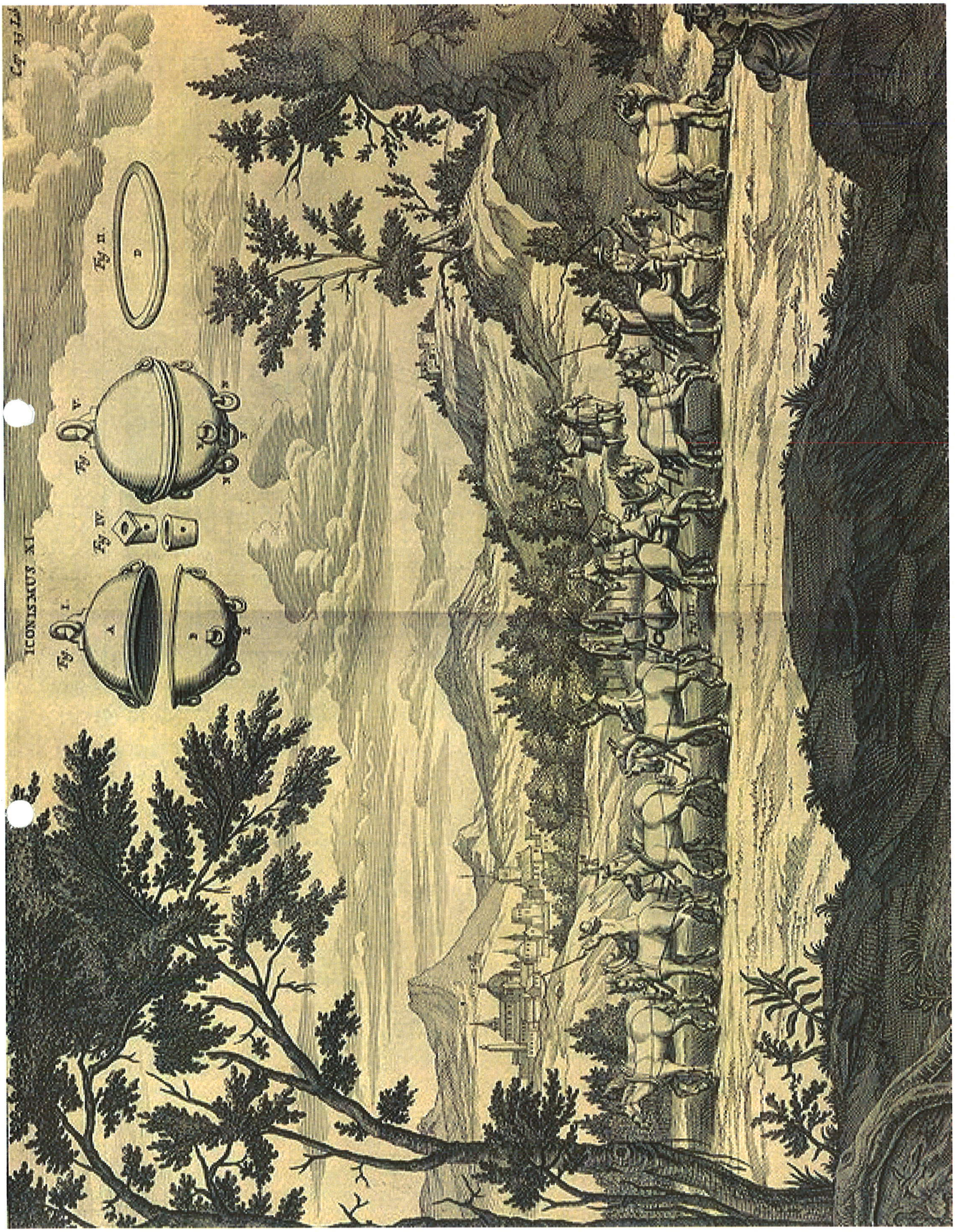
PAOLO CHIGGIATO CERN TE-VSC JUAS-2012

VACUUM TECHNOLOGY FOR



PARTICLE ACCELERATORS

UNIT 1 INTRODUCTION

① WHY VACUUM IS NEEDED IN PARTICLE ACCELERATORS ?

Beams interact with gas molecules and are deviated from their paths. The interaction results in particle losses either by

