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Oleg B. Malyshev

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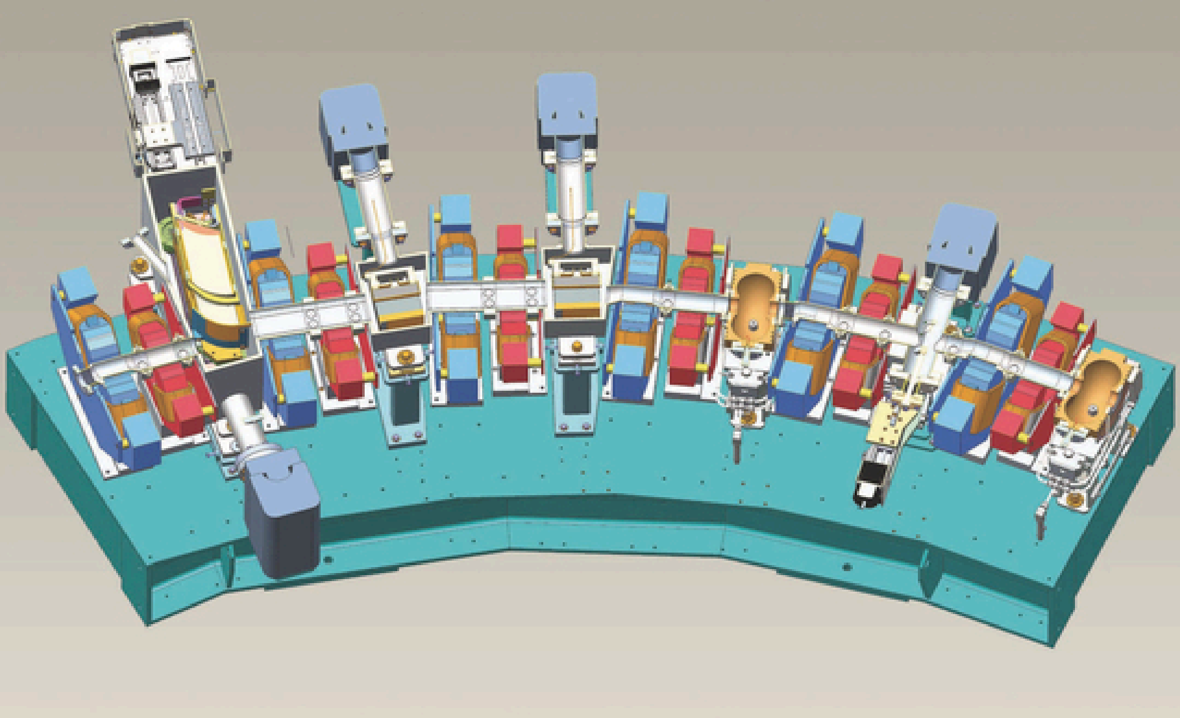
Modelling, Design and Operation of Beam Vacuum Systems



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Dr. Oleg B. Malyshev
Editor

Nomenclature

A [m^2]	Vacuum chamber cross section area or volume per unit of axial length
$A(r, t)$ [W/m^3]	Source term of energy input on the electrons
a [m]	Vacuum chamber or channel height or width
a	A constant in equations
B [T]	Magnetic field
$B(r, t)$ [W/m^3]	Source term of energy input on the lattice
b [m]	Vacuum chamber or channel width or height
C [m^2/s]	Distributed pumping speed of pumping holes or slots per unit axial length
$C_{\mathrm{e/a}}$ [J/(kg·K)]	Specific heat of the electronic/lattice system
c [m^2/s]	Distributed pumping speed per unit axial length
D [m^2/s]	Knudsen diffusion coefficient
D	Accumulated dose of particle bombarding a surface
– D or D_γ	Photon dose
○ D or D_γ [photons]	Total photon dose
○ D or D_γ or D_L [photons/m]	Photon dose per unit of axial length
○ D or D_γ or D_A [photons/m^2]	Photon dose per unit of area
– D or D_e	Electron dose
○ D or D_e [electrons]	Total electron dose
○ D or D_e or D_L [electrons/m]	Electron dose per unit of axial length
○ D or D_e or D_A [electrons/m^2]	Electron dose per unit of area
– D or D_i	Ion dose
○ D or D_i [ions]	Total ion dose
○ D or D_i or D_L [ions/m]	Ion dose per unit of axial length
○ D or D_i or D_A [ion/m^2]	Ion dose per unit of area

