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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.

There are a number of such effects such as photon-, electron-, and ion-stimulated desorption, inductive heat, radiation damage of vacuum chamber material, etc.

There are a number of different types of charged particle accelerators with various specifications to vacuum. Common in all these specifications is that the unwanted effect due to the presence of residual gas in a vacuum system should be negligible. Generally speaking, the particle accelerators are designed to generate, accelerate, form, and transport the charged particle beams with some required beam characteristics [6, 7] to an area of application such as an interaction point in colliders [8–10] and solid, liquid, or gaseous targets [11, 12], or to the device(s) where the beam used for generating photons in SR sources [13, 14] (in dipoles, wigglers undulators or free electron lasers [FELs]), etc. In all these cases the loss rate of charged particles due to unwanted *beam–gas interactions* should be below a tolerable level, defined by a process or a phenomenon for which the beam is generated. The beam–gas interactions of different natures are well described in literature (for example: see Ref. [7], p. 155 in Ref. [15]) and are summarised in Table 1.1.

The interactions of high energy particles with gas atoms, molecules, or any other type of a target (other particles in gaseous, liquid, or solid state) are determined in terms of an interaction cross section, σ, a probability the beam particles to interact with the atoms of target. When a charged particle beam of intensity, I, crosses a target of thickness dx with a density of atoms n, the change in beam current is

$$dI = -I\sigma n\, dx. \tag{1.1}$$

The charged particle beam moves with a velocity, v, passing through the thickness dx with time dt: $dx = v\, dt$. Thus, Eq. (1.1) can be rewritten as follows:

$$\frac{dI}{dt} = -I\sigma n v. \tag{1.2}$$

The cross section is a constant having the dimension of an area, i.e. m^2 in SI. However, a widely practical unit is also a barn: 1 barn = 10^{-28} m^2. The interaction

Table 1.1 The beam–gas interactions.

Beam–gas interactions		**Type of affected beam particles**
Inelastic	Bremsstrahlung	e^+, e^-
	Ionisation energy loss	All particles
	Electron capture	Low energy A^+, A^{Z+}
	Electron loss	A^+, A^-, A^{Z+}
	Nuclear reactions	All particles
Elastic	Single Coulomb scattering	All particles
	Multiple Coulomb scattering	$A^{Z+}, \overline{p}$
	Gas ionisation	
Space charge	Ion cloud space charge	Negatively charged beams
	Electron cloud space charge	Positively charged beams

cross sections depend on the nature and energy of colliding particles. These cross sections can be found in specialised literature, for example, in the booklets, provided by the Particle Data Group (PDG) [16], in Refs. [17, 18] and on p. 213 in Ref. [7].

1.2.2 Problems Associated with Beam–Gas Interaction

The potential problems for particle accelerators associated with beam–gas interaction were shortly described in the following.

1.2.2.1 Beam Particle Loss

In the case of storage rings, the beam current, I, decays with time t as

$$I = I_0 \exp\left(-\frac{t}{\tau}\right), \tag{1.3}$$

where τ is the total beam lifetime. There are numerous effects that define the intrinsic beam lifetime τ_{beam} such as quantum effect, Touschek effect, and particle lifetime, etc., and a beam–gas interaction lifetime τ_{gas} is defined as

$$\frac{1}{\tau_{\text{gas}}} = v \sum_i \sigma_i n_i, \tag{1.4}$$

where n is the residual gas density for a gas species i, σ is the beam–gas interaction cross section, and v [m/s] is a velocity of beam-charged particles [19, 20].

Then the total beam lifetime is defined as

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{beam}}} + \frac{1}{\tau_{\text{gas}}}. \tag{1.5}$$

Shorter lifetime requires more often interruption of the user's operation of particle accelerator to top up the beam; therefore the longer the total beam lifetime, the better.

Thus, the criteria for a **good vacuum** in the storage rings can be defined as

$$\tau_{\text{gas}} > \tau_{\text{beam}}. \tag{1.6}$$

In linacs, the beam lifetime is not an issue, so the criterion for a 'good vacuum' would be a tolerable beam loss rate due to a beam–gas interaction.

1.2.2.2 Background Noise in Detectors

The beam–gas interaction debris and Bremsstrahlung radiation may increase background noise in a detector at interaction points in colliders and in other sensitive instruments in a machine. In this case the criterion for a 'good vacuum' is a tolerable noise in detectors or instruments due to the beam–gas interactions in the interaction region. One should consider that the source of the debris or radiation could be quite far away from a detector or an instrument or within a line of sight for radiation and upstream/downstream of nearest dipoles for charged debris/particles.

1.2.2.3 Residual Gas Ionisation and Related Problems

The beam–gas interaction causes not only the beam losses but also gas molecule ionisation. Therefore, gas species ions and electrons with low energies are generated along the beam pass. These ions can create an ion cloud with a *space charge* that affects the negatively charged beam quality such as an emittance grow, a tune shifts, tune spreads, coherent collective multi-bunch instabilities, and a reduced beam lifetime due to increased local pressure (see pp. 129 and 165 in [15]). These effect are called the *fast ion instability* and the *ion trapping instability*.

In the case of positively charged beams, the electrons generated from the beam–gas interaction, together with photoelectrons and secondary electrons, are added in the *electron cloud* (see p. 133 in [15] and Chapter 8), also causing the beam emittance to grow.

The ions generated with positively charged beams can cause an *ion-induced pressure instability* (see Chapter 9), a quick pressure increase in the beam vacuum chamber.

The ionisation cross section of the residual gas molecules by beam particles is one of the key parameters for the ion-induced pressure instability.

