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Effects of a Long Low-gap in-vacuum Undulator on the impedance and beam lifetime

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Abstract

Possible installation of a long low-gap in-vacuum undulator in the NSLS-II storage ring could result in several impedance-related and beam lifetime issues. High impedance of the low-gap undulator can result in beam instabilities and beam-induced overheating of the undulator itself. These issues have been preliminary studied using analytical formulae, computer simulations and experience of operations with existing in-vacuum undulators.

Depending on the device location, the minimum gap and the overall ring-average residual gas pressure, an in-vacuum undulator (IVU) may appreciably shorten the elastic gas scattering component of the beam lifetime. When the latter becomes comparable to the Touschek lifetime, a significant reduction of the total beam lifetime will occur. Here this effect is studied by applying some well-known analytical formulas, as well as insights from NSLS-II operating experience. Finally, the issue of IVU radiation damage also needs to be looked at, and potentially addressed with a dedicated collimation system.

Geometric impedance

A long low-gap in-vacuum undulator (IVU) is proposed to install in the NSLS-II storage ring. The length of the proposed undulator is 4 m and the smallest gap is 3 mm, its geometric and resistive-wall impedance could result in beam instabilities and overheating the foil covered the undulator magnets.

For a variable-gap IVU, analytical estimate, numerical simulations and beam-based measurements of the impedance have been performed at Diamond Light Source [1]. Total impedance of a vacuum chamber is considered as a sum of the geometric and the resistive-wall components. The broadband geometric impedance of the IVU chamber is predominantly determined by the tapered transitions connecting the IVU to the regular vacuum chamber.

The vacuum chamber of the Diamond IVU includes flat tapered transitions with a variable vertical aperture from $2b$=5 mm (closed) up to $2b$=30 mm (open). The entrance and exit vertical aperture of the IVU vacuum chamber is $2d$=18.4 mm, the length of the tapered transition is l=108.5 mm, and the width of parallel copper plates forming the transition is w=84 mm. Fig. 1 shows the model used for the wakefield simulation, it is represented by a rectangular tapered collimator if $b<d$, and by a rectangular tapered cavity if $b>d$. The separation length between the two tapers was chosen as l_{ID}=500 mm. Although the actual length of the undulator is 2480 mm, this simplification is possible because the contribution of the flat part to the geometric broadband impedance is negligible, as it was checked by the wakefield simulations performed with varied length of the central part.

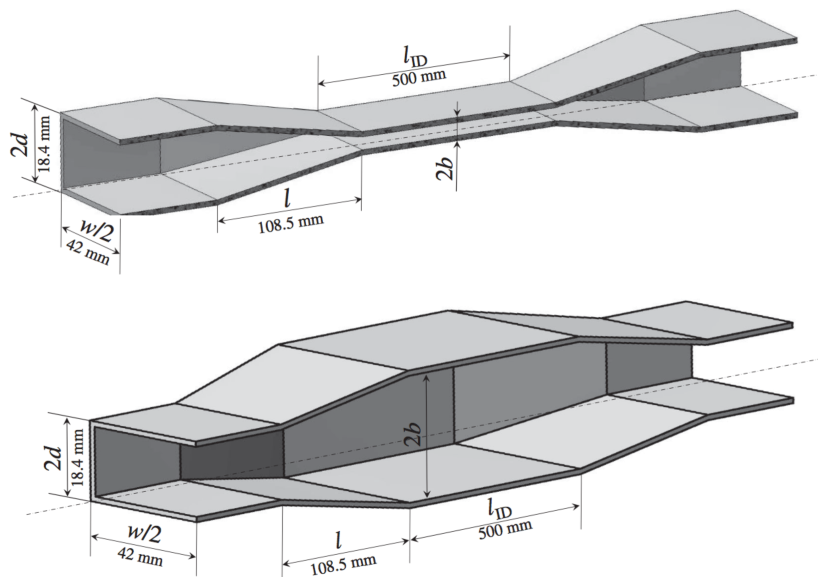

Fig. 1. IVU model used for wakefield simulations.