d [m]	Tube or orifice diameter
E	Energy of charged particles
– E [MeV, GeV, TeV]	Energy of particles in the beam
– E_0	Rest energy, e.g. $E_0 = 0.511$ MeV for electron and $E_0 = 938.27$ MeV for proton
– E_e or E [eV, keV]	Energy of test electron in ESD and SEY measurements
– E_i or E [eV, keV]	Energy of test ion in ISD
– E_{des} [eV]	Desorption energy
$\mathcal{E}$ [V/m]	Electric field
F [m]	Vacuum chamber cross section circumference or surface area per unit axial length
f	Fraction of beam ions ($0 < f < 1$)
g [W/(m^3·K)]	Electron–phonon coupling
$H_{(\mathrm{index})}$ [ions/s] or [ions/(s·m)]	Ion flux
I [A]	Charged particle beam current
– I_e [mA]	(Photo)electron current
– I_i [mA]	Ion current
I [J]	Mean ionization potential
J [molecules/(s·m^2)]	An impingement rate
$K_{\mathrm{e/a}}$ [W/(m·K)]	Thermal conductivity of the electronic/lattice system
Kn	Knudsen number
K_q	Charge state of ions
L [m]	Length of vacuum chamber
M [kg/mol] or [amu]	Molecular molar mass
Mh_i	A number of hits on facet i' in TPMC model
Mp_i	A number of particles pumped by facet i in TPMC model
m [kg]	(molecular) mass
N [molecules]	A number of molecules in a volume
N	A number of generated molecules in TPMC model
n [molecules/m^3]	Number density of gas
n_e [molecules/m^3]	Thermal equilibrium gas density (in Chapters 7 and 9)
n_e [electrons/m^3]	Electron density (in Chapters 8 and 10)
P [Pa]	Pressure
$\mathbf{P}$ [W/m]	Power dissipation per unit axial length
R [m]	Bending radius of dipole magnet
R or ρ	Photon reflectance (reflectivity coefficient)
R_z [μm]	Mean surface roughness
r [m]	Radius

Q [molecules/s] *or* Q^* [Pa·m^3/s]	Local gas flux
q [molecules/(s·m^2)] or q^* [Pa·m/s]	Specific outgassing rate
q [molecules/(s·m)] or q^* [Pa·m^2/s]	Gas desorption flux per unit axial length
S [m^2/s]	Distributed pumping speed per unit axial length
S_{eff} [m^3/s]	Effective pumping speed
$S_{\text{id}} = A\bar{v}/4$ [m^3/s]	Ideal pumping speed
S_p [m^3/s]	Pumping speed of a lumped pump
$S = FL\bar{v}/4$ [m^3/s]	Ideal wall pumping speed of accelerator vacuum chamber of length L
S_A [m/s]	Specific pumping speed (pumping speed per unit of surface area)
s [molecules/m^2]	Surface molecular density, a number of adsorbed molecules
s_0 [molecules/m^2]	A number of adsorption sites
T [K]	Temperature of gas or walls of vacuum chamber
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
v [m/s]	Bulk velocity
$\bar{v}$ [m/s]	Average molecular velocity
v_{rms} [m/s]	Root-mean-square molecular velocity
$\mathbf{W}$	Transmission probability matrix
w	Transmission probability
x and y [m]	Transversal coordinate
Z	Atomic number
Z_{eff}	Effective charge of projectile ion, screened by electrons
z [m]	Longitudinal coordinate along the beam vacuum chamber

α	Sticking probability of molecules on vacuum chamber walls
α	Exponent in Eqs. (4.29), (4.34), and (4.35) for $\eta(D)$
β	Capture coefficient
Γ	Photon flux
– Γ [photons/s]	Total photon flux
– Γ or Γ_L [photon/(s·m)]	Linear photon flux (photon flux per unit of axial length)
– Γ or Γ_A [photon/(s·m^2)]	Photon flux per unit surface area

