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Gas dynamics modelling for particle accelerators

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ABSTRACT

Design of an accelerator vacuum chamber requires an input from different scientific disciplines such as surface science, material science, gas dynamics, particle beam dynamics, and many others. Although vacuum scientists work on the boundary field between these disciplines, gas dynamics is the one that allows joining them to the vacuum science for particle accelerators. The vacuum requirements (usually UHV or XHV) in particle accelerators are defined by beam–gas interactions that should be negligible compared to other phenomena that limit the quality of the beam. At such low pressures the main source of gas in the vacuum chamber is a molecular desorption from materials used for the vacuum chamber and its components. The outgassing rates vary over a very wide range and depend on material, cleaning procedure, treatments, temperature, bombardment by particles and accumulated irradiation dose. The gas dynamics is used to design the research facilities to accurately measure and to study outgassing rates at different conditions. By applying these data to the accelerator vacuum design, one would have to consider that outgassing is often non-uniform and changes with time with different functions. The most time-efficient way of beam vacuum optimization is using a 1D diffusion model where all parameters are defined as a function of longitudinal coordinate (along the beam path). A full 3D modelling with TPMC codes provides much more accurate results, however, being time consuming work is not ideal for pumping and design optimization and is used for complex components and for finalized design.

1. Introduction: vacuum required in the particle accelerators

In general, charged particle accelerators are designed to generate, accelerate, form and transport the charged particle beams with some required beam characteristics [1,2] to the experimental area such as an interaction point in colliders [3–5], solid, liquid or gaseous target [6,7], or to the device(s) where the beam used for generating photons in synchrotron radiation sources [8,9] or powerful RF (drive beam) [10]. In all these cases the loss rate of charged particles due to unwanted beam–gas interactions should be below some tolerable level. For example, in the case of the storage rings the beam current I decays with time t as:

$$I = I_0 \exp\left(-\frac{t}{\tau}\right), \tag{1}$$

where τ is the total beam lifetime. There are numerous effects that define the intrinsic beam lifetime τ_{beam} due to different Quantum, Touschek, particle lifetime, etc., and there is beam–gas interaction lifetime τ_{gas} defined as:

$$\frac{1}{\tau_{gas}} = c\sum_i \sigma_i n_i, \tag{2}$$

where n is the residual gas density for a gas specie i, σ is the beam–gas interaction cross section, and c [m/s] is a velocity of beam charged particles [1,11].

The total beam lifetime is defined as:

$$\frac{1}{\tau} = \frac{1}{\tau_{beam}} + \frac{1}{\tau_{gas}}. \tag{3}$$

The criteria for a 'good vacuum' in the storage rings is:

$$\tau_{gas} \gg \tau_{beam}. \tag{4}$$

There are also other effects that might define vacuum specifications in an accelerator or in some sections of it:

– The beam–gas interaction might have a strong positive feedback on beam quality:

Abbreviations: ESD, Electron stimulated desorption; ISD, Ion stimulated desorption; PSD, Photon stimulated desorption; SIP, Sputter ion pump; SR, Synchrotron radiation; TPMC, Test Particle Monte-Carlo method; TMP, Turbo-molecular pump; UHV, Ultra high vacuum; XHV, Extreme high vacuum.

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Nomenclature

A [m^2] vacuum chamber cross section
$C = \rho S$ or $C = \alpha S$ [m^3/s] distributed pumping speed
c [m^2/s] distributed pumping speed per unit axial
D [m^2/s] Knudsen diffusion coefficient
e [C] electron charge
F [m] vacuum chamber surface area per unit axial (the cross section circumference)
I [A] charged particle beam current
L [m] length if vacuum chamber
n [molecules/m^3] volume molecular density
n_e [molecules/m^3] thermal equilibrium gas density
q [molecules/(s·m)] gas desorption flux per unit axial
$S = FL\bar{v}/4$ [m^3/s] ideal wall pumping speed
s [molecules/m^2] surface molecular density
t [s] time
$U = u/L$ [m^3/s] the vacuum chamber conductance;
$u = AD$ [m^4/s] specific vacuum chamber conductance per unit axial length
V [m^3] vacuum chamber volume
$\bar{v}$ [m/s] average molecular velocity
z [m] longitudinal coordinate along the beam vacuum chamber
α sticking probability of molecules on vacuum chamber walls
Γ [photon/(s·m)] photon intensity per unit axial length
Φ [electron/(s·m)] electron intensity bombardment per unit axial length
σ [m^2] ionisation cross section of the residual gas molecules by beam particles
χ [molecules/ion] the ion stimulated desorption yield
η or η_γ [molecules/photon] PSD yield
η_e [molecules/electron] ESD yield
η_t [molecules/(s·m^2) or Pa·m] specific thermal outgassing rate
ρ pumping mesh or beam screen transparency

