

INFLUENCE OF RESISTIVE WALL IMPEDANCE ON THE VSX LIGHT SOURCE

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Abstract

We describe the calculated resistive wall impedance of the vacuum chamber and the corresponding growth rate of coupled-bunch instabilities for the VSX light source, a Japanese third generation VUV and soft X-ray source with a beam energy of 2 GeV. The impedance calculation was performed for the normal Al vacuum duct and the SiC duct, a higher-order mode (HOM) absorber of the damped RF cavity. The impedance of the Al vacuum duct with a narrow vertical aperture is sufficiently high at low frequencies for exciting a transverse coupled-bunch instability. On the other hand, the SiC duct does not cause a serious problem about coupled-bunch instabilities and it gives only a small contribution to the broad-band impedance related to single-bunch instabilities.

1 INTRODUCTION

The VSX light source [1] is a third generation synchrotron radiation source for producing a highly brilliant light in the VUV and soft X-ray region. It is designed to attain a low emittance of about 5 nmrad for DBA lattice [2] and 16 long straight sections (14.3m x 4, 7m x 12) for 14 insertion devices, injection magnets and RF cavities. Since small bore radii of the quadrupole and sextupole magnets and a narrow magnetic gap (less than 20 mm) of the insertion device are required, the vacuum chamber of the storage ring has a small aperture. As a result, the resistive wall impedance of the vacuum chamber become considerable. Furthermore, the circular SiC duct is installed on both ends of each RF cavity in order to damp the HOMs generated in the cavity [3]. The resistive wall impedance of the SiC duct should be estimated, because the resistivity of SiC, 0.2 Ωm , is higher in eight orders of magnitude than that of Al. In addition, the radiation damping force of the ring, a defense against instabilities, is not strong because of its low beam energy ($E=2\text{GeV}$). Therefore, coupled-bunch instabilities due to the resistive wall impedance may be occur below the design beam current of 400mA. In this paper, we report the influences of the normal Al vacuum duct and the SiC duct on the VSX storage ring in terms of beam instabilities.

2 RESISTIVE WALL IMPEDANCE

2.1 Al vacuum duct

Almost all vacuum ducts of the VSX storage ring will be made of Al alloy. Figure 1 shows the cross-sectional view of the vacuum duct for quadrupole and sextupole magnets. The vacuum duct for bending magnets has almost the same cross section. Here, we approximate all the ring vacuum ducts by a circular Al pipe with a length of the ring circumference C ($=388.45\text{m}$) and a pipe radius b ($=1.8\text{cm}$). The longitudinal and transverse resistive wall impedances of this circular pipe are given by

$$\frac{Z_l^{\text{Al}}(\omega)}{n} = (1 - i) \frac{Z_0 \delta_1}{2b}, \quad (1)$$

$$Z_t^{\text{Al}}(\omega) = (1 - i) \frac{Z_0 R \delta_1}{b^3} \quad (2)$$

with

$$n = \omega/\omega_0, \quad \delta_1 = \sqrt{\frac{2\rho_1}{\omega \mu_0}}. \quad (3)$$

Here, Z_0 , ω_0 , $R(=C/2\pi)$, μ_0 , ρ_1 and δ_1 are the characteristic impedance of vacuum, the angular revolution frequency, the average ring radius, the magnetic permeability of vacuum, the resistivity and skin depth of Al. Both impedances vary like $\omega^{-1/2}$ and increase at low frequencies. The transverse resistive wall impedance reaches to 0.38M Ω/m at the revolution frequency 771.8 kHz.

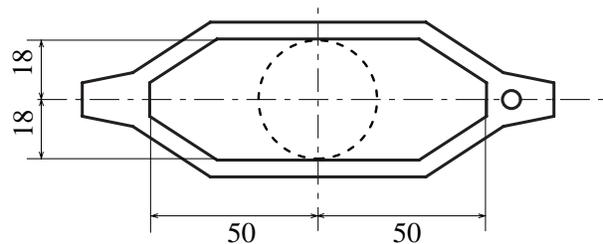


Figure: 1 Cross section of the Al vacuum duct for quadrupole and sextupole magnets. Dimensions are in unit of mm. A pipe indicated by a dotted circle was used in the impedance estimation.

2.2 SiC duct

Figure 2 shows the cross section of the SiC duct. This duct consists of an inner SiC layer and an outer Al layer, which were joined by sintering. The total length of the SiC duct is 90 cm for three RF cavities.

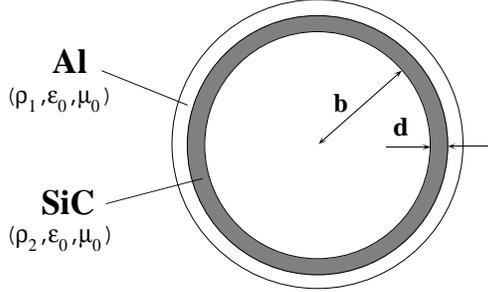


Figure: 2 Cross section of the SiC duct ($b=7\text{cm}$, $d=1\text{cm}$).

