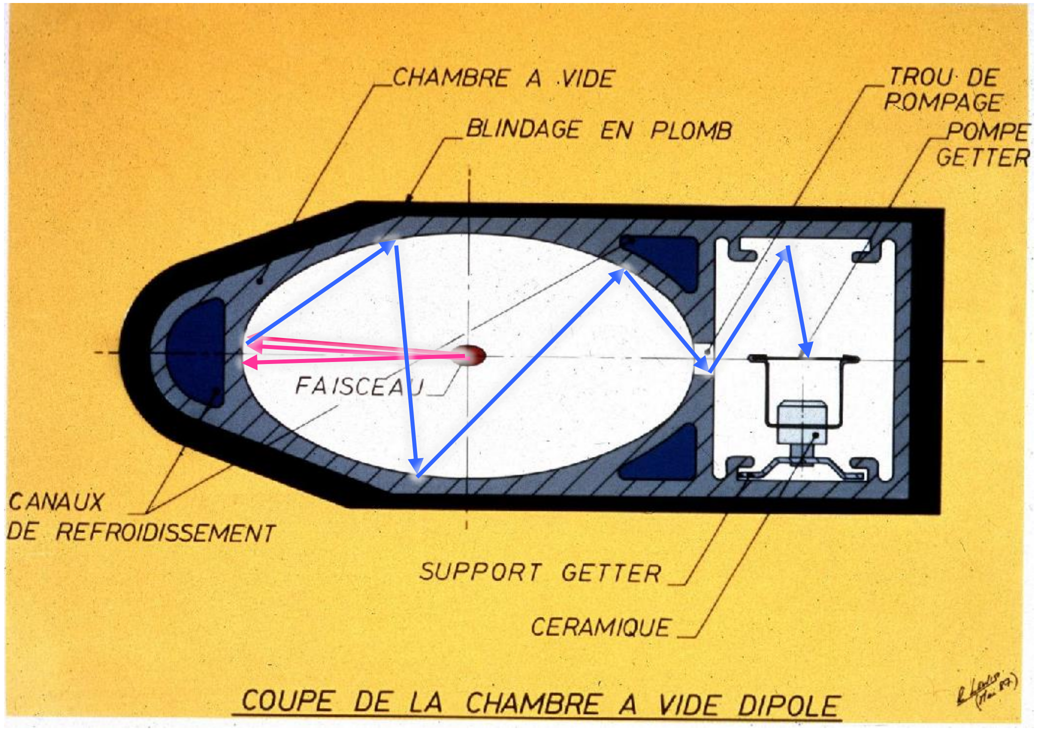
SOLEIL Design

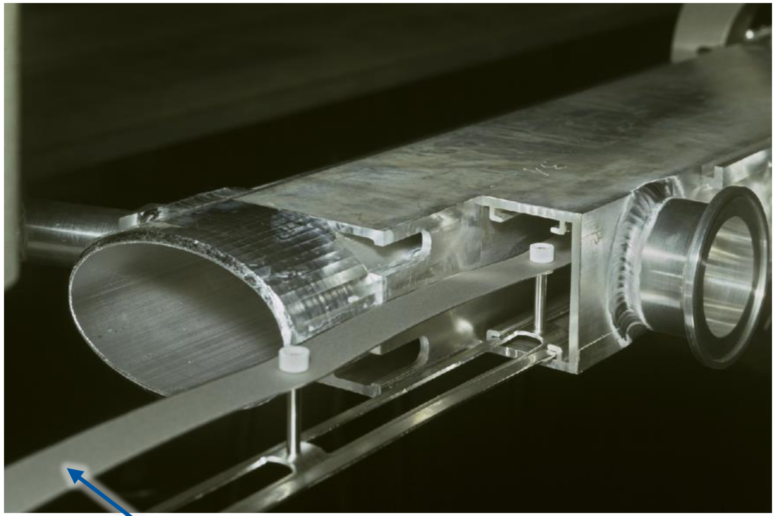


(C. Herbeaux *et al.)*

- Soleil « crotch » power absorber: Water cooled copper (Glidcop) (256 W/mm^2)
- A **sawtooth profile** is machined in order to distribute the SR power on a wider area

… heavy consequences on design





NEG strip:
30 mm wide (27 active)
Both sides pump
Stick. Coeff:
~ 0.1 (CO, CO_2, N_2)
~ 0.05 (H_2)