The ionisation cross sections of the residual gas molecules for positrons and protons were reported in the literature, for example, see [7], Refs. [7, 21–26], and references within. Following the Bethe theory, the ionisation cross sections can be calculated with the following equation:

$$\sigma = 4\pi\left(\frac{\hbar}{mc}\right)^2 (M^2x_1 + Cx_2) = 1.874\times 10^{-20}\ \mathrm{cm}^2(M^2x_1 + Cx_2), \tag{1.7}$$

where $x_1 = \frac{1}{\beta^2}\ln\left[\frac{\beta^2}{1-\beta^2}\right] - 1$, $x_2 = \beta^{-2}$, $\beta = \frac{v}{c} = \sqrt{1-\left(\frac{E_0}{E}\right)^2}$, and E and E_0 are the total and rest energy of a particle, respectively. The coefficients M^2 and C for various gases were reported in Ref. [21]. Table 1.2 reproduces the reported data for the gases that are usually present in vacuum chamber of particle accelerators. The ionisation cross sections calculated with Eq. (1.7) are shown in Figure 1.1 for positron and electron (or proton) beams as a function of their particle energy. It should be noted that the ionisation cross sections depend only on the velocity of the ionising particle, but neither on its charge nor on its mass. However, the energy of the ionising particles depend on their mass; thus the graph for the electron and positron ionisation cross sections and a function of energy are the same, while the proton energy for the same velocity is larger by a proton/electron mass ratio, thus shifting the proton energy axis by this ratio.

1.2.2.4 Contamination of Sensitive Surfaces

In some specific areas of the accelerator, the vacuum requirement might be specified by a *surface–gas interaction*. For example, the Ga–As photocathode lifetime is very sensitive to oxygen-containing gases such as CO, CO_2, H_2O, O_2, etc. [27, 28]; the FEL mirrors are sensitive to hydrocarbon gases [29]. In such cases, the specification for vacuum can include the maximum *total* pressure and the maximum *partial* pressure for particular gas species.

Table 1.2 Values and standard deviation (s.d.) of M^2 and C in Eq. (1.7).

Gas	M^2		C	
	Value	**s.d.**	**Value**	**s.d.**
H_2	0.695	0.015	8.115	0.021
He	0.774	0.030	7.653	0.037
He[a)]	0.7525	—	8.068	—
CH_4	4.23	0.13	41.85	0.20
H_2O	3.24	0.15	32.26	0.47
CO	3.70	0.15	35.17	0.19
N_2	3.74	0.14	34.84	0.20
O2	4.20	0.18	38.84	0.47
Ar	4.22	0.15	37.93	0.19
CO_2	5.75	0.073	57.91	0.27

a) Theoretical value.
Source: From Ref. [31].

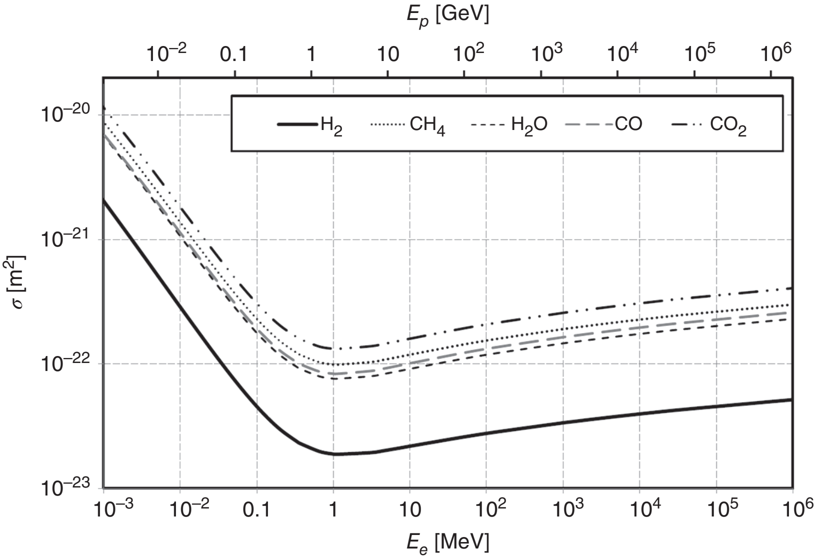

Figure 1.1 The ionisation cross sections for H_2, CH_4, H_2O, CO, and CO_2 as a function of beam energy for protons (top horizontal axis E_p) and electrons and positrons (bottom horizontal axis E_e).

1.2.2.5 Safety and Radiation Damage of Instruments

The beam–gas interaction may affect not only the beam. The Bremsstrahlung radiation due to beam–gas interaction should be seriously considered in the design phase because it may be a source of the following:

- *A risk to personnel safety*:
  - ○ A residual radioactivity of the vacuum chamber and equipment in an accelerator tunnel.
  - ○ It can also be important for radiation safety during accelerator operation, for example, Bremsstrahlung radiation on an SR beamline could be so significant that it is unsafe for a human to operate the beamline.
- *Radiation damage of instruments*:
  - ○ An induced material damage and corrosion, damage of accelerator instrumentation, cables, and comptrollers inside and outside of vacuum chamber or even in an accelerator tunnel.
  - ○ An increased risk of quench in superconducting magnets and radio frequency (RF) cavities.

1.2.3 Vacuum Specifications

Thus, vacuum specifications are defined by *a tolerable level* of direct or indirect disturbance, primarily to the quality of charged particle beam, as well as to all accelerator components due to the presence of residual gas species in an accelerator vacuum chamber. The vacuum specifications could be defined for each part, section, or sector of the machine in relation to a *location and time*:

- *Location (where a specified vacuum is required)*:
  - ○ Local for a component, for examples:
    - ■ 10^{-10} Pa between the electron gun and first bending magnet.
    - ■ Average pressure along an incretion device should be less than 10^{-9} Pa.
  - ○ Average for a large section of the machine, for examples:
    - ■ Average pressure along the storage ring should be less than 10^{-8} Pa.
    - ■ Average pressure along transfer line should be less than 3×10^{-7} Pa.
  - ○ Combination of both, for examples:
    - ■ Average pressure along the storage ring should be less than 10^{-8} Pa and local pressure bump should not be greater than 2×10^{-7} Pa.
- *Time (when this specification should be reached)*:
  - ○ 100 hours vacuum lifetime at $I = 560$ mA after 100 A h conditioning (for Diamond Light Source, DLS)
  - ○ $P(N_2\ \mathrm{eqv}) = 10^{-6}$ Pa after bakeout and a week of pumping (for a booster)
  - ○ $n(H_2\ \mathrm{eqv}) = 10^{15}\ \mathrm{m}^{-3}$ after two years conditioning, corresponding to 100 hours vacuum lifetime for the Large Hadron Collider (LHC)