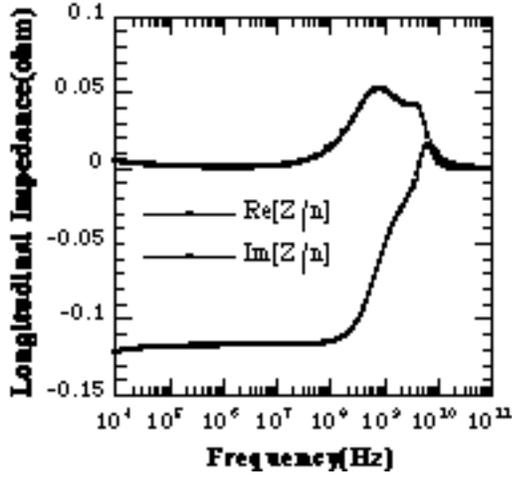


Figure: 3 Longitudinal resistive wall impedance of the SiC duct.

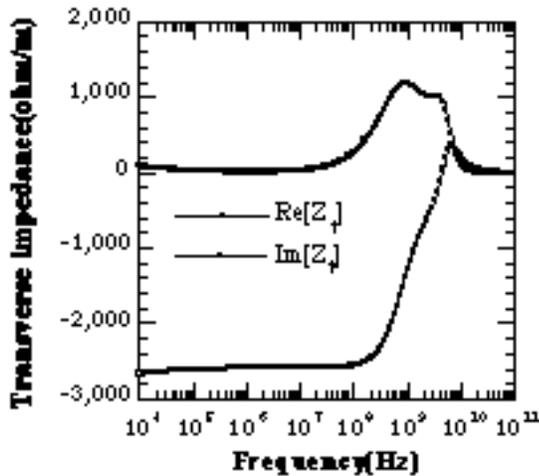


Figure: 4 Transverse resistive wall impedance of the SiC duct.

The resistive wall impedance of the SiC duct is obtained by solving the Maxwell equations analytically [4]. The longitudinal impedance of the SiC duct with a length of L is given by

$$Z_l^{\text{SiC}}(\omega) = \frac{L}{2\pi\epsilon_0 b c \left[\frac{ib\omega}{2c} - i \left\{ \frac{\omega}{\lambda_{2c}} + \frac{\lambda_{2c}}{\omega} \right\} \frac{J_1(\lambda_2 b) + \kappa N_1(\lambda_2 b)}{J_0(\lambda_2 b) + \kappa N_0(\lambda_2 b)} \right]} \quad (4)$$

where

$$\kappa = \frac{i \left(\frac{\omega}{\lambda_{2c}} + \frac{\lambda_{2c}}{\omega} \right) J_1(\lambda_2(b+d)) - \left(\frac{\omega}{\lambda_{1c}} + \frac{\lambda_{1c}}{\omega} \right) J_0(\lambda_2(b+d))}{\left(\frac{\omega}{\lambda_{1c}} + \frac{\lambda_{1c}}{\omega} \right) N_0(\lambda_2(b+d)) - i \left(\frac{\omega}{\lambda_{2c}} + \frac{\lambda_{2c}}{\omega} \right) N_1(\lambda_2(b+d))} \quad (5)$$

$$\lambda_{1,2} = \frac{1+i}{\delta_{1,2}} = \sqrt{\frac{\mu_0 \omega}{2\rho_{1,2}}} (1+i) \quad (6)$$

Here, J_0, J_1, N_0, N_1 are the Bessel functions and $b, d, c, \epsilon_0, \rho_2$ and δ_2 are the inside radius and thickness of the SiC layer, the speed of light, the permittivity of vacuum, the resistivity and skin depth of SiC. The transverse impedance is also given by an analytic expression [4]. However it is not shown here, because it is too long. The calculated longitudinal and transverse impedances of the SiC duct are shown in Figures 3 and 4. The real parts of these impedances are not remarkable at low frequencies, though they have a broad peak at high frequencies. Each impedance can be approximated by a broad-band resonator model with a Q-value of 0.3–0.6 and a resonant frequency of 4–5GHz. In addition, one can find a rough connection between the longitudinal and transverse impedances, $Z_l^{\text{SiC}} \sim (2c/b^2\omega_0)(Z_t^{\text{SiC}}/n)$.

3 COUPLED-BUNCH INSTABILITIES

3.1 Longitudinal growth rate

The growth rate of longitudinal symmetric coupled-bunch mode μ for a beam with the number of bunches k_b and the bunch current I_b is given by [5]

$$g_l^\mu = \frac{e\alpha k_b I_b}{4\pi E \omega_s} \sum_{p=-\infty}^{+\infty} \left\{ \omega_p^1 - \omega_s \right\}^2 e^{-\left\{ \frac{\sigma_1^2 \{ \omega_p^1 - \omega_s \}^2}{2c^2} \right\}} \cdot \text{Re} \left[\frac{Z_l(\omega_p^1)}{n} \right] \quad (7)$$

$$\omega_p^1 = (pk_b + \mu + \nu_s)\omega_0, \quad \omega_s = \nu_s \omega_0$$

α, ν_s , and σ_1 are the momentum compaction factor, synchrotron tune and bunch length. The parameter values of the ring used for the calculation are summarized in reference [2]. For the beam current of 400mA ($k_b=648, I_b=0.62\text{mA}$), the calculated growth rates of the circular Al pipe and the SiC duct are less than 0.1 sec^{-1} and negligible as compared with the longitudinal radiation damping rate (81 sec^{-1}).