→ particle - molecule scattering

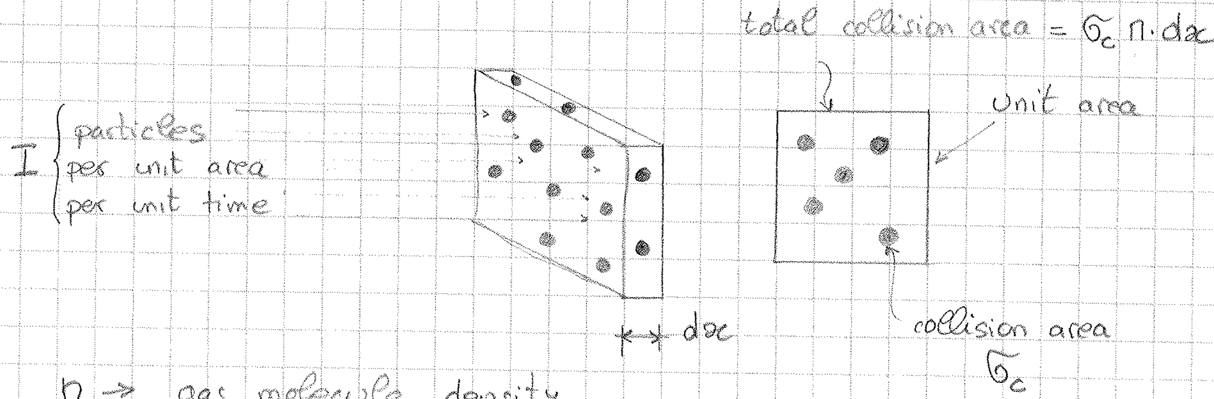
or

→ beam instabilities

The gas-beam interaction is more critical in storage ring than in linear accelerators or transfer lines. In the former, the same beams have to circulate for many hours without excessive losses; instabilities can accumulate and spoil the desired beam performance. In the transfer lines, beams pass only once.

② HOW DO BEAM PARTICLES AND GAS MOLECULES INTERACT ?

a) Definition of cross-section / mean free path / beam lifetime



n → gas molecule density

The beam particle losses while passing through dx are

$$dI = -I\,\sigma_c \cdot n\,dx$$

$$\rightarrow \frac{dI}{I} = -\sigma_c\, n\, dx \rightarrow I = I_0 \cdot e^{-x \cdot \sigma_c \cdot n}$$

$$I = I_0 \cdot e^{-\frac{x}{\ell}} \quad \text{where } \ell = \frac{1}{\sigma_c \cdot n}$$

l is the mean free path of the beam particles in the gas phase.

beam speed

$$I = I_0 \cdot e^{-x\cdot\sigma_c\cdot n} = I_0 \cdot e^{-\frac{v}{v}\cdot x\sigma_c n} = I_0 \cdot e^{-\frac{t}{\tau}}$$

$$\tau = \frac{1}{v\cdot\sigma_c\cdot n}$$

τ is called the "beam lifetime".

In case of more than one particle interaction, the cross sections are added: $\sigma_{TOT} = \sigma_1 + \sigma_2 + \dots$

As a consequence: $\frac{1}{l_{TOT}} = \frac{1}{l_1} + \frac{1}{l_2} + \dots$ and $\frac{1}{\tau_{TOT}} = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \dots$

As a first approximation, the order of magnitude of σ_c is that of the geometrical cross section for the relevant process:

$\sigma_c \approx r^2$

- atomic interactions: $(10^{-8})^2 = 10^{-16}\ cm^2$
- nuclear interactions: $(10^{-12})^2 = 10^{-24}\ cm^2 = \mathbf{1\ b}$

$[1\ b = 1\ barn = 10^{-24}\ cm^2]$

$\Rightarrow$ Nuclear reactions can be, in general, neglected

b) Processes of beam-gas interaction.

increase betatron amplitude $\leftarrow$ ELASTIC $\rightarrow$ SINGLE AND MULTIPLE COULOMB SCATTERING (*)

particles lost at the RF acceptance limit or momentum dynamic aperture $\leftarrow$ INELASTIC $\rightarrow$

- BREMSSTRAHLUNG (*)
- IONIZATION ENERGY LOSS
- ELECTRON CAPTURE AND ELECTRON LOSS
- NUCLEAR REACTION

ELASTIC SCATTERING :

The process is described by the classical Rutherford scattering. It can be shown that for Coulomb scattering :

$$\frac{1}{\tau} \propto Z^2 \cdot P$$

where Z is the atomic number of the gas molecule.
P is the residual gas pressure

INELASTIC SCATTERING :

Charged particles passing through matter become deflected by strong electrical fields from the atomic nuclei. This deflection is associated to a particle acceleration → the particle loses energy through emission of radiation ⇒ <u>bremsstrahlung.</u>
Excessive losses of particle energy move the particle out of accelerator energy acceptance. ⇒ particle loss.
This process is much more important for $\bar{e}$ than p^+.
Here again :

$$\frac{1}{\tau} \propto Z^2 \cdot P$$

<u>IMPORTANT CONSEQUENCE</u> ⇒ In addition to gas molecule density, the number of proton per molecule plays a crucial role in beam-gas interactions.
As an example, the same pressure of hydrogen and CO has not the same effect on beam lifetime.

③ WHAT IS THE VACUUM LEVEL NEEDED IN PARTICLE ACCELERATORS.

The beam lifetime defined by the residual gas should be longer than those imposed by other losses, for example beam collisions or limited aperture offered by collimators and scrapers.