The residual gas composition may include a number of different gas species, and their relative concentration may vary along the beam path due to the fact that vacuum conductivity and pumping speed of the pumps are different for each gas. The best way to specify the required pressure or gas density is to express it in nitrogen equivalent (for room temperature machines) or hydrogen equivalent (for cryogenic machines). To calculate the equivalent pressure, all what is needed is the beam–gas interaction cross sections for each gas, σ_i. Then the *N_2 equivalent pressure* can be calculated as

$$P_{\mathrm{N_2\ eqv}} = \sum_i \frac{\sigma_i}{\sigma_{\mathrm{N_2}}} P_i, \tag{1.8}$$

where P_i is a partial pressure for gas i. Similarly, the H_2 *equivalent gas density* can be calculated as

$$n_{\mathrm{H_2\ eqv}} = \sum_i \frac{\sigma_i}{\sigma_{\mathrm{H_2}}} n_i. \tag{1.9}$$

It is worth mentioning that, in many cases, accelerator scientists consider that residual gas can be somehow ‘completely eliminated’ from a beam chamber. So, it may take some time and effort on working together with accelerator scientists to calculate the effect of beam–gas interactions, to set up a tolerable level of vacuum and define vacuum specifications for a whole machine and all of its components. It is very important that at early stages of accelerator design, a vacuum scientist is involved in feasibility studies to check whether and how these vacuum specifications can be met.

Based on these, the accelerator vacuum design objectives are as follows:

- Defining all sources of residual gas in vacuum chamber with and without a beam;
- Calculating required pumping, type of pumps, and their locations;
- Defining the means of pressure measurements, their types, and locations;
- Defining the necessary procedure for material selection, cleaning, and treatments (polishing, coating, firing baking, etc.);
- Providing the results of modelling for the gas density (or pressure) profile along the beam path and at any specific location.

1.2.4 How Vacuum Chamber Affects the Beam Properties

A vacuum chamber is required to provide vacuum to meet vacuum specification for the beam particles.

The walls of a vacuum chamber set the boundary conditions for the beam electromagnetic field and, therefore, can interact directly with a beam. The electric conductivity and a shape of vacuum chamber walls can affect the longitudinal and transversal wakefields limiting a maximum current, increasing beam emittance and energy spread. In general, an electric conductivity of vacuum chamber walls could be specified in a wide range from high conductivity to insulating.

The surface of vacuum chamber or the components may be additionally specified for low photoelectron yield (PEY) and secondary electron yield (SEY), low or high photon reflectivity.

The walls of the vacuum chamber should be transparent for the magnetic field of magnetic components of accelerator such as dipoles, quadrupoles, sextupoles, and kickers: i.e. vacuum chamber walls should be non-magnetic.

The pressure (or gas density) inside vacuum chamber could be up to 15 orders of magnitude lower than outside; thus the material should be suitable for vacuum chamber, i.e. sufficiently dense for providing an efficient barrier for gas molecule and atom penetration and diffusion through vacuum chamber walls. Desorption of molecules from vacuum chamber inner walls and in-vacuum components are the main source of gas in a vacuum system. Therefore the material should be UHV (or even XHV) compatible.

Finally, a vacuum chamber should be produced. Thus it should be mechanically strong and stable, the cost and availability of material should be accounted for, and it is important to consider how easy to manufacture, store, make joints, etc.

All the required properties limit a list of materials that could be used for an accelerator vacuum chamber. The most common materials are 316LN and 304L stainless steel, copper, aluminium, titanium, and their alloys, ceramics, and glass (see Chapter 4 for details). Other materials can also be used, such as carbon or beryllium tubes in detector vacuum chamber.

Various surface treatments can be applied to change some surface properties. Surface polishing reduces the RF surface resistance and increases the photon reflectivity, while the surface roughing increases the RF surface resistance and photon absorption and also reduces PEY and SEY.

Thin and thick film coatings are often applied to provide the required properties. For example,

- Stainless steel chamber can be coated with copper to provide better electric conductivity.
- A low SEY coating can be applied to suppress electron cloud (see Chapter 8).

1.3 First Considerations Before Starting Vacuum System Design

1.3.1 What Is the Task?

When the design phase of a new machine starts, a vacuum system designer needs a lot of information that should be included or considered.

(1) What type of machine is going to be designed and built?
  - Collider (circular or linear).
  - SR (or photon) source.
    - ▪ Which generation of the SR source (defined by a key parameter – beam emittance, ε)?
      - • First generation uses ‘parasitic’ SR from dipoles in storage rings and synchrotrons ($\varepsilon \sim 300$–1000 nm·rad, incoherent radiation).
      - • Second generation is a specialised SR source with SR from dipoles and wigglers ($\varepsilon \sim 100$ nm·rad, incoherent radiation).
      - • Third generation is a specialised SR source with SR from incretion devices (wigglers and undulators: $\varepsilon_x \sim 3$–20 nm·rad, $\varepsilon_y \sim 0.01\varepsilon_x$, incoherent radiation) and can also use SR from dipoles.
      - • Fourth generation is a specialised photon source (such as FELs) with coherent beam and small emittance $\varepsilon_x \sim 10$–300 pm·rad.
  - Charged particle beam acceleration, transport, and delivery to the users.
  - Is your task designing the whole machine or only a part? Which part?

(2) What are the main beam parameters?
  - The type of accelerated charged particles.
    - ▪ Electrons, positrons, protons, (heavy) ions, and other particles.
  - A charge of particles.
  - Beam energies.