A set of formulae from [2] was used to calculate low-frequency geometric impedance of the tapered transitions. The longitudinal impedance is assumed to be inductive at low frequencies (constant normalized impedance $Z_{||}/n$):

$$\frac{Z_{\|}}{n} = -i\frac{Z_0\omega_0}{4\pi c}\int_{-\infty}^{\infty}(g')^2F\left(\frac{g}{w}\right)dz, \tag{1}$$

where $g'=dg/dz$, $g(z)$ is the vertical gap profile along the longitudinal axis z, w is the full width, Z_0≃377Ω is the free space impedance, $n=\omega/\omega_0$, ω_0 is the revolution frequency. The function $F(g/w)$ is defined as

$$F(x) = \sum_{m=0}^{\infty}\frac{1}{2m+1}\mathrm{sech}^2\phi_m \tanh\phi_m, \tag{2}$$

and the argument of hyperbolic functions in (2) is $\phi_m=(2m+1)\pi x/2$.

Fig. 2 shows the normalized impedance $Z_{||}/n$ of one ID section (two tapered transitions) as a function of the gap height 2b: formula (1) and simulation results from 3D codes CST Particle Studio and GDFIDL. Extrapolation to the gap 2b=3mm gives the normalized impedance $Z_{||}/n$=0.63mΩ. Fig. 3 shows the loss factor

$$k_{\|} = \frac{1}{2\pi}\int_{-\infty}^{\infty}Z_{\|}(\omega)h(\omega)\mathrm{d}\omega, \tag{3}$$

of two tapered transitions calculated using CST Particle Studio for a Gausian bunch with power spectrum $h(\omega)=\exp(-\omega^2\sigma_s^2/c^2)$, where σ_s =3mm is the r.m.s. bunch length. Extrapolation to the gap $2b$=3mm gives the loss factor (geometric impedance only) $k_{||}$=0.015V/pC.

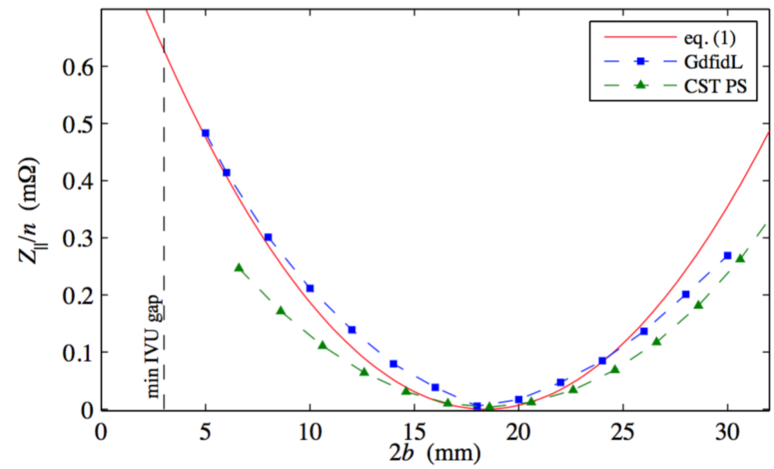

Fig. 2. Longitudinal normalized impedance as a function of gap.

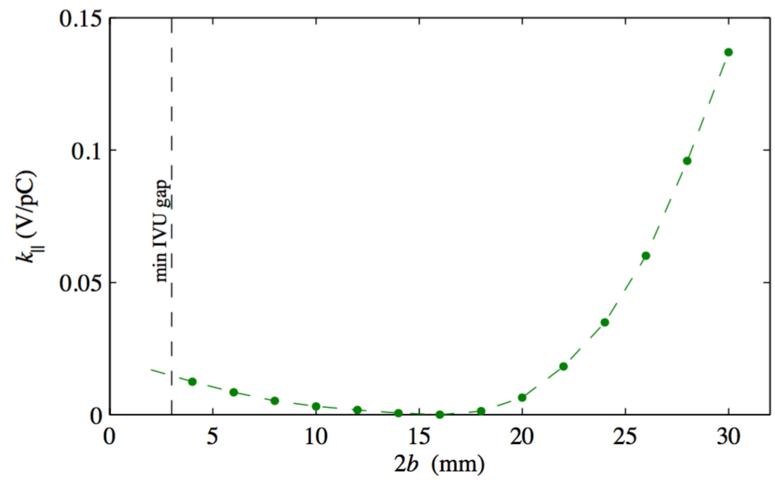

Fig. 3. Longitudinal loss factor (geometric impedance) as a function of gap.

