TRANSVERSE IMPEDANCE OF SMALL-GAP UNDULATORS FOR NSLS-II*

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Abstract

We discuss the transverse impedance resulting from the use of small-gap undulators in the proposed NSLS-II storage ring. For superconducting undulators, the impedance arises due to the tapered elliptical vacuum chamber. For in-vacuum permanent magnet devices, the impedance results from a more complex geometry. We consider both cases and report results obtained using the electromagnetic simulation program GdfidL.

INTRODUCTION

In the future NSLS-II storage ring it is planned to install both superconducting and in-vacuum permanent magnet undulators with 5 mm vertical aperture. In this paper, we present GdfidL [1] calculations of the transverse wakefield and impedance due to these devices. An approximate relation determining the threshold of the transverse coupled mode instability is given by [2]

$$\frac{e^2 N_e^{th}\,\beta_y}{4\pi\,\gamma\, m\, c^2\,\nu_s}\,\kappa_y \cong 0.7\,, \qquad (1)$$

where N_e^{th} is the number of electrons in a bunch at threshold, β_y is the average value of the betatron function in the undulator, γmc^2 is the electron energy and ν_s is the synchrotron tune. The kick factor κ_y is defined by

$$\kappa_y = \frac{c}{\pi}\int_0^{\infty} dk\, \mathrm{Im}\, Z_y(k)\, e^{-k^2\sigma_s^2}\,, \qquad (2)$$

where $Z_y(k)$ is the transverse impedance and σ_s is the rms bunch length of a Gaussian electron bunch. For a broad-band resonator impedance with resonant wavenumber k_r, shunt impedance R and quality factor Q,

$$\kappa_y^{res} \cong \frac{c}{2\sqrt{\pi}\,\sigma_s}\frac{R}{Q} \qquad (k_r\sigma_s > 1). \qquad (3)$$

For a warm chamber of length L, half-gap b, and conductivity $\sigma_{cond} = 6\times10^7\,/\Omega-m$ (copper), the resistive wall gives a contribution

$$\kappa_y^{rw} \cong 0.58\frac{c Z_0}{4\pi}\frac{2 s_0 L}{b^4}\sqrt{\frac{s_0}{\sigma_s}}\,, \qquad (4)$$

where [3], $s_0 = \left(2b^2 / Z_0\sigma_{cond}\right)^{1/3}$. For a $4^o K$ copper chamber, the extreme anomalous skin effect [4] yields

$$\kappa_y^{ease} \cong 0.21\frac{c Z_0}{4\pi}\frac{2 s_a L}{b^4}\left(\frac{s_a}{\sigma_s}\right)^{2/3}, \qquad (5)$$

with $s_a = 1.65\left(b^3 / Z_0\,\alpha\right)^{1/5}$ and $\alpha = 1.54\times10^{15}\,/\Omega-m^2$, the ratio of the conductivity to the mean free path.

TAPERED ELLIPTICAL VACUUM CHAMBER FOR A SUPERCONDUCTING SMALL-GAP UNDULATOR

The geometry of the tapered elliptic vacuum chamber is presented in Figure 1. The small-gap magnet region of the elliptic vacuum chamber for the superconducting undulator is fixed and has major axis $2a_s$=15mm and minor axis $2b_s$ = 5 mm with a magnet section length of 2000 mm. The tapers must smoothly transition between the magnet section and the regular beam pipe, which has a major axis $2a_b$ = 50 mm and minor axis $2b_b$ = 25 mm.

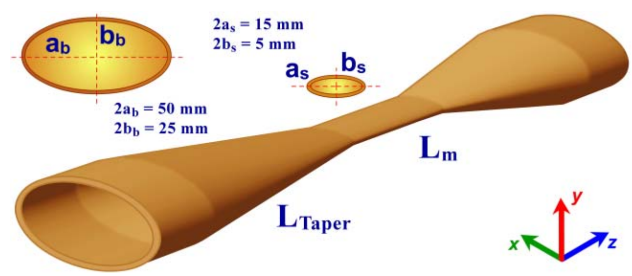

Figure 1: Tapered elliptical vacuum chamber for superconducting small-gap undulator.