  - Beam intensity (current and peak current, number of particles per bunch, bunch length and spacing).
  - Beam transversal sizes
    - Often it is sufficient to know minimum and maximum values for whole machine or for different sectors of machine.
3) Is there SR and what are the main parameters?
  - Sources of SR: dipoles, quadrupoles, wigglers, undulators, FEL, etc.
  - Critical photon energy ε_c for dipole and wigglers, or photon energy/-ies for undulators and FELs.
  - Photon flux, Γ, onto vacuum chambers, SR absorbers, beam collimators, etc..
  - Photon reflectivity.
4) Are there any of the following problems in consideration and what mitigation techniques can be applied?
  - Electron machines
    - Fast ion instability.
    - Ion trapping instability.
  - Positron, proton, and other machines with a positive charge
    - Electron cloud
    - Ion-induced pressure instability.
  - Heavy ion machines
    - Heavy ion induced pressure instability.
    - Ion induced pressure instability.
    - Electron cloud.
5) Are there specific components?
  - Electron, proton or ion guns.
  - Solid, liquid or gaseous targets.
  - Antimatter sources (for positrons, antiprotons).
  - Interaction regions.
  - Incretion devices (wigglers, undulators, FELs).
  - Mirrors.
  - Beam windows.
6) Beam pipe temperature.
  - Room temperature.
  - Mainly room temperature with short cryogenic sections.
  - Mainly cryogenic.
  - Fully cryogenic.
7) Are there specific problems affecting vacuum design?
  - High power loss, high radiation damage, etc.

This list is of required information is certainly not complete and may significantly vary per task; however, it could be a good starting checklist for a beam vacuum system design.

1.3.2 Beam Lattice

A beam lattice is a magnet structure for the accelerator to drive and focus the charged particle beam. The beam lattice defines the location, orientation, length, and magnetic field strength of dipole, quadrupole, and sextupole magnets and insertion devices. It also defines the best location for beam instrumentation, such as the beam position monitors, the beam scrappers, and SR power absorbers and tapers.

The choice of a vacuum system philosophy, pumping system methods, location and size of vacuum pumps, and the choice and location of other vacuum instrumentations is dictated by the beam lattice components and beam instrumentation. Ideally, vacuum instrumentation should fit within an available space. However, if the provided space is insufficient to meet the required vacuum specification, possible solutions should be discussed with accelerator lattice, magnet, and RF scientists and engineers and mechanical designers.

1.3.3 Beam Aperture and Vacuum Chamber Cross Section

1.3.3.1 Required Mechanical Aperture

The size of the beam vacuum chamber should be sufficient to accommodate the beam. The beam can be round, elliptical, or even ‘flat’ (when one transversal dimension is much greater than the other one. The charge density $\rho(x, y)$ of a beam for a Gaussian distribution of particles can be described as [30]

$$\rho(x,y) = \frac{Nq_e}{2\pi\sigma_x\sigma_y} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right), \tag{1.10}$$

where N is a number of particles of charge q_e in the beam, x and y are the horizontal and vertical distances from the centre of the beam, and σ_x and σ_y are the horizontal and vertical transverse r.m.s. beam sizes. That means that the charge density is lower by a factor of $e^{-1/2}$ for particles located at coordinates $(x, y) = (\pm\sigma_x, 0)$ or $(x, y) = (0, \pm\sigma_y)$:

$$\rho(\sigma_x, 0) = \rho(0, \sigma_y) = \rho(0, 0)e^{-1/2} = 0.607\rho(0, 0). \tag{1.11}$$

To avoid the loss of beam particles due to collision with vacuum chamber walls, the vacuum chamber’s horizontal and vertical dimensions, a and b, should be much larger than σ_x and σ_y, respectively. The relative charge density of the beam for various x/σ_x and y/σ_y ratios is shown in Table 1.3.

The beam size can be calculated from beta functions $\beta_{x,y}$, emittance $\varepsilon_{x,y}$, dispersion function $D(z)$, and momentum p of the beam provided by a beam lattice design as follows [31]:

$$\sigma_x = \sqrt{\beta_x\varepsilon_x}, \quad \sigma_y = \sqrt{\beta_y\varepsilon_y} + \left|D(z)\frac{\Delta p}{p}\right| \tag{1.12}$$

These values should normally be provided by accelerator scientists from the results of their lattice design of the machine. However, this gives just some ideas about the required size of a vacuum chamber. In the beam lattice design, there is an ideal beam orbit and also, ideally, the centre of the beam should travel along this ideal orbit, and the longitudinal axis of the beam vacuum chamber should coincide with the ideal beam orbit (see Figure 1.2a). However, in practice, the beam can fluctuate with time around the *ideal orbit* occupying a greater space

Table 1.3 Reduction of relative beam charge density as a function of distance from the beam centre.

x/σ_x or y/σ_y	$\rho(a)/\rho(0)$
0	1
1	0.607
2	0.368
3	0.223
4	0.135
5	8.21×10^{-2}
6	4.98×10^{-2}
7	3.02×10^{-2}
8	1.83×10^{-2}
10	6.74×10^{-3}
15	5.53×10^{-4}
20	4.54×10^{-5}

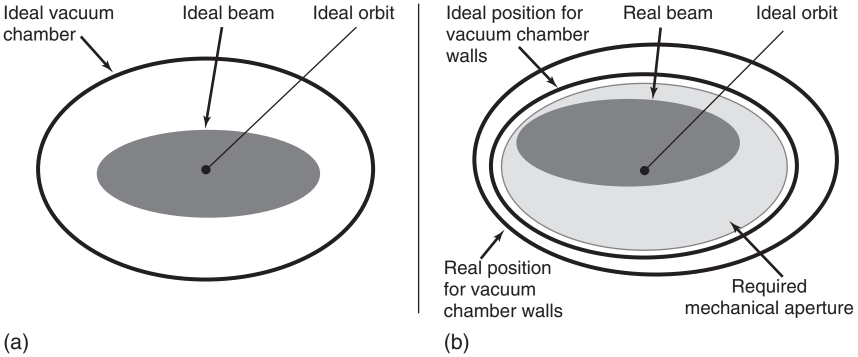

Figure 1.2 Ideal (a) and real (b) positions of a beam and vacuum chamber in respect to the ideal orbit.

called a ‘close orbit’. A complicated numerical analysis with nonlinear beam optics performed by accelerator scientists will come with a *required mechanical aperture* (also known as a ‘beam stay clear’) as a function of the longitudinal coordinate (see Figure 1.2b).

