LONGITUDINAL AND TRANSVERSE IMPEDANCES OF XFEL KICKER VACUUM CHAMBER

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Abstract

In European XFEL project beam delivery system the kicker magnet vacuum chamber design is composed of the ceramic pipe coated with Titanium Stabilized High Gradient Steel. In this paper the results of the study for the longitudinal and transverse impedances for such a laminated vacuum chamber are presented. The field matching technique is used to calculate the vacuum chamber impedances. The loss and kick factors are given.

INTRODUCTION

In European XFEL facility [1] the simultaneous functioning of many experimental stations is reached by the system of fast flat top kickers able to direct individual bunches through different sets of undulators. The kicker magnets are the striplines surrounding a sputtered ceramic vacuum chamber. The beam distribution system consists of 10 kickers with a maximum field of 0.375 mrad. Magnet length of between 0.3 and 1 m are foreseen. The magnet vacuum chamber is a ceramic round pipe with inner radius 10 mm, coated inside by the special thin metallic film: Titanium-Stabilized High-Grade Steel (TSHGS) of 0.7 μm thickness.

The longitudinal and transverse impedances of kicker magnets represent the substantial contributing element leading to extra induced energy spread in the bunch and the head-tail kick [2,3]. We calculate the longitudinal monopole and transverse dipole components of impedance using the field matching technique taking into account the finite thickness of the vacuum chamber layers.

To evaluate impedances the ultrarelativistic approximations for the impedances of two-layer tube are used [4-6]. The ultrarelativistic approximation for the impedances is valid for the frequency range of $\omega/\omega_c << 1$, where $\omega_c \sim \gamma c/b$ with γ-the Lorenz factor, b-the vacuum chamber radius and c- the speed of the light. The spectrum of excited EM fields due to bunch interaction with surrounding structure is extended to the frequencies of up to $\omega_b \sim c/\sigma$ with σ the r.m.s bunch length. In XFEL kicker $\sigma_z = 25\mu m$, $b = 10mm$ and $\omega_b/\omega_c \sim 0.02 - 0.01$ for electron energies 10-25 GeV.

For large but finite γ the dipole term of the impedance in ultrarelativistic approximation contains logarithmical dependence on ω/ω_c that should be taken into account to correctly evaluate the high frequency part of the spectrum. In addition, the very low frequency part of the dipole impedance with this term is finite that results on correct calculation of the kick factor.

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IMPEDANCE OF TWO-LAYER TUBE

In this section we give a short overview of the ultrarelativistic approximation for monopole and dipole impedances of two-layer tube with arbitrary wall thickness and material, following the Refs. 4-6. The geometry of the vacuum chamber is presented in Fig.1

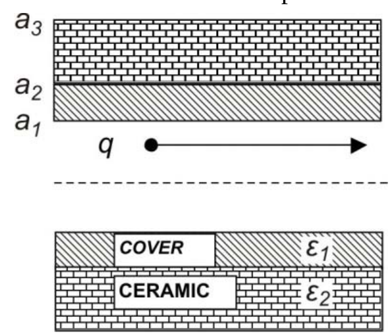

Figure 1: Ceramic tube with inner cover.

The ultrarelativistic presentation for the monopole term of the longitudinal impedance is given as [4-6]

$$\tilde{Z}_{\parallel}(k) = \frac{jZ_0}{\pi k a_1^2}\left(1 - \frac{2}{ka_1}\frac{Q_{33}}{Q_{23}}\right)^{-1} = \frac{jZ_0}{\pi k U(k)} \quad (1)$$

where $Z_0 = 377\Omega$, $k = \omega/c$ and Q_{ij} are the elements of field transformation matrix derived in [3] that depend on the layer's thickness and the material.