  - The residual gas molecules ionised by the beam can be trapped by negatively charged beam and cause in their turn the ion induced beam instability (p. 129 in [1])

- There are a few beam–gas–surface interaction effects with strong positive feedback:
  - Free electrons due to gas ionisation as well as photo and secondary electron emission are responsible for beam induced electron multipacting (causing the pressure increase) and electron cloud (causing the beam emmitance grow) (p. 132 in [1],[12]),
  - The ion induced pressure instability (see Section 5),
  - Heavy ion induced pressure instability [13].

- The gas–surface interaction may limit the performance of in-vacuum instrumentation such as:
  - the photocathode in the electron gun [14,15], its degradation depends on residual gas density and composition,
  - the reflection coefficient degradation in mirrors for free electron lasers,
  - etc.;

- The beam–gas interaction might affect the radiation safety for people and equipment: for example, Bremsstrahlung radiation from some beamlines at synchrotron radiation sources [16].

The aim of this paper is to describe the main problems in gas dynamics modelling of beam vacuum for different type particle accelerators, as well as some possible solutions.

2. Sources of gas in vacuum system

2.1. Residual gas from atmosphere

After installing a vacuum chamber in its place in an accelerator, the atmospheric gases are pumped away followed by leak detection. No detectable leaks are tolerable. Therefore, there is no residual gas from atmosphere; it is not a source of gas for the most of UHV systems.

Gas can be injected into the vacuum system when it is required (for example for gaseous targets in some experiments). It is usually a well-controlled process, and a proper differential pumping system should be designed.

2.2. Thermal outgassing

The process when the gas molecules, originally physically bounded to surface or solved in the vacuum chamber material, are released from a surface into a vacuum chamber is called the thermal desorption (or thermal outgassing). Thermal desorption defines vacuum in a vacuum system without a beam, or in the presence of a beam without beam loses, SR, RF heat, etc. The outgassing is characterised by the specific outgassing rates η_t. The outgassing rates depend on many factors such as choice of material, surface roughness, cleaning procedure, temperature and duration of bakeout, pumping time, surface temperature, etc. [17–24]. A lot of data is available from the literature for different sets of such factors. For practical application in accelerators design, it is worth mentioning here that for unbaked stainless steel, copper and aluminium after 100 h pumping the specific outgassing rates η_t are below 10^{-9} mbar·l/(s·cm^2), mainly H_2O [25]. A value of $\eta_t = 10^{-12}$ mbar·l/(s·cm^2) is commonly reached after 24-h bakeout at 300 °C for stainless steel and 150 °C for aluminium and copper [17]. The main outgassing gas specie is hydrogen (90–99%), other species (CO, CO_2 and CH_4) have a much lower value. All other species are negligible in a vacuum system designed and cleaned to UHV specifications. The specially prepared surfaces may reach a much lower value of $\eta_t = 10^{-15}$ mbar·l/(s·cm^2) [22–24].

Another possibility is applying the non-evaporable getter (NEG) coating on entire inner surface of vacuum chamber, this 1-μm Ti–Zr–V or Ti–Zr–Hf–V coating not only reduces outgassing rate much below other materials but also provides distributed pumping speed that results in the pressure below the sensitivity of modern UHV/XHV gauges such as an extractor gauge [26,27].

Thermal outgassing is negligible in vacuum system with vacuum chambers at cryogenic temperatures.

2.3. Photon stimulated desorption

Photon stimulated desorption (PSD) is one of the major sources of gas in the presence of SR. Gas molecules may be desorbed from a surface when and where photoelectrons leave and arrive at a surface [28,29]. Therefore, due to photon reflectivity and photoelectron spatial distribution, PSD happens where photons impact directly, where photons can be reflected and where photoelectrons