The beam size may significantly vary along the beam trajectory. A real mechanical vacuum chamber should not be exactly the same as a required mechanical aperture but should fully accommodate it.

The mechanical design should also consider mechanical tolerances and misalignments in the shape of vacuum chamber, axial twist, longitudinal bends (after manufacturing or after placing of vacuum chamber supports due to gravity), etc., so the real vacuum chamber cross section is usually slightly larger than the required mechanical aperture.

A beam vacuum chamber could be of the same cross section for the entire machine, making this the most economical solution for vacuum chamber; however, it could be not optimal and cost effective for an accelerator. In practice, in many machines there are a few typical cross sections of the vacuum chamber for different components or sections of the machine.

1.3.3.2 Magnet Design

A large cross section would provide more space for the beam and better vacuum conductance of its vacuum chamber. However, an upper limit for the dimensions of the beam vacuum chamber is dictated by the magnet design. The cost of magnets (dipoles, quadrupoles, etc.) increases approximately quadratically with a gap between the magnet poles where a beam vacuum chamber is placed. The smaller the gap, the smaller the size of the magnet coils and the lower the cost of the magnet. The larger the gap, the harder (or even impossible) it is to reach the required magnetic field strengths. Thus, there must be balanced considerations in choosing a vacuum chamber cross section between the required mechanical aperture to accommodate the beam and the magnet design.

1.3.3.3 Mechanical Engineering

A vacuum chamber should meet a number of specifications related to mechanical engineering. The vacuum chamber should be mechanically stable: i.e. it should not deform due to gravity, the atmospheric pressure, and the Laurence force during magnet quenches; it should not crack due to temperature expansion and cooling; it shouldn't vibrate; etc.

The material choice may also be dictated by required electrical conductivity, thermal conductivity, the cost of material and the space, and cost restrictions. The choice of material and mechanical stability will define the vacuum chamber wall thickness, which is an additional element in a trade-off between the required mechanical aperture and the magnet design.

A real vacuum chamber is not ideal, the vacuum chamber dimensions have certain accuracy; there could be some imperfections at the welds and joints, mechanical and thermal deformations, twists and bends of vacuum chamber; and the shape of vacuum chamber may also deform under vacuum. The position of the vacuum chamber is not ideal: there are misalignments and non-linearity of straight components, especially elastic and plastic deformation of long vacuum chambers between two supports due to the gravity, so the axis of the beam vacuum chamber may be offset from the ideal orbit (see Figure 1.2b). All these considerations must also be included in the specification of the vacuum chamber minimum aperture and require either larger dimension than an ideal vacuum chamber and/or small tolerances for these dimensions.

1.3.3.4 Other Factors Limiting a Maximum Size of Beam Vacuum Chamber

As it was described above, the beam chamber should accommodate the beam, so the beam chamber size's *lower limit* is defined by the beam size (a required mechanical aperture) and mechanical imperfection of vacuum vessel. The beam chamber size's *upper limit* is defined by available gap(s) in magnetic components and vacuum chamber wall thickness. A few other factors limiting the maximum size of a beam chamber cross section should be also considered:

- The cost of the vacuum chamber and components increases with its size.
- There are components in particle accelerators (for example, undulators) where the vacuum chamber apertures and shape are defined by these components.
- A vacuum chamber could be also an integral part of other components, for example, a cryogenic vacuum chamber inside a superconducting magnet.
- A beam screen could be placed inside a bigger vacuum chamber, for example, as a part of a bellows assembly or as an SR screen in cryogenic vacuum chamber.

1.3.4 Vacuum Chamber Cross Sections and Preliminary Mechanical Layout

The shape of a beam is either round or elliptic. So-called flat beams are the elliptic ones with $\sigma_x \gg \sigma_y$). Therefore, the shape of the beam vacuum chamber is also often either round or elliptic. These shapes are easy to manufacture and quite convenient in mechanical design for placing inside many magnetic components, dipoles, quadrupoles, sextupoles, etc., without changing the vacuum chamber shape. However, other shapes are also widely used: square, rectangular, hexagonal, and octagonal (see Figure 1.3), as well as a variety of other shapes.

The vacuum conductance of a beam vacuum chamber could be insufficient (too low) to meet required vacuum specification. In this case another chamber (usually called an antechamber) is placed parallel to the beam chamber and is connected to it with a slot over the entire length of antechamber. The antechamber can be used either over the entire length of the machine, on some sections only, or just for specific components.

There are three main types of antechamber:

- Large antechamber with a cross section much larger than that of beam chamber for increasing vacuum conductance of a narrow beam vacuum chamber (see Figure 1.4a).

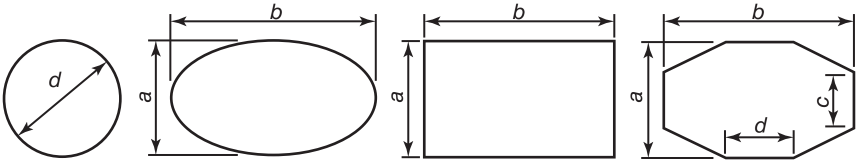

Figure 1.3 Examples of a beam chamber cross sections: round, elliptic, rectangular, and octagonal with inner dimensions (wall thickness and outer dimensions are not shown).

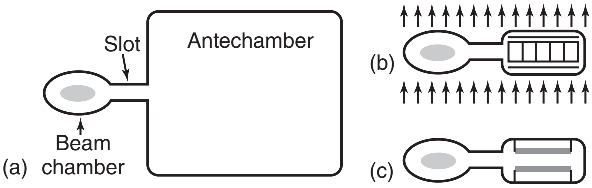

Figure 1.4 Examples of a beam chamber with an antechamber: (a) a large antechamber for increasing a vacuum conductance, (b) an antechamber with a distributed SIP in a dipole magnetic field, and (c) an antechamber with a distributed NEG strip pumps.