For the transverse impedance, the formulae published in [3] were used:

$$Z_y(k) = -i\frac{Z_0}{2\pi b_0} \times \int_{-\infty}^{\infty} \frac{\xi^2}{\sinh^2\xi} \sum_{n=0}^{\infty} \delta_n \frac{H(k_n,k)+H(k_n,-k)}{2ik_n b_0} d\xi, \quad (4)$$

where $k=\omega/c$ is the wave number, $2b_0=b+d$, $\delta_n=1$ if n=0 and $\delta_n=2$ if $n>0$,

$$k_n b_0 = \sqrt{(kb_0)^2 - \xi^2 - (\pi n)^2}, \quad (5)$$

$$H(p,k) = \int_{-\infty}^{\infty}\int_{-\infty}^{z_1} S'(z_1)S'(z_2)e^{i(p+k)(z_1-z_2)}dz_1 dz_2, \quad (6)$$

$S'=dS/dz$, $S(z)=[g(z)-b_0]/b_0$, $g(z)$ is the vertical gap profile along z axis. These formulae have been derived using the boundary perturbation method assuming a taper of infinite width, $w \to \infty$.

The vertical kick factor

$$k_\perp = \frac{1}{2\pi}\int_{-\infty}^{\infty} Z_\perp(\omega)h(\omega)d\omega, \tag{7}$$

calculated using impedance (4) and the power spectrum $h(\omega)=\exp(-\omega^2\sigma_s^2/c^2)$ of a Gaussian bunch with σ_s =7mm is presented in Fig. 4 as a function of gap height $2b$ in comparison with the results of CST Particle Studio and GDFIDL. Extrapolation to the gap $2b$=3mm gives the kick factor k_y=325V/pC m.

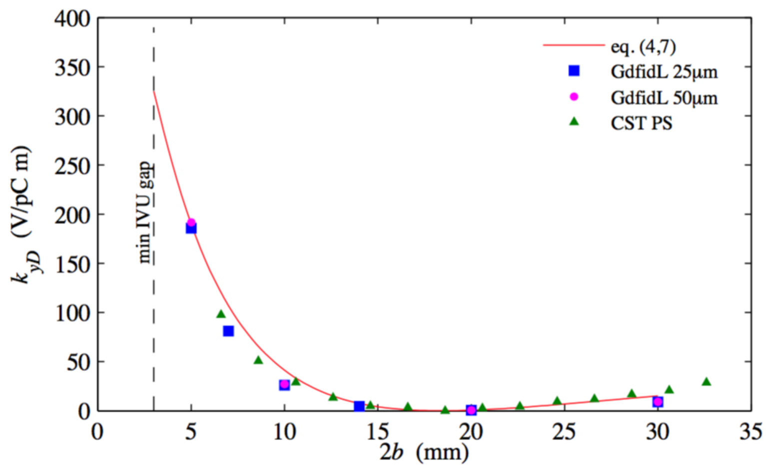

Fig. 4. Vertical kick factor (geometric impedance) as a function of gap.

Resistive-wall impedance

In spite of the copper foil covering the magnets, resistive-wall impedance of the long (4 m) undulator with a narrow gap (3 mm if closed) makes considerable contribution into the loss and kick factors. Formulae to calculate the resistive-wall impedance have been derived analytically for the round and flat vacuum chambers [4]. Two parallel plates is a quite good approximation of the in-vacuum undulator because the width of the foil covered IVU magnets is much larger than the gap height of closed IVU. If the wall thickness is much larger than the skin depth

$$\delta_s(\omega) = \sqrt{\frac{2c}{\mu_r\sigma_c Z_0|\omega|}}, \tag{8}$$

the longitudinal $Z_{||}/L$ and transverse $Z_\perp/L$ impedances per unit length are

$$\frac{Z_{||}^{rw}}{L} = (1+i)\frac{1}{2\pi b}\sqrt{\frac{Z_0\rho}{2c}}\,\omega^{1/2} \tag{9}$$

$$\frac{Z_{\perp}^{rw}}{L} = (1+i)\frac{1}{\pi b^3}\sqrt{\frac{cZ_0\rho}{2}}\,\omega^{-1/2} \tag{10}$$

where c is the speed of light, μ_r and σ_c are the relative permeability and conductivity of the chamber material, respectively; Z_0 is the free space impedance; b is the half-aperture. Beam-induced power per unit length is

$$\frac{P_{rw}}{L} = f_0 N_b k_{\parallel}^{rw} \left(\frac{I_{av}}{N_b f_0} \right)^2 , \tag{11}$$

where I_{av} is the average beam current, N_b is the number of bunches, f_0 is the revolution frequency.

