Vacuum 84 (2010) 760–764

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Improvement of beam lifetime and vacuum system of the PF-AR

Yasunori Tanimoto*, Tohru Honda, Takashi Uchiyama, Takashi Nogami

Photon Factory, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

A R T I C L E I N F O

Article history:
Received 30 October 2008
Received in revised form
19 March 2009
Accepted 6 June 2009

Keywords:
Accelerator
Synchrotron light source
Vacuum system
Beam lifetime

A B S T R A C T

Successive improvements have been performed on the vacuum system for the Photon Factory Advanced Ring (PF-AR) at the High Energy Accelerator Research Organization (KEK). The main purpose is to prolong electron beam lifetime for stable operation as an intense pulsed X-ray source. In the past three years, a total of 61 sputter ion pumps (SIPs) were additionally installed, and the increased effective pumping speed amounts to 13% of total. Comparison between calculated and observed beam lifetimes indicates that the lifetime is restricted mainly by the residual gas scatterings and that improvement of the vacuum will realize still longer lifetime. Sudden beam lifetime drops caused by dust trappings have been investigated for many years. The frequency of the lifetime drops has decreased as operation time elapsed after a large-scale reconstruction. Effect of distributed ion pumps (DIPs) on the lifetime drops has also been investigated experimentally.

1. Introduction

For the former e^+/e^- colliding experiment TRISTAN in KEK, the Accumulator Ring (AR), an injector to the Main Ring (MR), started its operation in 1983. After the AR completed its original role in 1994, the ring was transformed into a 6.5 GeV dedicated pulsed X-ray source to complement the 2.5 GeV Photon Factory storage ring (PF-ring), and in 1997 the AR was renamed to the PF-AR.

Since the original vacuum system was not tolerant to increasing demand for higher intensity Synchrotron Radiation (SR) and more stable operation, the PF-AR underwent a major upgrade in 2001, in which the vacuum system was almost entirely renewed [1]. By the end of 2005, the beam lifetime increased by 7 times and the maximum stored current increased by 50%.

Both observation and calculation of the beam lifetime suggested that electron beam loss was still dominated by beam-gas scatterings, in other words, improving total pumping speed would increase the beam lifetime. Further improvement, therefore, has been performed by installing additional 61 SIPs since 2006, and the increased effective pumping speed amounts to 13% of total. Currently achieved performances of the PF-AR vacuum system as well as ring main parameters are listed in Table 1.

Owing to the prolonged beam lifetime, re-fill frequency of the PF-AR is now twice a day, whereas it used to be 12 times a day before the upgrade. However, the scheduled beam injection is sometimes disordered when unexpected lifetime drop happens. This lifetime drop phenomenon, presumably caused by dust trappings, has been a perpetual nuisance since the beginning of the AR operation [2]. As one of the remedies for this problem, switching the distributed ion pumps (DIPs) off during user operation has been tested because DIP is considered as one of the dust sources. Although the beam lifetime is slightly reduced by the DIP-OFF operation, the reinforcement of the SIPs has enabled it as an option to improve the lifetime drop problem.

2. Correlation between beam lifetime and vacuum pressure

After the large-scale reconstruction in 2001, the beam lifetime grew favorably as the vacuum pressure decreased with the SR dose [3]. Fig. 1 shows the growth of the beam lifetime as $I\tau$ (the product of the stored beam current and the beam lifetime) and the progress of the vacuum chamber conditioning with the decrease of P_{av}/I (observed average pressure normalized by the stored beam current). The beam lifetime is still growing gradually due to the improvement of the vacuum system.

The injection beam energy was raised from 2.5 GeV to 3.0 GeV in September 2002 when the integrated current reached 80 A h. The reason of the energy change was to avoid strong beam instabilities in lower energies, and the change resulted in increased injection current from 40 mA to 60 mA.