– Γ_{mrad} [photon/(s·mrad)]	Photon flux from the beam in dipole magnetic field into 1 mrad bend
γ	The Lorentz factor: $\gamma = E/E_0$
δ	Secondary electron yield
ε	Photon energy
ε_c	Critical energy of SR
η or η_e or ξ [molecules/electron]	ESD yield
η or η_γ [molecules/photon]	PSD yield
η_t [molecules/(s·m^2)] or [Pa·m]	Specific thermal outgassing rate
η' or $\eta_e{}'$ or ξ' [molecules/electron]	ESD yield from cryosorbed gas (secondary ESD)
η' or $\eta_\gamma{}'$ [molecules/photon]	PSD yield from cryosorbed gas (secondary PSD)
Θ	Electron flux (surface bombardment intensity)
– Θ [electron/s]	Total electron flux
– Θ or Θ_L [electron/(s·m)]	Electron flux per unit axial length
– Θ or Θ_A [electron/(s·m^2)]	Electron flux per unit surface area
Θ [mrad or °]	Incidence angle of bombarding particles
$\theta = s/s_0$	Normalised surface coverage
ν_0 [s^{-1}]	Oscillation frequency of bound atom/molecule
ρ	A pump capture efficiency (or a capture coefficient), pump mesh or beam screen transparency
$\rho(x, y)$ [C/m^3]	Beam charge density
τ [s]	Beam lifetime, an average residence time of sorbed molecule on a surface
σ [m^2]	An ionisation cross section of the residual gas molecules by beam particles, an interaction cross section (in Chapter 1)
σ_x and σ_y [m]	Transverse r.m.s. beam sizes
χ [molecules/ion]	ISD yield
χ' [molecules/ion]	ISD yield from cryosorbed gas (secondary ISD)

Physical Constants

c	Speed of light in vacuum	$c = 299\,792\,458$ m/s
k_B	Boltzmann constant	$k_B = 1.380\,650\,4(24) \times 10^{-23}$ J/K $= 1.380\,650\,4(24) \times 10^{-23}$ Pa·m^3/K
h	Plank's constant	$h = 6.626\,069\,57 \times 10^{-34}$ m^2·kg/s
q_e	Elementary charge	$q_e = 1.602\,176\,46 \times 10^{-19}$ C
N_A	Avogadro constant	$N_A = 6.022\,140\,76 \times 10^{23}$ mol^{-1}
R	Ideal gas (Regnault) constant	$R = 8.314\,459\,8(48)$ J/(mol·K) or Pa·m^3/(mol·K) or kg·m^2/(mol·K·s^2)

List of Abbreviations

AC	angular coefficient method
ESD	electron-stimulated desorption
ISD	ion-stimulated desorption
NEG	non-evaporable getter
PEE	photoelectron emission
PEY	photoelectron yield
PSD	photon-stimulated desorption
RGA	residual gas analyser
SEE	secondary electron emission
SEY	secondary electron yield
SIP	sputter ion pump
SR	synchrotron radiation
TD	thermal desorption
TPMC	test particle Monte Carlo method
TMP	turbo-molecular pump
TSP	titanium sublimation pump
UHV	ultra-high vacuum
XHV	extreme high vacuum

Frequently Used Vacuum Units and Their Conversion

Vacuum Units

	Pa	**mbar**	**Torr**	**bar**	**Atmosphere at sea level**
Pa	1	10^{-2}	$7.500\,62 \times 10^{-3}$	10^{-5}	$9.869\,2 \times 10^{-6}$
mbar	100	1	0.750 062	10^{-3}	$9.869\,2 \times 10^{-4}$
Torr	133.322	1.333 22	1	$1.333\,22 \times 10^{-3}$	$1.315\,8 \times 10^{-3}$
bar	10^5	10^3	750.062	1	0.986 92
atm	$1.013\,25 \times 10^5$	$1.013\,25 \times 10^3$	760	1.013 25	1

Conversion of Frequently Used Units

Amount of gas	PV	$N = \frac{PV}{k_B T}$	$n_{\mathrm{mol}} = \frac{PV}{RT}$	$m = M\frac{PV}{RT}$
Units	$\mathrm{Pa \cdot m^3} = 10\,\mathrm{mbar \cdot l}$	molecules	mol	kg
Gas flow	$\frac{d(PV)}{dt}$	$\frac{dN}{dt}$	$\frac{dn_{\mathrm{mol}}}{dt}$	$\frac{dm}{dt}$
Units	$\mathrm{Pa \cdot m^3/s} = 10\,\mathrm{mbar \cdot l/s}$	molecules/s	mol/s	kg/s
Specific outgassing rate	$\frac{1}{A}\frac{d(PV)}{dt}$	$\frac{1}{A}\frac{dN}{dt}$	$\frac{1}{A}\frac{dn_{\mathrm{mol}}}{dt}$	$\frac{1}{A}\frac{dm}{dt}$
Units	$\mathrm{Pa\,m/s} = 10^5\,\mathrm{mbar \cdot l/(s \cdot cm^2)}$	$\mathrm{molecules/(s \cdot cm^2)}$	$\mathrm{mol/(s \cdot cm^2)}$	$\mathrm{kg/(s \cdot m^2)}$

Monolayer (ML)

A monolayer (ML) is a one-molecule thick layer of closely packed molecules of gas on a geometrically flat surface.