Results of the transverse impedance in low frequency limit and the kick factor for the tapered vacuum chamber are independent of magnet section length (the distance between the two tapers). So to greatly ease the numerical computation, the length of the magnet section is taken to be 100 mm rather than 2000mm for an NSLS-II undulator. To estimate the contribution of the tapered elliptic vacuum chamber to the transverse impedance, the imaginary part of the transverse impedance in low frequency (ImZy(ω→0)) and the kick factor κ_y for a 3 mm bunch length are computed for the taper length L_{Taper}= 180mm. The wake field is shown in Figure 2 and the real and imaginary parts of the impedance in Figure 3.

A tapered elliptic chamber with the taper length L_{Taper}=180mm gives κ_y=190V/pC/m and ImZy(ω→0)=6.5kΩ/m. Increasing the taper length leads to decreasing of κ_y and $\mathrm{Im}Z_y$(ω→0) inversely proportional to L_{Taper}. The taper length of the elliptic

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vacuum chamber is chosen to optimize its contribution to the total impedance as well as space in the ring.

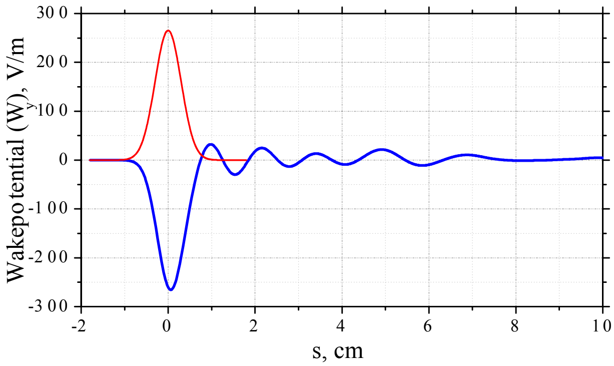

Figure 2: Transverse wakepotential in the tapered elliptic vacuum chamber (L_{Taper}=180mm).

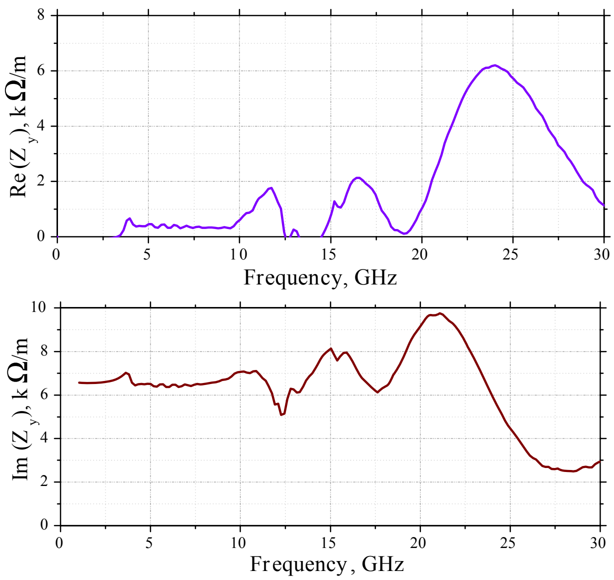

Figure 3: Real and imaginary parts of the transverse impedance in the tapered elliptic vacuum chamber (L_{Taper}=180mm). Impedances correspond to FFT of the computed wakepotential up to s=1.5m.

It should be noted that resonance peaks are observed inside the vacuum chamber in all cases of the transverse impedance calculations. These peaks are not fully resolved with a wakefield range of 1.5m. A more detailed investigation of the electrodynamic properties of the tapered elliptic vacuum chamber uncovered the existence of trapped modes. These modes have been identified and classified [5].