Fig. 5 shows the beam-induced power per unit length P_{rw}/L as a function of the gap height $2b$, the bunch length is 3mm, the average beam current is 500mA, the number of bunches is 1000. The power at the 3mm gap is P_{rw}/L =31.5W/m.

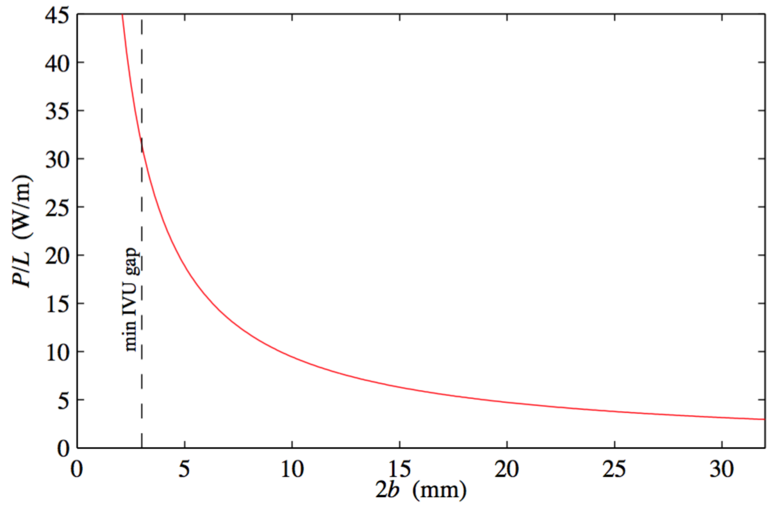

Fig. 5. Beam-induced power per unit length P_{rw}/L as a function of the gap.

Fig. 6 shows the vertical kick factor (Gaussian bunch, r.m.s. length is 3mm) per unit length k_y/L as a function of the gap height $2b$. The kick factor at the 3mm gap is k_y/L=655V/pC m^2.

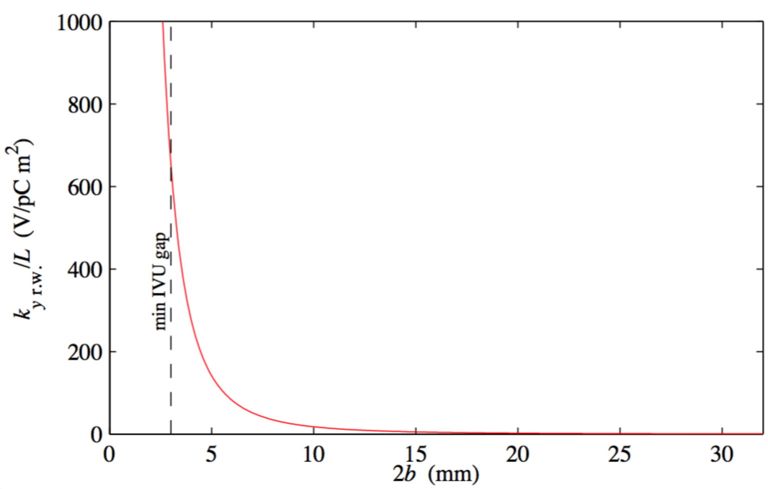

Fig. 6. Vertical kick factor (resistive-wall) per unit length as a function of the gap.

Beam-based measurements of vertical kick factor

The vertical kick factor of the Diamond IVU has been measured [1] as a function of the gap height by the orbit bump method [5]. The geometric impedance of the taper transitions has been computed using CST Particle Studio and GDFIDL codes and calculated with formulae (4-7). The resistive-wall impedance of the copper foil covering the IVU magnets has been calculated with formulae (9,10). The measurement and simulation results are summarized in Fig. 7 representing the vertical kick factor k_y as a function of the ID gap $2b$. The kick factor k_y includes both the geometric and resistive-wall contributions. The total measured kick factor is shown in red dots with error bars. The simulated results are represented by green triangles (CST Particle Studio) and blue squares (GDFIDL). The solid line represents the impedance calculated with the formulae.

Since the analytical calculations and the wakefield simulations have been carried out for the simplified model shown in Fig. 1, the contribution of other components of the ID vessel were not taken into account. There is a significant gap-independent part (180 V/pC m) of the kick factor introduced by the other components: step transitions, electrostatic beam position monitors, bellows and resistive walls. Extrapolation to the gap $2b$=3mm gives the kick factor k_y=1210V/pC m.