In practical estimations for the gases present on rough surface of accelerator vacuum chamber, an approximate value of $1\ \mathrm{ML} \approx 10^{15}$ molecules/cm^2 can be used.

Introduction

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A large number of good books related to vacuum science and technology have already been written. Thus, the International Union for Vacuum Science, Technique and Applications (IUVSTA) and American Vacuum Society (AVS) have published on their websites a list of 'Textbooks on vacuum science and technology published, 1922–2003', prepared by Kendall B.R. [1] which a list of textbooks on vacuum science and technology published in 1922–2003, prepared by Kendall B.R., which has 136 book titles, including [2–6]. A few more books were published in recent years to represent a modern level of knowledge in the rarefied gas dynamics and modelling, design of vacuum system and vacuum technology, and vacuum instrumentation and materials [7–10]. However, these books do not cover a number of specific problems related to vacuum systems of charged particle accelerators and other large vacuum systems. The lack of this specialist education materials was covered by CERN Accelerator Schools in 1999, 2007, and 2017 (published in their proceedings [11–13]) and in vacuum-related articles in the *Handbook of Accelerator Physics and Engineering* [14], related to a number of different aspects of vacuum science, technology, and engineering for particle accelerators. The proceedings of two workshops on vacuum design of synchrotron radiation (SR) sources were also published by AIP [15, 16]. However, there are a very small number of publications related to accelerator vacuum chamber modelling and optimisation, including selecting and manipulating the input data to the model [17–19], although there were a few presentations at conferences, workshops, schools, and short courses on this subject.

This book aims to help vacuum scientists and engineers in the gas dynamics modelling of accelerator vacuum systems. It brings together the main considerations, which have to be discussed and investigated during modelling and optimisation in a design of particle accelerator vacuum system, as well as to give some analytical solutions that could be useful in vacuum system design optimisation. This includes, first of all, an analysis of experimental data that should be used as inputs to analytical models; secondly, an understanding of what physical and chemical processes are happening in the vacuum chamber with and without a

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beam; and thirdly, choosing and applying a model (or available software) and interpreting the results. It is expected that readers have theoretical knowledge and practical experience in vacuum science and technology, thermodynamics, gas dynamics and some basic knowledge in particle accelerators.

The structure of the book corresponds to a workflow in the design of accelerator vacuum chamber:

(1) *Chapter 1* describes *first considerations* at the beginning of work on a new machine such as what type of machine and what vacuum specifications, rough vacuum estimations, etc.
(2) *Chapters 2–5* provide an *input data* for gas dynamics models:
   - Synchrotron radiation(SR) is one of the main characteristics required in modelling of vacuum systems of many particle accelerators. Chapter 2 describes photon flux, critical energy, power, and angular distribution from dipoles, quadrupoles, wigglers, and undulators. The authors were writing the formulas in the format that could be useful for the vacuum designers.
   - Chapter 3 is focused on two important effects in the interaction between SR and vacuum chamber walls: photon reflectivity and photoelectron production. These two effects play a significant role in the photon-stimulated desorption processes in room temperature and cryogenic beam chambers, and the beam-induced electron multipacting and should also be considered in the ion induced pressure instability.
   - Chapter 4 describes the main materials used in accelerator vacuum chambers, their cleaning procedure, thermal outgassing, and electron-, photon-, and ion-stimulated desorption.
   - Chapter 5 is devoted to a very special vacuum technology – non-evaporable getter coating.
(3) *Chapters 6–10* describe the *gas dynamics models*:
   - Chapter 6 describes vacuum system modelling using two main approached: a one-dimensional diffusion model and a three-dimensional test particle Monte Carlo method. We recommend reading this chapter before the following Chapters 7–10.
   - Chapter 7 describes specific problems of particle accelerators at cryogenic temperature.
   - Chapter 8 demonstrates how vacuum chamber design of positively charged machines can be affected by mitigation of beam-induced electron multipacting and e-cloud.
   - Chapter 9 describes the ion-induced pressure instability, another potential problem of positively charged machines, gas dynamics model, a number of analytical solutions, and stability criteria.
   - Chapter 10 is fully devoted to the heavy ion machine vacuum problems and solutions. We recommend reading Chapters 6–9 before this chapter.