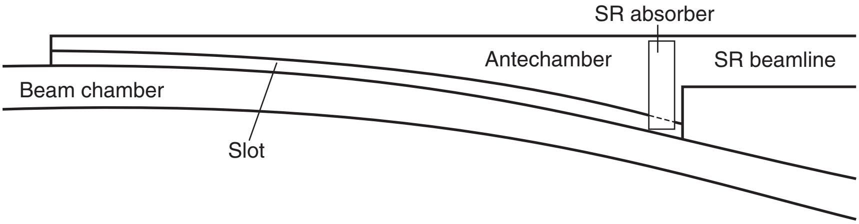

Figure 1.5 An example of a beam chamber with an SR antechamber, a slot between them, SR absorber, and beginning of SR beamline.

- Relatively small antechamber for placing distributed vacuum pumps, which usually are sputter ion pumps (SIPs) operating in a dipole and quadrupole magnetic field or the non-evaporable getter (NEG) strips (see Figure 1.4b,c).
- SR beam antechamber (see Figure 1.5)
  - for separating SR and charged particle beam at the beginning of SR beamlines where SR and charged particle beam coexist in the same vacuum chamber,
  - for more efficient absorption of SR with specially designed SR absorbers,
  - for reducing photoelectron production in the beam chamber,
  - for reducing SR background in detector,
  - for protecting cryogenics or sensitive equipment.

In general, the vacuum chamber cross sections for each machine are optimised in a multi-iteration process considering all limits, wishes, and acceptable and unacceptable solutions for each special field involved in the design: beam lattice, magnets, cryogenics, vacuum, mechanical design, radiation protection, health and safety, etc.

1.3.5 Possible Pumping Layouts

Pumping technology provides a wide range of possible vacuum solution based on different pumping layouts.

1. The lumped pumping layout shown in Figure 1.6a consists of
   - a beam vacuum chamber
     - simple, without an antechamber,

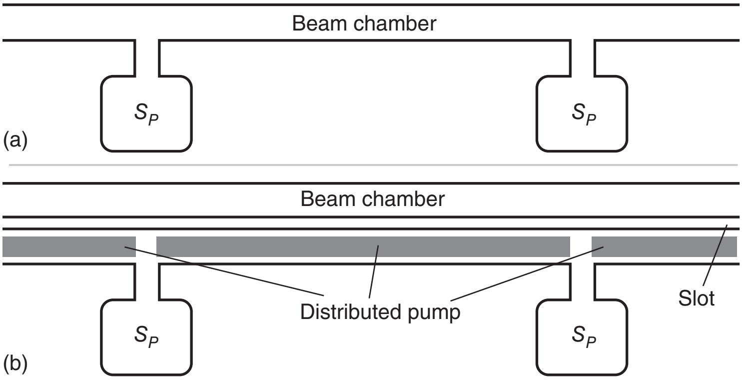

Figure 1.6 A beam chamber between two lumped pumps (a) without an antechamber and (b) with an antechamber containing a distributed pump.

    - ○ or with a large antechamber for increasing vacuum conductance,
  - and the pumps with pumping units located at a certain distance from each other.
2. The distributed pumping layout shown in Figure 1.6b consists of
   - a beam vacuum chamber,
   - with an antechamber containing the distributed pump along entire length of the antechamber,
   - and the pumps or pumping units located at a certain distance from each other.
3. The NEG coated vacuum chamber is used for UHV/XHV conditions. In this case an entire vacuum chamber is coated with NEG film – no antechamber required. NEG coated chambers are discussed in detail in Chapter 3.

The lumped pumps can be any of the following pumps (but not limited to) or combination of two or even three of them in one same unit:

- Sputter ion pump (SIP)
- Titanium sublimation pump (TSP)
- NEG pumps
- Turbo-molecular pump (TMP) backed up by a roughing pump or pumping station
- Cryopumps

1.4 First and Very Rough Estimations

Before choosing a possible pumping layout and starting mechanical design of vacuum system, we have to *roughly estimate* the number and size of pumps required to meet vacuum specifications. First of all it is necessary to define all sources of residual gas in a vacuum chamber with and without a beam. Most commonly these are thermal outgassing of vacuum chamber and in-vacuum components, beam-stimulated gas desorption (photon-stimulated desorption [PSD], electron-stimulated desorption [ESD], ion-stimulated desorption [ISD], heavy ion-stimulated desorption [HISD]) and gas injection.

Knowing what is available and from previous experience, we have to work out what thermal outgassing can be expected from the material of a vacuum chamber and likely applied cleaning and preparation procedures. For example, the specific thermal outgassing rate of $\eta_t = 10^{-12}$ [mbar·l/(s·cm^2)] (or 10^{-9} [Pa·m/s] in SI units) is routinely obtained on baked stainless steel chambers, in the following analysis, we will use this value as a constant average value.

A total internal surface area of a vacuum chamber, A_{tot} [cm^2], can be roughly estimated (or guessed). Then the total outgassing rate is

$$Q_{\text{tot}} = \eta_t A_{\text{tot}}. \tag{1.13}$$

To reach the required pressure of P_{spec}, the total pumping speed S_{tot} should be greater than

$$S_{\text{tot}} > \frac{Q_{\text{tot}}}{P_{\text{spec}}} = \frac{\eta_t A_{\text{tot}}}{P_{\text{spec}}}. \tag{1.14}$$

Since a vacuum conductance of the beam chamber was not considered here, *this is a lower limit estimate of total required pumping speed.*

A minimum required number of pumps N_p and the average distance between them $\langle L_p \rangle$ can be estimated for a machine or its section with a total length of accelerator, L_{tot} [m], considering that the pumping speed of lumped pumps used in accelerators usually varies in the range $100\,\text{l/s} < S_p < 1000\,\text{l/s}$, as follows:

$$N_p = \frac{S_{\text{tot}}}{S_p} = \frac{\eta_t A_{\text{tot}}}{P_{\text{spec}} S_p}; \tag{1.15}$$

$$\langle L_p \rangle = \frac{L_{\text{tot}}}{N_p} = \frac{P_{\text{spec}} S_p L_{\text{tot}}}{\eta_t A_{\text{tot}}}. \tag{1.16}$$

Similarly, rough estimations can be performed for the machines with a beam-stimulated desorption (PSD, ESD, ISD). For example, vacuum modelling of the machines with SR requires the calculated values of the SR critical energy ε_c and the total photon flux Γ_{tot}. The required conditioning time allows estimating the average photon dose D [photons/m], which, in turn, allows estimating the average PSD yields, η_γ [molecules/photon].