IN-VACUUM PERMANENT MAGNET UNDULATOR

A 3D-Model of the in-vacuum permanent magnet undulator (IVPMU) is shown in Figure 4. This model is motivated by the geometry of the X13 Mini Gap Undulator [6] currently operating at the NSLS X-Ray Ring and has been tailored to meet the NSLS-II requirements. The device consists of two magnet arrays of width w_m=100 mm and thickness 34 mm located inside a rectangular vacuum chamber of width w_{vc} = 180 mm and the height h_{vc} = 170 mm. The gap between two magnet arrays can be varied. For that reason the tapered transition consists of two parts: a fixed portion between the regular beam pipe and the undulator vacuum chamber; and a flexible height portion with one end fixed to the interior of the undulator vacuum chamber and the other end fixed to the moveable magnet array. The flexible portion only consists of flat upper and lower conductive plates with no side walls. For simplicity in the 3D model, we used a continuous smooth taper.

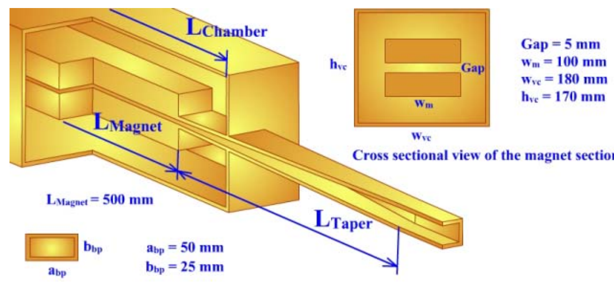

Figure 4: 3D-Model of the in-vacuum permanent magnet undulator.

Calculation of the transverse impedance in this geometry shows that the driving charge can excite strong resonant modes in the structure. The field strength of generated modes depends on the taper angle. The number of resonances in the structure is proportional to the magnet length. The frequency of the resonant modes depends on the gap between the two magnet arrays.

The modes in the IVPMU structure can be classified as in waveguide theory. The lowest frequency mode corresponds to a coaxial rectangular waveguide with an inner conductor of width 100 mm and height 85 mm. The next highest mode corresponds to an H-waveguide mode. Some higher modes correspond to a rectangular waveguide having a height of 5 mm.

In this paper, we present results of the numerical computation of the transverse wakepotential (for a 3 mm bunch length) and impedance for the IVPMU structure with a 500 mm magnet section length, a 590 mm vacuum chamber length and a 180 mm taper length (Figure 6 and Figure 7). Results can be compared with those presented earlier for the tapered elliptic vacuum chamber. The NSLS-II in-vacuum undulators will be 3000mm in length. GdfidL calculations exploring the length dependence of the impedance of IVPMU structures are now under consideration.

Figures 5 and 6 show the transverse wakepotential and impedance, respectively, for the considered geometry. The first resonant peak has a frequency f_1≈270 MHz. Its frequency depends on the magnet length inside the vacuum chamber, $f=c(p/2L)$, where c is velocity of light, p is the number of field variation in z-direction. The transverse wakepotential has a long range tail. This preliminary geometry of the in-vacuum permanent magnet undulator has a larger contribution to the transverse impedance than the elliptic vacuum chamber for superconducting small-gap undulator as can be seen from a comparison of the kick factors and transverse impedance in low frequency limit for the both structures. The kick factor and the transverse impedance for the presented IVPMU geometry are κ_y=425V/pC/m (to be compared with the kick factor κ_y=190V/pC/m in the elliptic vacuum chamber) and $\mathrm{Im}Z_y(\omega \to 0)$=39kΩ/m (to be compared with $\mathrm{Im}Z_y(\omega \to 0)$=6.5kΩ/m in the elliptic vacuum chamber), respectively.