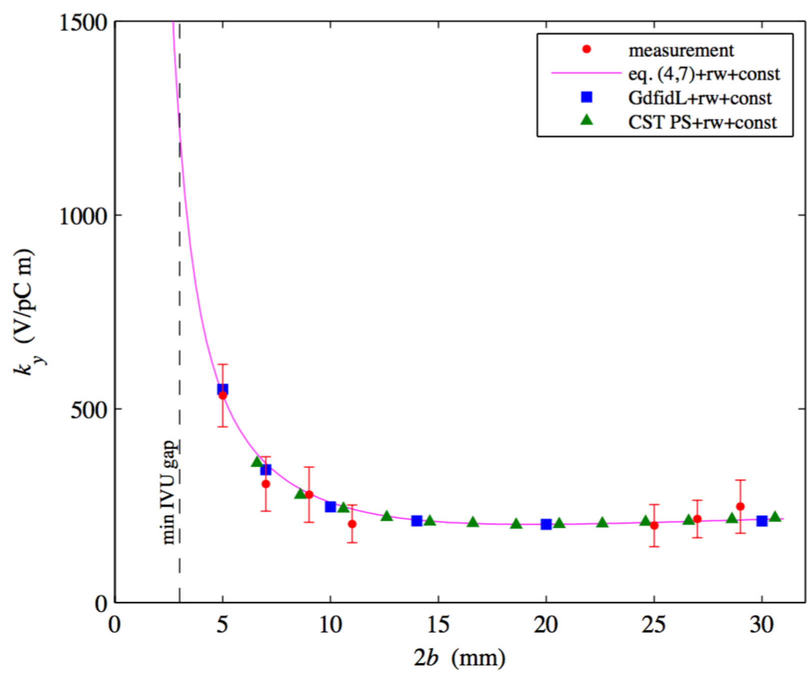

Fig. 7. Vertical kick factor as a function of the IVU gap.

Beam lifetime

We assume here that after the IVU installation the overall residual gas pressure does not increase and that the beam remains stable. We also ignore (likely miniscule) bunch-lengthening due to an added longitudinal impedance of the IVU device. In this case, the only IVU effect to the beam lifetime is due to a potential shortening of the elastic gas-scattering lifetime component. The mechanism of this effect is that beam electrons elastically scatter on the residual gas ions, then undergo large amplitude transverse oscillations and finally end up lost on transverse aperture(s), for instance the one presented by an IVU. The elastic gas-scattering lifetime is given by [6],

$$\frac{1}{\tau_{el}} = \frac{4r_e^2 Z^2 \pi n c}{2\gamma^2}\left[\frac{\langle\beta_x\rangle}{A_x} + \frac{\langle\beta_y\rangle}{A_y}\right], \qquad (12)$$

where $A_{x,y}$ are the horizontal and vertical acceptances, given by the minimum value of aperture, a(s), squared and divided by the beta function at that location, $A=\min(a(s)^2/\beta(s))$, n and Z are the concentration and the atomic number of the residual gas ions. For simplicity, only a single concentration and atomic number are shown in (12). If the specific composition of the residual gas is known, the scattering rate for each ion specie is calculated separately from (12), and then these rates are summed up to obtain the total gas scattering rate. Its inverse gives the overall elastic gas scattering lifetime.

To apply (12) to the case of an IVU we note that the horizontal aperture would typically be quite large, so below we will ignore the horizontal term in (12). Presently the minimum vertical acceptance in the NSLS-II ring, A_y =2 μm, is due to the insertion devices such as HXN IVU, which is 3 m long and is centered in a short straight (β_y=1.17 m in the center). This IVU can operate down to 5 mm full gap. Closing the gap of such a device further down, and/or making the device longer, would lower the acceptance accordingly and result in the reduction of the gas scattering lifetime. For instance, as shown in Fig. 8, a 3 mm full gap IVU (blue curve) results in a 20% lower elastic gas scattering lifetime (compared to that due to the HXN IVU at 5 mm gap), if the total device length is 1 m, while a 4 m long device reduces this lifetime by as much as a factor of 4.