Example: LHC (from www.lhc-closer.es)

Beam lifetime due to collisions at the interaction points

$$N = \mathcal{L} \cdot \sigma_c \ \frac{\text{collisions}}{s}$$

$\mathcal{L}$ = luminosity $\simeq 10^{34}\ cm^{-2} \cdot s^{-1}$

σ_c = cross section for p^+-p^+ collision at 7 TeV $\stackrel{!}{=} 110 \times 10^{-3}\, b$

$$= 10^{34} \cdot 110 \times 10^{-27} \cong 10^{9} \ \frac{\text{collisions}}{s}$$

for a fully-filled LHC (2808 bunches):

$$N = 3.6 \times 10^{5} \ \frac{\text{collision}}{\text{bunch} \cdot s} \rightarrow 2 \text{ points of collision}: 7.2 \times 10^{5}$$

the initial number of protons per bunch is 1.15×10^{11}

$$\Rightarrow \frac{1}{\tau_{pp}} = \frac{7.2 \times 10^{5}}{1.15 \times 10^{11}} \simeq 6 \times 10^{-6}\ s^{-1}$$ probability of collision per second and per proton

beam lifetime due to p-p collisions $\quad \tau_{pp} = 1.5 \times 10^{5}\ s = 40\ h$

It comes out that the beam lifetime due to collisions with the residual gas should be of the same order or, preferably, longer. For the LHC, the design value for beam-gas interactions is

$$\tau_{gas} \approx 100\ h$$

this corresponds to a gas density of about $10^{15}\ \frac{\text{molecules } H_2}{m^3}$ →

$$\text{beam lifetime} = 100\,h \times 3600\,\frac{s}{h} = \tau$$

$$\frac{1}{\tau} = \frac{\text{nr of protons lost in 1 second}}{\text{initial nr of proton in a bunch}} = \frac{N_e}{N_0}$$

$$N_0 = 1{,}15 \times 10^{11}$$

$$\frac{1}{\tau} = \underbrace{\sigma}_{\approx 50\,mb} \cdot \overbrace{\rho}^{\text{H density}} \times \overbrace{\ell_{LHC}}^{27\,Km} \times \underbrace{f}_{\text{lap per s} = \frac{c}{\ell_{LHC}}}$$

$$N_e = \sigma \times \rho_H \times \ell_{LHC} \times N_0 \times f$$

$$\Rightarrow \rho_H = \frac{10^{-2}}{3600} \times \frac{1}{\underbrace{(50 \times 10^{-3} \times 10^{-28})}_{\sigma\,[m^{-2}]} \cdot 27 \times 10^3 \cdot 11111} \approx 2 \times 10^{15}\,\frac{\text{H nucleous}}{m^3}$$

$$\Rightarrow \rho_{H_2} \approx 10^{15}\,\frac{H_2 \text{ molecules}}{m^3} = 10^9\,\frac{H_2 \text{ molecules}}{cm^3}$$

In the experimental areas, the gas density requirement is two orders of magnitude lower:

$$\Rightarrow (\rho_{H_2})_{exp.} \approx 10^{13}\,\frac{H_2 \text{ molecules}}{m^3}$$

to minimize the detectors' background.

<u>What is the gas density in air?</u>

$$PV = nRT \Rightarrow PV = N_{atm} \cdot K_B \cdot T \Rightarrow \rho_{atm} = \frac{\overbrace{P}^{1\,atm \approx 10^5\,Pa}}{\underbrace{K_B}_{1{,}38 \times 10^{-23}\,\frac{J}{K}} \cdot \underbrace{T}_{292\,K}} \cong 2{,}5 \times 10^{25}\,\frac{\text{molecules}}{m^3}$$

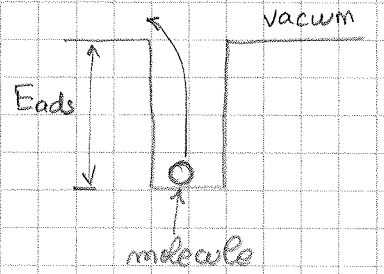
with the beam circulating

from 2.5×10^{25} to 10^{13} $\Rightarrow$ 12 to 13 orders of magnitude lower !

$\Rightarrow$ A) How can we achive this low density?

$\Rightarrow$ B) Where is the gas coming from?

A) This low density can be achieved by adsorbing the residual gas onto dedicated surfaces in the beam pipe vacuum.



Probability of excaping from the surface $\propto e^{-\frac{E_{ads}}{kT}}$

$\Rightarrow$ average time of sojourn $\propto e^{\frac{E_{ads}}{kT}}$

$e^{\frac{E_{ads}}{kT}} \gg$ typical time of accelerator running

$\Rightarrow$ Two possibilities

$e^{\frac{E_{ads}}{kT}}$
- $\nearrow$ E_{ads} large $\Rightarrow$ chemical pumping (getter)
- $\searrow$ T small $\Rightarrow$ cryogenic pumping

B) Once the atmospheric gas is extracted, the main source of gas is the material of the beam pipes, in particular its surface. In many accelerators, the gas desorption is stimulated by the beam by particle impingement and induced heating.

- $\to$ electron
- $\to$ proton
- $\to$ ion
- $\to$ photons