An important case is the ceramic pipe with internal metallic coating. The permeability of ceramic is given by $\varepsilon_2 = \varepsilon_0 n^2$ with n refraction index, ε_0 the vacuum dielectric constant. The radial propagation constant χ_2 in ceramic material without losses is an imaginary quantity $\chi_2 = jk\sqrt{n^2 - 1}$. For practical application, the good approximation follows from $|a_1\chi_1| >> 1$ in metallic layer and $|a_2\chi_2| = ka_2\sqrt{n^2-1} >> 1$ in ceramic layer. The first condition is valid for the metallic layer with the skin depth much smaller than the radius of the tube. The second condition is valid if the wave length of the field in ceramic layer is much smaller than the radius of vacuum chamber. Both conditions are satisfied for practically all important cases and for function $U(k)$ we get the following analytical presentation [4]

$$U(k) = a_1^2 + 2\frac{a_1\varepsilon_1}{\chi_1\varepsilon_0}\frac{1 - j\alpha\, th(\chi_1 d_1)tg(kn'd_2)}{th(\chi_1 d_1) - j\alpha\, tg(kn'd_2)} \quad (2)$$

where $\alpha = \frac{\chi_2}{\chi_1}\frac{\varepsilon_1}{\varepsilon_2}$ and $n' = \sqrt{n^2 - 1}$. As we see the impedance is oscillating function and at frequencies $k n' d_2 = \pi l \; (l = 0,1,2,...)$ the impedance is given by finite thickness metallic tube impedance

$$U(k) = a_1^2 + 2\frac{a_1\varepsilon_1}{\chi_1\varepsilon_0} cth(\chi_1 d_1) \qquad (3)$$

At frequencies $k n' d_2 = \pi/2 + \pi l$ ($l = 0,1,...$) we get

$$U(k) = a_1^2 + 2\frac{a_1\varepsilon_1}{\chi_1\varepsilon_0} th(\chi_1 d_1) \qquad (4)$$

For both set of frequencies the impedance is independent of the ceramic layer.

To obtain a correct ultrarelativistic approximation for XFEL kicker dipole impedance, we kept in asymptotic presentation the logarithmic dependence term on γ. The dipole term of the impedance for large but finite γ is given as [5,6]

$$\tilde{Z}_T^{(1)} = \frac{jZ_0}{\pi a_1}\left(\frac{k^2 a_1^2}{2} - 1 + ka_1 \frac{ka_3 A^+ + (1+2k^2 a_3^2 P_0) B^+}{ka_3 A^- + (1+2k^2 a_3^2 P_0) B^-}\right)^{-1} \qquad (5)$$

where $P_0 = \ln(ka_3/2\gamma) + C_E$, $C_E = 0.577216$ is the Euler constant, and coefficients $A^{\pm}, B^{\pm}$ are determined via the field transformation matrix elements Q_{ij} [5,6].

XFEL KICKER

The XFEL kicker magnet vacuum chamber is a stripline: the ceramic round pipe coated inside by the special thin metallic film of TSHGS. The internal radius of the pipe is 10 mm, the ceramic layer thickness 1 cm and the TSHGS thickness is about 0.7 μm.

The dielectric permeability of ceramic is taken equal to $\varepsilon_{cer} = \varepsilon_r \varepsilon_0 (1 + j\tan\delta)$ with relative dielectric permeability of the ceramic layer $\varepsilon_r = 9.1$ and $\tan\delta = 10^{-4}$. The TSHGS thin film dielectric permeability is equal to $\varepsilon_{cov} = \varepsilon_0 + j\sigma_c/\omega$ with the conductivity $\sigma_c \approx 2.0841 \times 10^6 \Omega^{-1} m^{-1}$.

Longitudinal Impedance and Loss Factor

Fig.2 and 3 present the real and imaginary parts of the longitudinal impedance calculated in ultrarelativistic approximation given by (1). For comparison the longitudinal impedance for the ceramic layer of infinite thickness without internal coating is given. As is seen the metallic film TSHGS increases the real part of impedance and reduces the imaginary part of the impedance. The loss factor for XFEL bunch is equal to 90.6 V/pC/m.