Since the PF-AR is not operated with full-energy injection, it is impossible to employ a continuous (top-up) injection scheme. In order to increase the average intensity of the SR, extending the beam lifetime is the most practical solution, which can be achieved by improving the vacuum pressure of the ring.

* Corresponding author.
E-mail address: yasunori.tanimoto@kek.jp (Y. Tanimoto).

0042-207X/$ – see front matter
doi:10.1016/j.vacuum.2009.06.044

Table 1
Parameters of the PF-AR machine and the vacuum system.

Beam energy	6.5 GeV
Injection beam energy	3.0 GeV
Circumference	377 m
Natural emittance	260 nm rad
Bunch number/harmonic number	1/640 (exclusive single-bunch mode)
SR critical energy	26 keV
Initial stored current	60 mA
Beam lifetime of 60 mA beam	20 h
Dynamic pressure with 60 mA beam	3.6×10^{-7} Pa
Static pressure	4×10^{-8} Pa
Main vacuum pumps	Ti sublimation pump (184), DIP (56), SIP (111)
Total effective pumping speed	~65 m^3/s
Average photon-stimulated desorption yield	1×10^{-5} molecules/photon
Total SR power from 60 mA beam	400 kW (from bending magnets)
Vacuum gauges	Inverted magnetron gauge (85)
Main beam duct material	OFHC Cu (6 mm thick)

The relationship between the two observed quantities in Fig. 1, the vacuum pressure and the beam lifetime, can be calculated with the operational parameters of the PF-AR. In our calculation of the beam lifetime as a function of the pressure, three main processes are considered as expressed in the following equation.

$$\frac{1}{I\tau} = \frac{1}{I\tau_B} + \frac{1}{I\tau_R} + \frac{1}{I\tau_T} \tag{1}$$

where three subindices for the lifetime τ denote the beam loss process due to Bremsstrahlung (inelastic scatterings with residual gas nucleus), Rutherford scattering (elastic scattering with residual gas nucleus), and Touschek effect (intra-beam scattering), respectively. Using the scattering cross-section and the vacuum pressure, Eq. (1) is rewritten to

$$\frac{1}{I\tau} = (\sigma_B + \sigma_R)\frac{c}{kT}\frac{P_{av}}{I} + \frac{1}{I\tau_T} \tag{2}$$

where σ_B and σ_R are the total cross-section of the Bremsstrahlung and Rutherford scatterings, respectively. And c is the velocity of light, k is the Boltzmann constant, and T is the temperature. For the simplicity of the calculation, we only consider CO as interactive gas with beam because the main residual gas species in well-conditioned vacuum systems are H_2 and CO, and the cross-sections in above two processes are almost proportional to the square of the atomic number. In the following calculation, the formulas to calculate lifetimes were derived from Ref. [4] and modified into our practical forms.

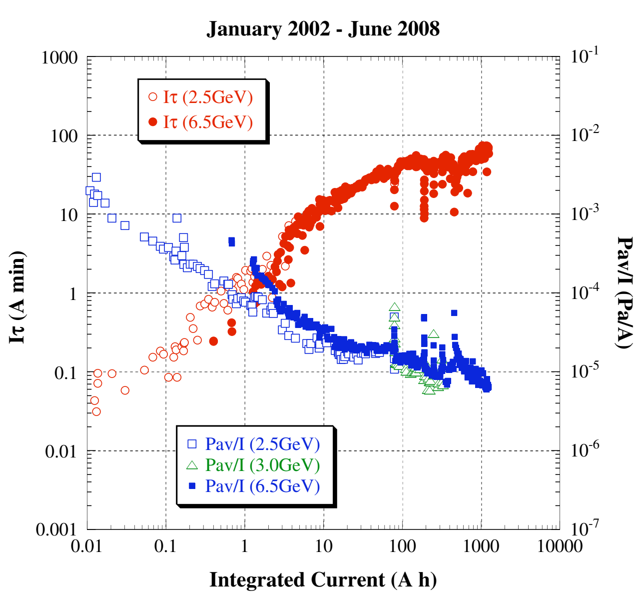

Fig. 1. Growth of the beam lifetime and progress of the vacuum chamber conditioning as a function of the beam dose since 2002.