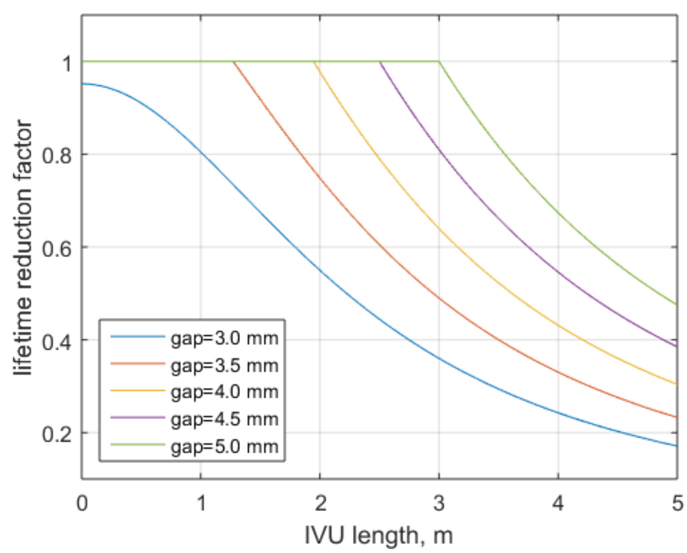

Fig. 8. Elastic gas-scattering lifetime reduction due to an IVU in a low-β straight calculated from (12).

What matters for the user operations, however, is the total (or overall) beam lifetime, so having a shorter gas-scattering lifetime is not necessarily a problem. The other two important beam loss processes are the inelastic gas scattering on residual gas ions, also known as bremsstrahlung, as well as the electron-electron scattering within a bunch, called the Touschek effect. The total lifetime is determined by

$$\tau_{total} = 1/(\tau_{el}^{-1} + \tau_{brem}^{-1} + \tau_{tous}^{-1}), \tag{13}$$

where τ_{brem} and τ_{tous} are the bremsstrahlung and the Touschek lifetimes respectively.

The bremsstrahlung lifetime, given by [6],

$$\frac{1}{\tau_{brem}} = \frac{16 r_e^2 Z^2 nc}{411} \ln\left[\frac{183}{Z^{1/3}}\right]\left[-\ln\varepsilon_{acc} - \frac{5}{8}\right], \tag{14}$$

where ε_{acc} is the limiting momentum acceptance, is typically larger than the elastic gas scattering lifetime. Taking the usual assumption of 1nT of N_2-equivalent residual gas pressure we can estimate both gas-scattering lifetimes from (12) and (14). The result is $\tau_{el} = 30$ hours (for the vertical acceptance of 2 μm due to 5 mm HXN gap assumed) and $\tau_{brem} = 70$ hours (assuming 2.8% momentum acceptance), i.e. the bremsstrahlung lifetime is a factor of 2.8 longer that the elastic one. Note that the absolute lifetime numbers depend linearly on the gas pressure and, in a more complicated way, on the ion specie composition. Both quantities need to be known along the beam path, and so far cannot be measured or modelled very accurately. However, the ratio of the two gas lifetimes is pressure-independent, and, due to the logarithm in (14), rather weakly depends on the specie composition. Therefore, the conclusion that the elastic gas scattering lifetime is significantly longer than the bremsstrahlung lifetime (more significant for more aggressive IVUs) should remain valid.

At NSLS-II, as well as at other high-brightness storage ring light sources, the dominant (shortest) lifetime contribution typically comes from the Touschek effect. For a given storage ring lattice, τ_{tous} depends on a number of parameters, such as the current per bunch, vertical emittance (more accurately the vertical beam size around the ring), momentum acceptance, bunch length, etc. Assuming the following parameter set for the purposes of this note: beam current of 0.5 mA/bunch, vertical emittance ε_y=8 pm, three damping wiggler operational lattice, 2.8% constant momentum acceptance, rms bunch length of σ_0=15 ps, and using the standard flat bunch regime formula [8], we obtain the Touschek lifetime of 4.1 hours.

To illustrate the IVU effect on the total ring lifetime, we now plug this Touschek lifetime number of 4.1 hours and the bremsstrahlung lifetime of 70 hours into (13). Then, for the elastic gas scattering contribution, we use the nominal value, $\tau_{el} = 30$ hours, scaled, for each IVU geometry, by the appropriate scaling factor from in Fig 8. The result is plotted in Fig. 9. One can see that a 4 m long IVU with 3 mm gap, for instance, would shorten the overall lifetime from 3.4 to 2.5 hours, i.e. by about 25%.