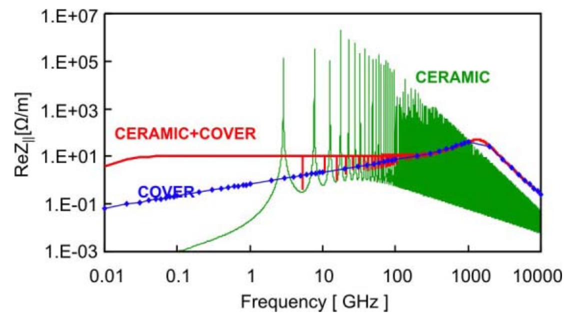

Figure 2: Real part of the longitudinal impedance for ceramic-TSHGS (blue) and ceramic (green) tubes.

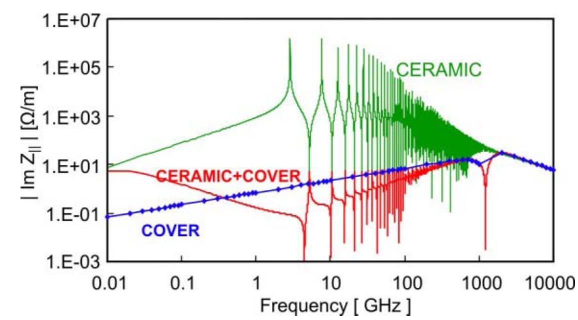

Figure 3: Imaginary part of the longitudinal impedance for ceramic-TSHGS (blue) and ceramic (green) tubes.

Transverse Impedance and Kick Factor

Figure 4 shows the real and imaginary parts of transverse dipole impedance. For comparison the ceramic tube of 1cm wall thickness and TSHGS tube with infinity wall thickness are shown .

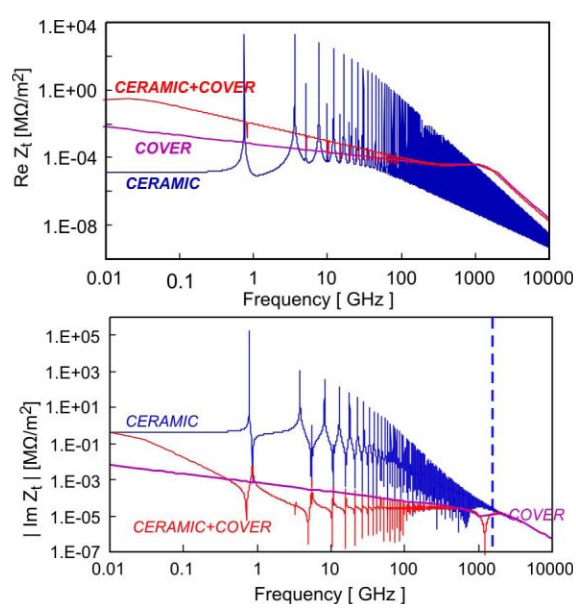

Figure 4: Real (top) and imaginary (bottom) parts of transverse impedance of XFEL kicker vacuum chamber

As can be seen from the figure the ceramic tube impedance in the low frequency region is constant while in high frequencies range it is characterized by the narrow-meshed periodical oscillations. Note that the oscillations amplitude decreases with the increasing of the wall thickness.

The fine structure of ceramic tube impedance (Fig. 5, top) is characterized by the periodically displaced high level maximums and low-level narrow-band resonance. For the fine structure of Ceramic- TSHGS tube impedance (Fig. 5, bottom) the high-level resonances disappear and the low-level notches appear instead of narrow-band low-level resonances of ceramic tube impedance.

The period of the oscillations is conditioned by the ceramic layer dielectric permeability and the thickness $d = a_3 - a_2$

$$\Delta f = c\Big/\sqrt{d(\varepsilon_r - 1)} \qquad (6)$$

that for our case is about $\approx 5.27\ GHz$.

In very high frequency region, the cover layer thickness surpasses the skin depth of the cover material $(\omega > 1.1THz)$ and the impedance of the ceramic-metal tube is fully determined by the cover layer material.