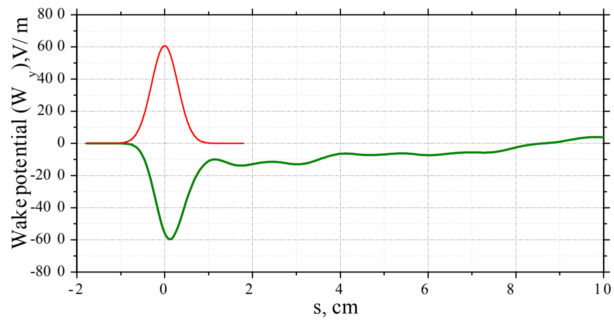

Figure 5: Short-range transverse wakepotential in in-vacuum permanent magnet undulator.

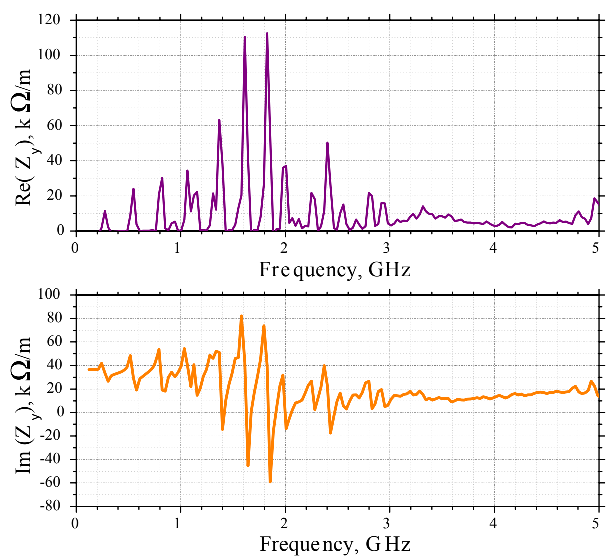

Figure 6: Low frequency behavior of the real and imaginary parts of the transverse impedance in in-vacuum permanent magnet undulator. Impedances correspond to FFT of the computed wakepotential up to s=7m.

Existence of the resonant modes at low frequencies can lead to couple bunch instabilities. This type of instability requires additional research. It should be noted that existence of the resonant mode has been observed experimentally (microwave measurements) in a structure similar to the IVPMU for NSLS-II [7]. From this point of view, frequencies of the resonant modes inside the IVPMU should be investigated more carefully due to their vicinity to harmonics of the RF frequency.

The short range wakefield in the IVPMU is predominantly determined by the tapers, and the long range wake depends on the cross-sectional geometry of the vacuum enclosure and the length of the magnet. Due to limitations on the mesh, we have not yet been able to carry out a systematic study of the length dependence.

SUMMARY

For NSLS-II, we consider a bunch of $N_e = 8\times 10^9$ electrons (0.5mA) with rms length $\sigma_s = 3.0mm$. The electron energy is 3 GeV and the synchrotron tune is $\nu_s = 0.009$. From Eq. 1, we see that to be below the TMCI threshold requires $\beta_y \; \kappa_y < 180 \; KV/pC$.

In the case of a superconducting undulator with 180mm taper length, the geometric kick factor is 190V/pC/m and that due to anomalous skin effect, Eq. 5, in copper $(s_a = 10\mu m)$ is (22 V/pC/m^2)xLength.

For an in-vacuum permanent magnet undulator, the geometric kick factor is 425V/pC/m and that due to the resistive wall, Eq. 4, in copper $(s_0 = 8\mu\, m)$ is (110V/pC/m^2)xLength.

Clearly, the in-vacuum devices present a larger impedance. Let us consider, 20 such devices each 3.5 m in length, and suppose the average vertical beta function in the undulators is $\beta_y = 3m$. These devices would yield $\beta_y \; \kappa_y = 49KV/pC$, corresponding to a threshold of about 1.8mA per bunch.

For comparison, we note that a broad-band resonator with $R/Q = 1M\Omega/m$, $\beta_y = 3m$ and resonant frequency greater than 20GHz, corresponds, Eq. 3, to $\beta_y \kappa_y = 84\,KV/pC$ and a threshold of 1.1mA per bunch.

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