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Design modelling and measured performance of the vacuum system of the Diamond Light Source storage ring

O.B. Malyshev [a], M.P. Cox [b,*]

[a] Accelerator Science and Technology Centre, STFC Daresbury Laboratory, Warrington, Cheshire WA4 4AD, UK
[b] Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot, Oxfordshire OX11 0DE, UK

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ABSTRACT

A one-dimensional diffusion model of the Diamond Light Source storage ring vacuum system is described and its predictions are compared with actual measured static (without beam) and dynamic (with beam) pressures over more than 2000 A h of beam conditioning at 3 GeV. An average specific thermal outgassing yield of $1 \cdot 10^{-11}$ mbar l/(s cm^2) during initial beam circulation is obtained, which reduces to $2 \cdot 10^{-12}$ mbar l/(s cm^2) after an accumulated beam dose of 1000 A h and an elapsed time of 769 days. In the presence of stored electron beam, the pressure rises as expected due to photon stimulated desorption (PSD). The PSD yield reduces with beam dose according to a (−2/3) power law as was applied in the model. Predicted and measured dynamic pressures generally agree within a factor of 2 over the whole range of beam conditioning dose studied.

1. Introduction

The UK national synchrotron facility, Diamond Light Source (Diamond), has been operating with circulating 3 GeV electron beam in the storage ring since September 2006. It generates synchrotron radiation from infra-red to X-rays for a wide range of applications in biology, physics, chemistry and medical research.

The Diamond 3 GeV electron storage ring is 561.6 m in circumference. It consists of 24 cells with 24 identical achromat (arc) sections each 17.35 m long and 24 straight sections (6 × 8.3 m long plus 18 × 5.3 m long), 21 of which are dedicated for insertion devices which are progressively being installed as the machine development continues. The remaining 3 straight sections are currently dedicated for radio frequency (RF) systems, injection and beam diagnostics. According to the design objective, the storage ring should achieve an operating pressure of 10^{-9} mbar (CO equivalent) or lower with 300 mA of stored beam after 100 A h of beam conditioning. The operating pressure is critical both for the lifetime of the stored beam and to control the Gas Bremsstrahlung radiation. *In-situ* bakeout is limited to the storage ring straight sections and front ends; the storage ring arcs are not bakeable *in-situ*. Details of the vacuum vessel cleaning, bakeout and installation have been published elsewhere [1].

The technical design, including the vacuum system design, was summarized in 2002 in the Diamond Design Report [2]. Some details of the vacuum system design and modelling were also published elsewhere [3–5]. In order to understand the design parameters and to refine the design model and parameters for future projects and upgrades, this paper compares the design performance of the vacuum system based on model studies with the actual measured performance.

During the detailed engineering and construction stage after publication of the Diamond Design Report some relatively minor changes were made to the vacuum system design and these have been incorporated into a revised model presented here.

Aspects of the measured performance of the Diamond storage ring vacuum system have already been reported [6] at an earlier stage in the beam conditioning process. For the purposes of comparison with the design model, more detailed measured data extending over 2000 A h of beam conditioning has been extracted from the data archive and analysed.

2. Diamond storage ring modelling

Modelling of a complex vacuum system such as the Diamond storage ring comprises several stages:

- Selecting a method of modelling
- Building a model and identifying required parameters
- Analyzing available experimental data and adopting them for use in the model

* Corresponding author. Tel.: +44 1235 778061.
E-mail address: matthew.cox@diamond.ac.uk (M.P. Cox).

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- Analyzing the results of the modelling
- Comparison of the modelling results with measurements of the real machine performance.

2.1. Model

When vacuum vessel drawings and desorption rate at every point on the surface are known and pump locations and pumping characteristics are defined, then the most accurate vacuum system modelling result can be obtained with the Test Particle Monte-Carlo (TPMC) code; for example, MOLFLOW written by R. Kersevan allows the building of accurate models of accelerator vacuum vessels. However, building the TPMC model and modifying it during design optimization is a time consuming process. The calculations with the code also require long computing time.

Another possibility is a diffusion model [2,3]. This is a one-dimensional (1D) model based on the equation of gas dynamic balance inside a vacuum vessel:

$$V\frac{\mathrm{d}P}{\mathrm{d}t} = q - cP + u\frac{\mathrm{d}^2P}{\mathrm{d}z^2}; \tag{1}$$

where P [mbar] is the local gas pressure at position z [m] on the longitudinal axis of the vacuum vessel; V [m^2] is the specific vacuum vessel volume per unit of vacuum vessel length; $q = \eta_t F/L + \eta_\gamma \Gamma / k_B T$ [mbar m^2/s] is the gas desorption flux per unit of vacuum vessel length where η_t [mbar m/s] is the thermal outgassing rate, F [m^2] is the vacuum vessel wall surface area, L [m] is the vacuum vessel length, η_γ [molecule/photon] is the photon stimulated desorption yield, Γ [photon/(s m)] is the incident synchrotron radiation (SR) photon flux, k_B is the Boltzmann constant [J/K] and T [K] is the gas temperature; $c = \rho A_{\mathrm{mesh}}\bar{v}/(4L)$ [m^2/s] is the distributed pumping speed, ρ is the capture factor for the pump including a pumping port and associated screening mesh, A_{mesh} [m^2] is the effective mesh area, $\bar{v}$ [m/s] is the mean molecular speed. $u = A_c \cdot D$ [m^4/s] is the specific vacuum vessel molecular gas flow conductance per unit axial length, A_c is the vacuum vessel cross-section; D is the Knudsen diffusion coefficient.