First, the cross-section of the Bremsstrahlung is given by

$$\sigma_B = \frac{4Z(Z+1)r_0^2}{137}\left(-\frac{4}{3}\ln\frac{\Delta E}{E} - \frac{5}{6}\right)\ln\left(183Z^{-1/3}\right) \tag{3}$$

where Z is the atomic number (6 or 8), $\Delta E/E$ is the acceleration radio frequency (RF) bucket height (8.2×10^{-3}), and r_0 is the classical electron radius. The calculated σ_B is then 6.7 barn for CO. Similarly, the cross-section of the Rutherford scattering is given by

$$\sigma_R = 2\pi r_0^2 (Z/\gamma\varphi_c)^2 \tag{4}$$

where γ is the Lorentz factor of the beam and φ_c is the critical angle for the beam loss by the Rutherford scattering.

In the PF-AR, the critical angle is normally limited by vertically narrowest magnet gap at one of five in-vacuum undulators. The calculated φ_c becomes 1.1 mrad when the minimum undulator gap is 20 mm. However, SR users often close the undulator gap to 10 mm and we observe 5–10% decrease in the beam lifetime. In this case, the calculated φ_c decreases to 0.53 mrad. But in the following calculation, we use $\varphi_c = 1.1$ mrad if not specified. The calculated σ_R is then 0.28 barn for CO.

For the calculation of the Touschek lifetime, we use the following approximate formula.

$$I\tau_T = \frac{8\pi e\gamma^3\varepsilon_x^{3/2}\sqrt{\kappa\beta_y}\sigma_s\left(\frac{\Delta E}{E}\right)^2 N_{bunch}}{r_0^2 C_{ring}\left(-\ln\left(\gamma^{-2}\frac{\beta_x}{\varepsilon_x}\left(\frac{\Delta E}{E}\right)^2\right) - 2.077\right)} \tag{5}$$

where e is the elementary charge, ε_x is horizontal emittance of the beam (260 nm rad), κ is the transverse coupling of the beam (1%), β_x and β_y are average beta-functions in horizontal (9.1 m) and vertical (8.9 m), respectively, σ_s is the bunch length (20 mm), N_{bunch} is the number of stored bunches (1 bunch), and C_{ring} is the circumference of the ring (377 m). Using these appropriate values from the PF-AR operational parameters, the calculated $I\tau_T$ becomes 270 A min.

Finally, we obtain the equation of the beam lifetime as a function of the average vacuum pressure,

$$I\tau = \left(3100\frac{P_{av}(CO)}{I} + \frac{1}{270}\right)^{-1} \tag{6}$$

where $I\tau$ is in a unit of A min and $P_{av}(CO)/I$ is in a unit of Pa/A.

This relationship is illustrated in Fig. 2. The curve represents the calculated lifetime and the dots represent the observed lifetime. For the conversion of the observed average pressure to the CO average pressure along the beam orbit, we assume that the ratio of the residual gas species is H_2:CO = 7:3 and the relative sensitivity of ionization gauges for each gas is 0.5 and 1.0, respectively. In addition, we assume that the ratio of the average beam orbit pressure to the average pressure measured by the gauges is 1.2. This ratio was determined to make the calculated lifetime from Eq. (6) consistent with recently observed lifetimes (the regime of $P_{av}(CO)/I$ in 10^{-6} Pa/A). Although some other gas species must reside in the vacuum ducts, the effect of the other gas species is integrated to the ratio 1.2. Therefore, the average pressure measured by the gauges P_{av} can be translated to the CO equivalent pressure along the beam orbit $P_{av}(CO)$, and the relation is given by