3.2 Transverse growth rate

The growth rate of transverse symmetric coupled-bunch mode μ is given by [5]

$$g_t^\mu = -\frac{ek_b I_b \omega_0 \beta_t}{4\pi E} \sum_{p=-\infty}^{+\infty} e^{-\left\{\frac{\sigma_t^2 (\omega_p - \omega_\xi)^2}{2c^2}\right\}} \cdot \text{Re}[Z_t(\omega_p^t)] \quad (8)$$

$$\omega_p^t = (pk_b + \mu + \nu_t)\omega_0, \quad \omega_\xi = (\xi_t/\alpha)\omega_0.$$

Here ξ_t , ν_t , and β_t are the chromaticity, betatron tune, and betatron function at the vacuum chamber.

From Eq. (8), we calculate the vertical growth rate of the Al pipe for $k_b I_b = 400 \text{ mA}$. The maximum growth rate ($\mu = 638$) is estimated to be about 390 sec^{-1} at $b = 18 \text{ mm}$ and $\xi_y = 0$, and it is much higher than the transverse radiation damping rate (41 sec^{-1}). Therefore the vertical coupled-bunch mode will be excited in the ring if no other damping mechanisms exist. In Figures 5 and 6, the dependences of the maximum growth rate on the betatron tune ν_y and the chromaticity ξ_y are shown. These figures suggest that the growth rate can be reduced by a smaller fraction of the betatron tune or a larger positive chromaticity.

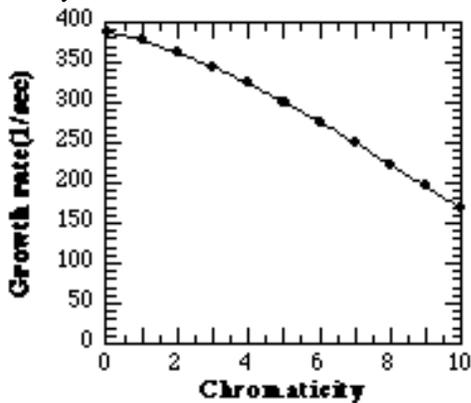


Figure: 5 Chromaticity dependence of the growth rate.

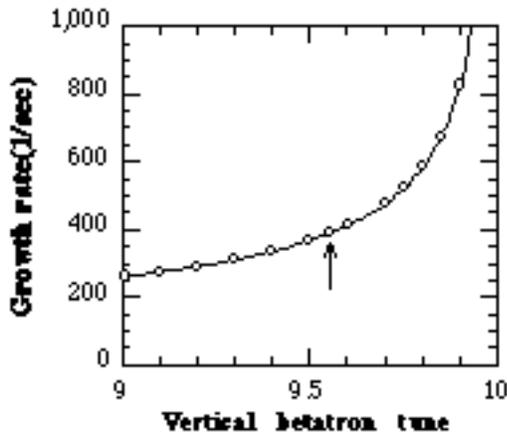


Figure: 6 Betatron-tune dependence of the growth rate. The arrow indicates the data point for the present design value of betatron tune ($\nu_y = 9.55$).

The transverse growth rate of the SiC duct is also calculated and found to be very low ($< 0.1 \text{ sec}^{-1}$) like the longitudinal one because of its broad impedance spectrum. The SiC duct cause neither transverse coupled-bunch instabilities nor longitudinal ones.

4 SINGLE-BUNCH INSTABILITIES

The resistive wall impedance of the Al vacuum duct decreases with the frequency and it is not considerable at high frequencies. Thus the influence of the Al vacuum duct on single bunch instabilities is probably small. The longitudinal and transverse broad-band impedances of the SiC duct is estimated from the approximated broad band resonator model to be $|Z_1^{\text{SiC}/n}|^{\text{BB}} \sim 0.1 \Omega$ and $|Z_t^{\text{SiC}}|^{\text{BB}} \sim 3 \text{ k}\Omega/\text{m}$. Both of them are much smaller than the broad-band impedances of the ordinary storage rings, which are usually dominated by discontinuities of the vacuum chamber such as bellows and transitions.

5 CONCLUSIONS

The resistive wall impedance of the Al vacuum chamber in the VSX storage ring will excite a transverse coupled-bunch mode with a growth rate of about 390 sec^{-1} , while it never causes longitudinal coupled-bunch instabilities. We need to prepare a transverse feedback system with a damping rate of about 1000 sec^{-1} , taking account of the insertion device vacuum ducts which is not considered here. The calculated impedance of the SiC is completely negligible for coupled-bunch instabilities and it is not substantial for single-bunch instabilities.

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