Two solutions of equation (1) exist in the quasi-equilibrium state when the condition $V\ dP/dt = 0$ is satisfied and also assuming that the parameters are independent of z. A vacuum vessel without a pumping port (when $c = 0$) is described with equation:

$$P\left(z\right) = -\frac{q}{2u}z^2 + C_{1a}z + C_{2a}; \tag{2}$$

and a vacuum vessel with a non-zero distributed pumping speed (i.e. $c > 0$), for example a pumping port covered with a mesh, is described as a vacuum vessel with a distributed pump:

$$P\left(z\right) = \frac{q}{c} + C_{1b}e^{\sqrt{\frac{c}{u}}z} + C_{2b}e^{-\sqrt{\frac{c}{u}}z}; \tag{3}$$

where the constants C_1 and C_2 depend on the boundary conditions.

The effective pumping speed was calculated for each pumping port separately with a TPMC code and was used in the diffusion model as uniformly distributed along a length equal to the overall length of the pumping port.

The vacuum vessel along the beam can in practice be considered as being divided into N longitudinal elements, each with $c = 0$ or $c > 0$. Every ith element lying between longitudinal coordinates z_{i-1} and z_i will be described by equation (2) or (3) with two unknowns C_{1i} and C_{2i}. The inter-element boundary conditions are taken as $P_i(z_i) = P_{i+1}(z_i)$ (single-valued pressure) and $\partial P_i(z_i)/\partial z = \partial P_{i+1}(z_i)/\partial z$ (zero net gas flow – assuming the conductances of the two elements are the same). There are several possible ways to write the boundary conditions for the first and the last elements. When the model includes the entire storage ring or its periodic parts, the periodic condition can be used (i.e. $P_1(z_0) = P_N(z_N)$ and $\partial P_1(z_0)/\partial z = \partial P_N(z_N)/\partial z$). However, during the design and optimisation work the periodic condition is not always fulfilled, and a simplification was applied where the first and the last elements have the same boundary conditions at both ends, i.e.: $P_1(z_0) = P_1(z_1)$ and $\partial P_1(z_0)/\partial z = \partial P_1(z_1)/\partial z$ for the first element and $P_N(z_{N-1}) = P_N(z_N)$ and $\partial P_N(z_{N-1})/\partial z = \partial P_N(z_N)/\partial z$ for the last one. The error due to simplified boundary conditions at the extremes of the modelled vacuum vessel has only a small influence on the calculated pressure distribution provided the first and the last elements are relatively short and the vacuum conductance of these elements is smaller than their pumping speed. These criteria are met at the location of vacuum pumps at the extremes of the arcs. In this case $C_{1i} = C_{2i}$ for $i = 1$ and $i = N$. Now for the N elements of the vacuum vessel we have a system of $2N-2$ equations with $2N-2$ unknowns, which can be easily solved with a numerical calculation package such as Mathcad.

The above analysis is strictly correct only in the limit of axially symmetric long vacuum vessels of uniform cross-section. For some parts of Diamond storage ring, this is approximately the case. However, this 1D analysis could be far from reality in the wide dipole magnet vacuum vessel. To assure the validity of these calculations, corroborating TPMC simulations were performed for some elements of the Diamond vacuum vessel [2]. No significant differences were found between the results of the 1D analysis described above and the TPMC simulations for most of vacuum vessel elements; some minor differences were found for dipole vacuum vessels: up to 10% for longitudinally averaged pressure along the beam path and up to 50% for local pressure along the beam path. This comparison showed that the 1D analytical method was sufficiently accurate for optimisation of the pressure profiles and the average pressure during the design of the Diamond vacuum system. The 1D analytical method is much faster, more convenient and more flexible than TPMC for calculations where many iterations in input parameters are required. Results for the updated vacuum system design were already published [4,5].

2.2. Input data

All materials used to build accelerators, such as stainless steel or copper, desorb gas into the vacuum system. This thermal desorption determines the base pressure in the storage ring without beam (static pressure). Thermal desorption is described by an outgassing rate η_t. The assumption based on experience from the Daresbury Synchrotron Radiation Source (information courtesy of R.J. Reid) was that for an *ex-situ* baked vacuum vessel which has been briefly vented to air and re-pumped, an outgassing rate of about 10^{-9} mbar l/(s cm^2) for H_2 and 10^{-10} mbar l/(s cm^2) for CO (in units commonly used in the vacuum community) will be reached after a few hours pumping, thereafter decreasing exponentially with additional pumping time. A value of outgassing rate two orders of magnitude lower should easily be obtained for carefully chosen and well-prepared materials after a few hundred hours of pumping at room temperature [7]. Since the cross-section of beam-gas interaction increases with atomic number squared [8] while the vacuum system conductance is greater for light gas species, the beam losses due to collisions with H_2 and CO (two main gases presented in residual gas spectrum of accelerators) are quite comparable; therefore a single gas model with the CO equivalent can be used. The values used in the model are shown in Table 1.