The authors believe that vacuum scientists and engineers, postdocs and PhD students will find the book very helpful in their work related to the gas dynamics modelling and vacuum design of charged particle accelerator vacuum systems. The authors would be happy to receive a feedback or comments to any part of this book. This includes questions related to clarity, consistency, typos, missing points, wish-to-see, etc.

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1

Vacuum Requirements

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1.1 Definition of Vacuum

The content of this book is fully related to vacuum, so it is reasonable to begin with its definition. It appears that the 'common sense' definition is very different from the scientific one. For example, Oxford Dictionaries [1] defines vacuum as 'a space entirely devoid of matter'. A space or container from which the air has been completely or partly removed, while Cambridge Dictionaries Online [2] gives a more accurate definition: 'a space from which most or all of the matter has been removed, or where there is little or no matter'. However, the scientific community refers to the ISO standards, ISO 3529-1:1981 [3], where the definition of vacuum is given as follows:

> "1.1.1
> **vacuum**
> A commonly used term to describe the state of a rarefied gas or the environment corresponding to such a state, associated with a pressure or a mass density below the prevailing atmospheric level."

In other words, in rarefied gas dynamics, a gas is in vacuum conditions as soon as its pressure per standard reference conditions is below 100 kPa. In practice, vacuum conditions apply when a vacuum pump connected to a closed vacuum vessel is switched on.

Theoretically, there is no limit for rarefication. However, in practice, there is a limit of what can be achieved and what can be measured. Nowadays, some modern vacuum systems may cover up to 15–16 orders of magnitude of gas rarefication, whereas the total pressure measurements are technologically limited to $\sim 10^{-11}$ Pa.

For convenience, 'to distinguish between various ranges or degrees of vacuum according to certain pressure intervals', ISO 3529-1:1981 also defines the ranges of vacuum:

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Low (rough) vacuum:	100 kPa to 100 Pa
Medium vacuum:	100 to 0.1 Pa
High vacuum (HV):	0.1 Pa to 10 μPa
Ultra-high vacuum (UHV):	below 10 μPa

A vacuum system designer should be aware that regardless the definition of the vacuum ranges given by ISO 3529-1:1981, a few alternative ranges with different boundaries and two more ranges (very high vacuum [VHV] and extremely high vacuum [XHV]) are used in vacuum community, for example, when each range covers exactly 3 orders of magnitude:

Low (rough) vacuum:	10^5 to 10^2 Pa
Medium vacuum:	10^2 to 10^{-1} Pa
High vacuum (HV):	10^{-1} to 10^{-4} Pa
Very high vacuum (VHV):	10^{-4} to 10^{-7} Pa
Ultra high vacuum (UHV):	10^{-7} to 10^{-10} Pa
Extremely high vacuum (XHV):	below 10^{-10} Pa

1.2 Vacuum Specification for Particle Accelerators

1.2.1 Why Particle Accelerators Need Vacuum?

All particle accelerators are built to meet certain user's specifications (e.g. certain luminosity in colliders; defined photon beam parameters in synchrotron radiation (SR) sources; specified ion or electron beam intensity, timing and a spot size on a target; etc.). The user's specifications are then translated to the specification to the charged particle beam parameters, which, in their turn, are translated the specifications to all accelerator systems where the specifications to vacuum system are one of the most important for all types of particle accelerators.

Ideally, charged particles should be generated, accelerated, transported, and manipulated without any residual gas molecules. However, residual gas molecules are always present in a real vacuum chamber. The energetic charged particles can interact with gas molecules and these interactions cause many unwanted effects such as loss of the accelerated particle, change of a charge state, residual gas ionisation, and many others [4, 5].

In practice, vacuum specifications for particle accelerators or other large vacuum system are set to minimise these effects of beam–gas interaction *to a tolerable level* when their impact on beam parameters is much lower than one from other physical phenomena. Thus, the particle accelerator vacuum system should provide the required (or specified) vacuum in the presence of the charged particle beam.

Not only the residual gas affects the beam, but the beam can also cause an increase of gas density by a beam-induced gas desorption in its vacuum chamber.