← SR fan

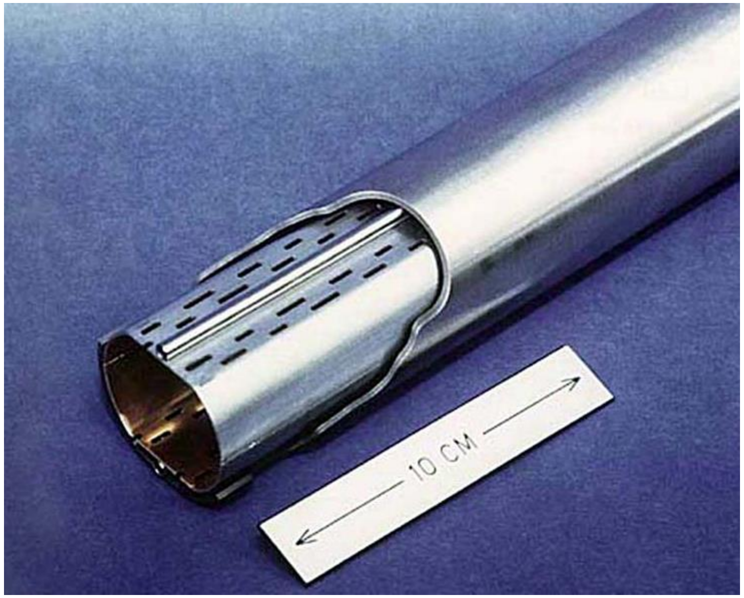
← molecule

LEP Design

(CERN LEP Vacuum group)

- Antechamber and distributed NEG pumping, water cooling and lead shielding

… heavy consequences on design



Courtesy N. Kos CERN TE/VSC

Courtesy N. Kos CERN TE/VSC

LHC Design

(CERN LHC Vacuum group)

- Perforated Cu colaminated beam screen to intercept the SR power protecting the 1.9 K cold bore and to allow a distributed pumping

Synch. Rad. Summary

- The photon fan generated by relativistic particles moving in a magnetic field is known as synchrotron radiation
- The spectrum of synchrotron radiation is described with high precision by well know analytical formulae
- Synchrotron radiation depends strongly on the mass of the radiating particle: for equal beam energy electrons generate much more SR than protons
- The SR fan is generated in the local plane of the orbit within a narrow cone
- The presence of synchrotron radiation must be considered in the design phase, since it can lead to heating problems and large photon-induced desorption yields
- The power and flux carried by the SR fan can be large: vacuum components must be designed in such a way to cope with this.
- In “extreme” cases (e.g. LEP or FCC-ee), the **critical energy** of the SR spectrum can be so high to present a formidable challenge in terms of radiation shielding and radioprotection

Some References

- C. Benvenuti, Molecular surface pumping: cryopumping, Cern Accelerator School, Vacuum technology, CERN 99-05

- V. Baglin, Cold/sticky systems, Cryo-pumping and vacuum systems, Cern Accelerator School, Vacuum in accelerators, CERN 2007-03 & CERN ACC-2023-009

- 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.

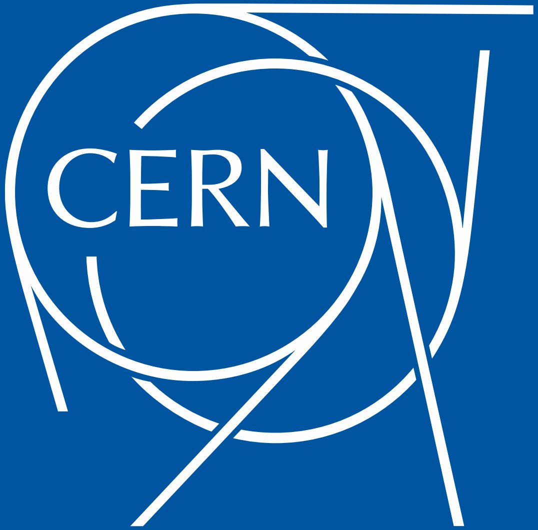
- Design and modelling of UHV systems of particle accelerators, O. Malyshev, Wiley.

Some Journals Related to Vacuum Technology

- Journal of vacuum science and technology A and B

- Vacuum

Thank you for your attention !!!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