In this case, the total outgassing rate is

$$Q_{\text{tot}} = \eta_t A_{\text{tot}} + \eta_\gamma \Gamma_{\text{tot}}. \tag{1.17}$$

The total pumping speed S_{tot} should be greater than

$$S_{\text{tot}} > \frac{Q_{\text{tot}}}{P_{\text{spec}}} = \frac{\eta_t A_{\text{tot}} + \eta_\gamma \Gamma_{\text{tot}}}{P_{\text{spec}}}. \tag{1.18}$$

The minimum required number of pumps N_p and the average distance between them $\langle L_p \rangle$ can be estimated as follows:

$$N_p = \frac{S_{\text{tot}}}{S_p} = \frac{\eta_t A_{\text{tot}} + \eta_\gamma \Gamma_{\text{tot}}}{P_{\text{spec}} S_p}; \tag{1.19}$$

$$\langle L_p \rangle = \frac{L_{\text{tot}}}{N_p} = \frac{P_{\text{spec}} S_p L_{\text{tot}}}{\eta_t A_{\text{tot}} + \eta_\gamma \Gamma_{\text{tot}}}. \tag{1.20}$$

One should not forget that *these estimations are very rough*, as they do not consider the vacuum conductance of beam chamber, they don't consider details of mechanical design, and all the input parameter values are very approximate. Accurate modelling will give the required number of pumps to be greater than N_p and the distance between them to be lower than $\langle L_p \rangle$; but this would be possible only when the mechanical design already exists.

Meanwhile, these simple calculations can quickly provide some initial information on how simple or, on the contrary, how challenging would it be to meet the required vacuum specification. The results and conclusions of these calculations allow estimating a scale of the task and could be sufficient for the first discussion on a vacuum system mechanical design – on how many pumping ports, possible type, and size of the pumps will be required overall.

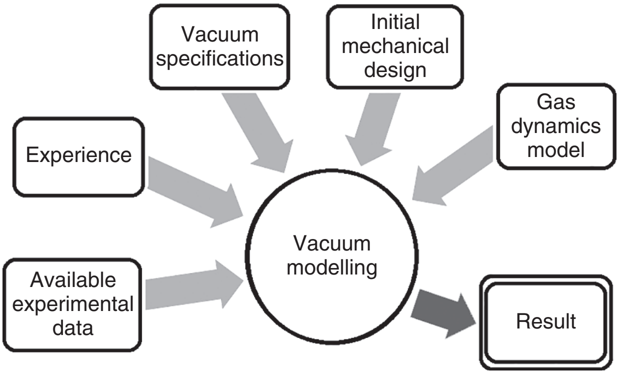

Figure 1.7 Initial considerations for vacuum modelling and design.

1.5 First Run of an Accurate Vacuum Modelling

When the initial mechanical design (or even a layout) of an accelerator and its vacuum chamber is available, a more detailed and accurate vacuum model can be built, taking into account all the vacuum conductances that have been ignored in the preliminary considerations. Chapters 2–5 describe the input data for the modelling (experimental results for TD [thermal desorption], PSD, ESD, and ISD and formulas for SR), the following Chapters 6–9 are devoted to the gas dynamics modelling, and the final Chapter 10 contains both experimental data and models for the heavy ion machine vacuum systems.

Now, using the preliminary mechanical layout, available experimental data, design, and operation experience from the past, one can draw up a rough vacuum design layout and, with the use of in-house or commercial software, perform vacuum modelling and obtain results on pressure (or gas density) profiles along the beam path, average gas density, more accurate results for the number of pumps, their locations, and required pumping speeds (see Figure 1.7). A few options could be considered and investigated to choose then which one is the most suitable and cost effective.

1.6 Towards the Final Design

In practice, a full vacuum system design cycle is more complicated. Schematically it can be shown as in Figure 1.8.

The design of a new machine is always based on experience of designing and operating of previous machines; this also includes the ‘it would be nice to have…’, ‘this was a good (or bad) idea to…’, practical ‘Do’s’ and ‘Don’ts’ (which could be true, or not necessarily true, or folklore).

A significant amount of *experimental data* is available in published journal papers, proceedings, preprints, reports, notes, and personal archives. These are the operation data for the running accelerators, the SR, and particle beamlines, many results were obtained in dedicated experiments in laboratories, on the

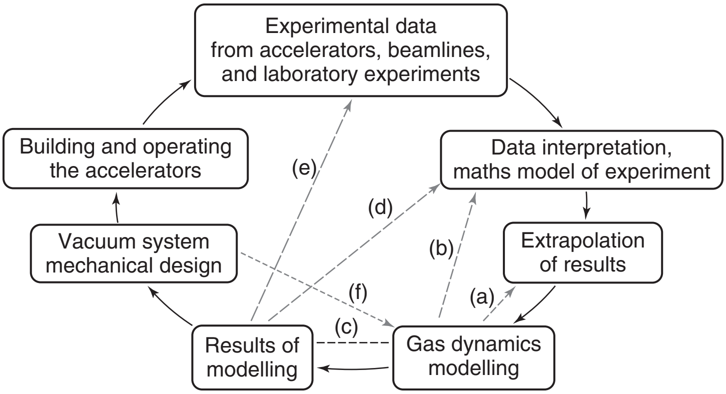

Figure 1.8 Modelling workflow diagram in vacuum system design cycle. (a) – extrapolation revision, (b) and (d) – data interpretation revision, (c) and (f) – vacuum model revision, (e) – experimental data revision or request for a new experimental study.

beamlines, or on the dedicated vacuum chamber inserts in the existing and operating machines. At this point it is extremely important to justify which results are more relevant to a newly designed machine. Ideally, all the experimental conditions should be as close as possible to the operation conditions on the future machine: materials, dimensions of vacuum chamber, surface cleaning and treatments, vacuum firing, bakeout, vacuum chamber temperature; energy, intensity, and dose of bombarding particles (SR, electrons, ions, etc.); and many other relevant parameters.