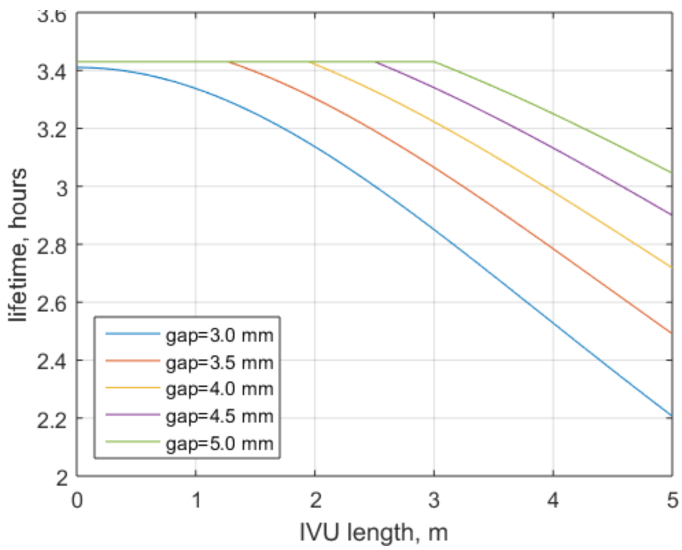

Fig. 9. Total lifetime for an IVU in a low-β straight (see assumptions in the text).

We must emphasize that this is just an illustrative example of a potential IVU impact on the beam lifetime for our particular choice of beam and vacuum parameters. Especially important are the parameters that define the Touschek lifetime. For instance, for a larger vertical emittance (NSLS-II lately runs in the range of 20-30 pm), the Touschek lifetime would be longer, $\tau_{tous} \sim \varepsilon_y^{1/2}$, so the relative reduction of the total lifetime due to the same IVU would be stronger. Conversely, the absolute value of the total lifetime with the IVU would still be higher than the corresponding number in Fig. 9 (plotted for $\varepsilon_y = 8\,\text{pm}$).

For completeness, another important issue related to beam lifetime, is that having an IVU serving as the minimum SR aperture for gas-scattering (and potentially Touschek) lifetime losses may not be optimal from the point of view of radiation damage to the device. This effect needs to be looked at and addressed, if needed, with a dedicated collimation system located elsewhere.

Conclusion

The impedance and lifetime issues of an in-vacuum undulator were studied using analytical formulae, computer simulations and beam-based measurements. The experimental data exist for the undulator (Diamond Light Source) with a smallest gap of 5 mm. As one can see in Fig. 5-7, both longitudinal (beam-induced power) and transverse (kick factor) impedance effects are growing fast at smaller gaps.

A summary of the impedance-related parameters and lifetime is presented in Table 1 for a 4-m long undulator with the gap of 3, 4, and 5 mm. The beam-induced power P_{rw} caused by the resistive-wall impedance is estimated with formula (11), the vertical kick factor $k_{\boldsymbol{y}}$ is obtained by extrapolation of the measured data. The lifetime is calculated assuming the IVU located in a low-β straight section, the lattice with three damping wigglers, and the following beam parameters: 0.5 mA/bunch, 8 pm vertical emittance, 2.8% momentum acceptance, and 15 ps r.m.s. bunch length.

Table 1. Impedance-related parameters and lifetime

IVU gap (mm)	P_{rw} (W)	k_y (V/pC m)	τ (hours)
5 mm	75	535	3.2
4 mm	95	740	3.0
3 mm	125	1210	2.5

For further feasibility analysis of a 4-m long undulator with 3-mm gap, the following studies should be completed:

- Accurate calculation of the IVU longitudinal and transverse impedance by wakefield simulations using realistic geometry.
- Thermal analysis.
- Beam-based impedance measurements of the IVUs already installed in NSLS-II.
- Vertical scraper studies at moderate average currents and variable fill patterns could determine the gas (and Touschek) fractions of the total beam lifetime.
- High current beam decay study under nominal operating conditions should help extrapolate beam lifetime to 500 mA total current.
- Developing proficiency with advanced vacuum modelling tools, i.e. MOLEFLOW/SYNRAD, successfully used at APS and elsewhere, should allow us to determine the residual ion pressure and composition along the beam path, from the measurements performed at the ion gauge locations. This should give higher confidence beam lifetime predictions.
- Radiation damage to the device and the use of a dedicated collimation system, located elsewhere, need to be looked into.

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