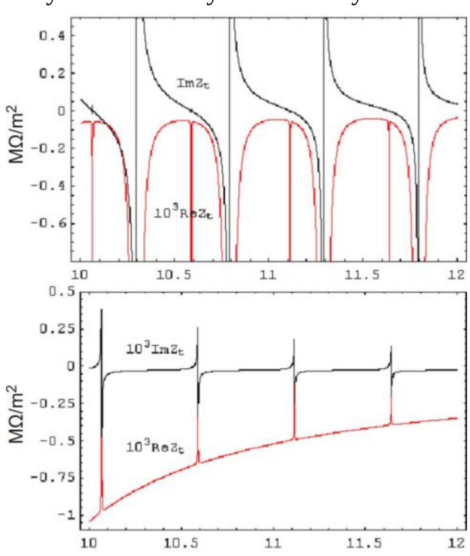

Figure 1: Fine structure of the ceramic (top) and ceramic-TSHGS tube (bottom) dipole impedance.

Note, that taking into account the logarithmical term in dipole impedance ultrarelatisitic approximation (5), the very low frequency asymptotic value ($\omega \to 0$) of the dipole impedance is finite and coincides with th exact solution that is independent of relativistic factor γ. In particular for the loss-less infinite ceramic wall

$$\tilde{Z}_{T,\omega\to 0} = -j\frac{Z_0}{2\pi a_1^2}\frac{\varepsilon_r - 1}{\varepsilon_r + 1} \qquad (7)$$

For the metallic finite thickness pipe the asymptotic value ($\omega \to 0$) is given by inner radius and thickness:

$$Z_{t,\omega\to 0} = -j\frac{Z_0}{2\pi a_1^2}\left(1 - \frac{a_1^2}{a_2^2}\right) \qquad (8)$$

The finite low frequency asymptotic behaviour of transverse dipole impedance (5) and negligible narrow-band resonances permit one the correct and straightforward calculation of the integral kick factor $k_\perp$ for the ceramic-metallic vacuum chamber. The dipole kick factor for XFEL bunch is 56.5 V/pC/m^2.

Fig.6 presents the kick factor for the XFEL ceramic-TSHGS kicker magnet vacuum chamber versus the ceramic layer thickness. The thickness of the cover is $0.7\mu m$

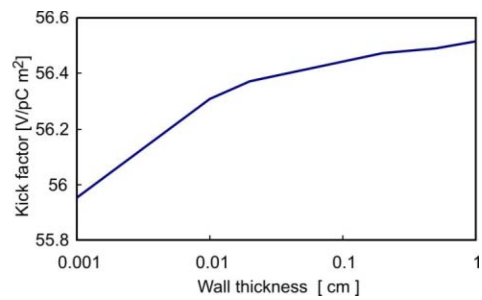

Figure 6: Kick factor of ceramic-TSHGS chamber versus ceramic layer thickness.

SUMMARY

The longitudinal and transverse impedances for the XFEL kicker vacuum chamber are calculated based on the field matching technique and taking into account the finite thickness of the walls. The longitudinal loss and transverse dipole kicker factors are calculated.

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REFERENCES

[1] The European XFEL, Technical Design Report, DESY 2006-097, July 2006.
[2] A.W. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators (Wiley, New York, 1993).
[3] B.W.Zotter and S.A.Kheifetz, Impedances and Wakes in High-Energy Particle Accelerators (World Scientific, Singapore, 1997).
[4] M. Ivanyan and V. Tsakanov, Phys. Rev. ST-AB, **vol. 7**, 114402, 5 pp., (2004).
[5] M. Ivanyan, E. Laziev, V. Tsakanov, A. Vardanyan, A. Tsakanian, and R. Wanzenberg, ICFA Beam Dyn. Newsletter, N45, pp. 125-138 (2008).
[6] M. Ivanian et al, Multi-Layer Tube Impedance and External Radiation , (to be published).