Furthermore, the following should be carefully considered when applying experiential data for modelling a new machine:

- The experimental data has experimental errors.[1]
- The experimental *data* has undergone an *interpretation* based on a model, which could have an *error*; the model error could be reported or not reported together with the results. Furthermore, one should keep in mind that although the models applied for data interpretation are quite simple, easy to apply, and most likely correctly employed, occasionally, the traditional models could not be applied to new materials and condition of experiment; thus the data interpretation could be incorrect.
- The data could be *insufficient*: for example, there could be no data for some gas species or data were reported for low photon dose, no data for some particles bombarding vacuum chamber walls, no data of desorption yields for certain energies of incident particles, etc. In this case, the *data can be extrapolated* based on existing knowledge, observations, experience, and consideration. The

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[1] Note that presently only the total pressure vacuum gauges can be calibrated down to $\sim 10^{-7}$ Pa. Below this pressure the gauges are not calibrated. Furthermore, there is no ISO standard for the partial pressure measurements and the RGA calibration yet. It is incorrect to apply the gauge correction factor for the RGA data. To address this problem, many vacuum groups in accelerator centres employ some in-house-developed RGA calibration procedures. Thus, the partial pressure data should be used with a great caution.

extrapolations can be used, but a vacuum designer should be careful with a level of confidence in such extrapolations.

- When a vacuum designer starts building a gas dynamics model, he/she might discover that the reported data can't be used for modelling of a new accelerator. For example, occasionally reported 'effective desorption yields' allow a comparison of different samples on the same measurement facility but can't be used for the gas dynamics modelling. However, more careful and detailed analysis of raw data may allow extracting the real desorption yields or indicate the need of new experiment.

A *gas dynamics model* should include all the physical phenomena that affect the gas density along the beam path. On the other hand, the model should not be unnecessary complicated. Room temperature vacuum systems can be modelled with a 1D gas diffusion model and a 3D test particle Monte Carlo (TPMC) model described in Chapter 6. A cryogenic vacuum chamber requires a more complicated model described in Chapter 7. High intensity accelerators with positively charged beam may suffer from two problems: a design of a vacuum system with electron cloud problem is discussed in Chapter 8, and a model for the ion induced pressure instability is described in Chapters 9 and 10. Models in Chapters 7–10 are more complicated than in Chapter 6 because they include more specific phenomena for particular types of accelerators. The applied gas dynamics model should have an error that could be related to the model itself (see Chapters 6–10). One should also consider the difference between a real vacuum chamber and a simplified vacuum chamber shape in the applied gas dynamics model (for example, a bellows unit shown as a tube) could also result in a difference between a predicted (modelled) and real behaviour of vacuum system.

The *results* of gas dynamics modelling may indicate that model is not as accurate as required, and then the gas dynamics model should be modified or changed. The results may also demonstrate that the errors and approximations are too large to take a critical design decision and a new dedicated experimental study is required.

When the results of gas dynamics modelling shows that the vacuum system layout, locations of pumps and their pumping speed allow to meet vacuum specifications; this can be implemented in the *vacuum system mechanical design*. This design is often somehow different from the original model (different location and available space for pumping ports, new components, other material of vacuum chamber or its components, smaller or larger aperture of vacuum chamber adopted for a new version of the beam lattice or a new magnets design). That requires performing the gas dynamic modelling for an updated vacuum system mechanical design. Usually, there could be a number of iterations in the design with various minor and major modifications until the design is finalised (frozen).

When the accelerator is finally built and in operation, one can compare the predicted and actual behaviour of vacuum system (for example, see Figure 1.9 demonstrating a comparison of modelling results and measured data for the DLS [32]). This experience can then be applied for future machines.

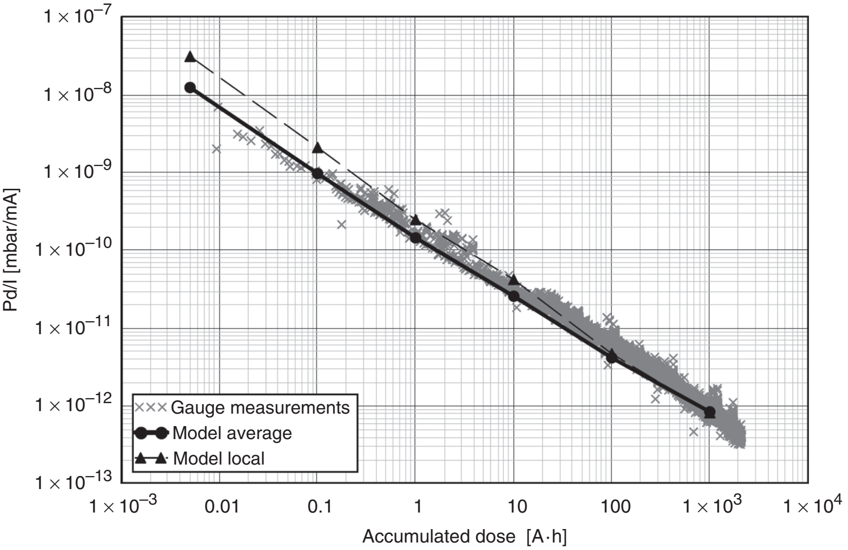

Figure 1.9 Modelling results versus measured data for the Diamond Light Source. Source: Wilson 2001 [26]. Reprinted with permission of Oxford University Press.

1.7 Final Remarks

The level of knowledge and expertise available in accelerator vacuum community is sufficient to design any type of accelerator with a high confidence. We aim to make a good design of accelerator vacuum system, which meets its specifications, allows for later improvements, and is economical, reliable, and maintainable. There could be two, three, or even more possible solutions to build vacuum system to the specification. It is very important to remember that any vacuum system design for an accelerator is a compromise between various system requirements, available technologies, and space restriction as well as considerations of time, cost, and practicality.

Gas dynamics modelling of vacuum system is a key process in verifying that everything is considered correctly in vacuum and mechanical design: input data, their accuracy and relevance, machine parameters, and specific problems.

The authors hope that this book would help with a design work for future charged particle accelerators.

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