STATUS OF IMPEDANCE MODELING FOR THE PETRA IV

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Abstract

The diffraction limited synchrotron light source envisioned for the PETRA IV project will require strong focusing to produce the small emittances in both planes. The large natural chromaticity together with small dispersion will require very strong sextupoles. In order to cope with high gradient magnets the radius of vacuum chamber tends to be in the range of 10 mm, which is very small compared to the current 40-mm wide elliptic chamber. The impedance element in the PETRA III was scaled down to fit into the smaller aperture so that the short range wakepotential can be computed numerically. For instance the beam position monitor (BPM) was reduced to 60% in dimension so that it can be used in PETRA IV. Even if the actual design of hardware does not exist yet, we assume that generic feature of PETRA III model is still valid. In this paper we report the up-to-date information on impedance model of PETRA IV together with the preliminary impedance budget based on the analytical formula. We also report the specific studies carried out to understand the kick-factor scaling with the chamber aperture whose radius is in the range of 8-12 mm.

INTRODUCTION

The PETRA IV project aims at upgrading the synchrotron radiation source PETRA III at DESY to the ultra-low emittance source PETRA IV based on the multi-band achromat (MBA) storage-ring lattice [1]. As a beam circulating in the storage ring interacts with its vacuum chamber surroundings via electromagnetic fields, the wake fields in turn act back on the beam and can lead to instability, which limit either the achievable current per bunch or the total current or even both. Depending on the operational modes, long range and short range wake fields need to be evaluated in order to achieve the performance goal. In this paper we report a status of impedance modelling performed for the PETRA IV project.

IMPEDANCE OVERVIEW

Impedance Budget

The preliminary impedance budget was established based on the assumption that the single bunch current will be limited by transverse mode coupling instability (TMCI). The formula for the threshold current is [2]

$$I_{th} = \frac{4\sqrt{\pi}(E/e)\omega_s \nu_\beta \sigma_\tau}{R Z_{t,eff}}, \qquad (1)$$

where R is the radius of the ring, $Z_{t,eff}$ is the effective transverse impedance, E is the beam energy, ω_s is the synchrotron frequency, ν_β is the betatron tune, and σ_t is the rms bunch length in time. The bunch length will be much longer than the one determined by the natutal energy spread of the lattice because we will use a harmonic rf system in order to mitigate the intrabeam scattering (IBS) effect. The study showed that a third harmonic rf system with 1.2 MV gap voltage can lengthen the bunch up to 22 mm for a timing mode whose operation requires 1 mA per bunch [1, 3]. Substituting the lattice parameters in Ref. [1] into Eq. (1) we set the transverse impedance budget less than 1.2 MΩ/m.

Working Impedance Model

Here we consider the major fraction of total geometric impedance of PETRA IV based on the current assumption that there will be twenty-two insertion device (ID) sectors in the ring. Per each ID sector, there will be one undulator chamber, ten button BPMs, two ID chamber BPMs, five bellows, five flanges, and five radiation absorbers. The wake potential of each element was computed by the program GdfidL [4] excited by 1-mm long bunch. The total wake potential, which consists of twnety-two ID sectors plus forty 500-MHz cavity cells and twenty 1500-MHz cavity cells, was obtained by summation. From the Fourier transformation of wake potential divided by the bunch specturm we obtained the total impedance which is shown in Fig. 1. The imaginary part of horizontal and vertical impedance were depicted for comparison. From this we computed the effective vertical impedance for various bunch lengths ; for 22-mm bunch length, for which the impedance budget is set, we found the effective impedance is 0.5 MΩ/m.

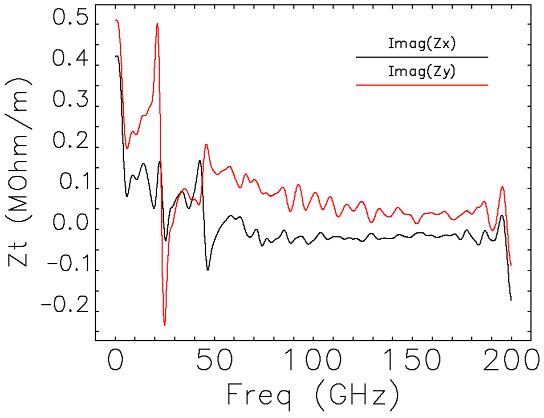

Figure 1: Geometric impedance of 22 ID sectors plus fundamental and harmonic rf systems.

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BEAM POSITION MONITORS

For the beam position monitor (BPM) we had used the same button developed for the PETRA III. However, the button was too big to fit into the 10-mm radius chamber of PETRA IV. So we reduced the button to 0.566 of original size with a new diameter of 8 mm and its thickness of 2 mm. This was housed in the cylindrical chamber whose diameter is 9 mm. The wake potential of this configuration was computed with the exciting bunch of 1-mm length and its impedance was included in Fig. 1.

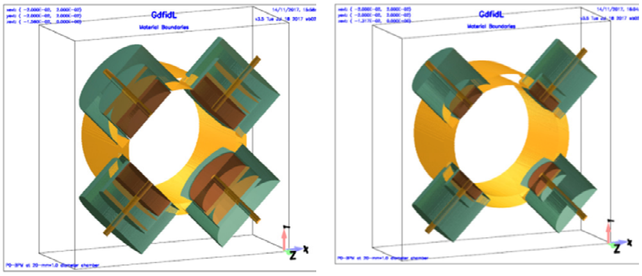

Figure 2: A BPM used in PETRA III installed at the 10-mm radius chamber (left) showing it is too big; its scaled model at the 10-mm radius chamber for PETRA IV application (right).

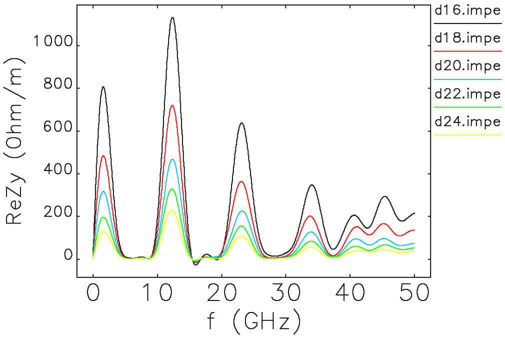

Figure 3: The vertical impedance of a BPM installed at the chamber with different aperture size from 16 mm to 24 mm.

Since the size of chamber is yet to be determined as the lattice design progresses, we had performed an investigative study how the impedance depends on the chamber aperture. For this study the BPM unit was installed in the circular beam pipe whose diameter varies from 16 to 24 mm. For each diameter its vertical wake potential was computed and its impedance was obtained by a Fourier transform. The real part of vertical impedance for different chamber aperture is shown in Fig. 3. We note that the resonant frequency is unchanged because we had used the same BPM unit for all cases. This is desirable because one design will fit all chambers. However, further analysis showed that the kick factor scales on the aperture as $K_y(D) \propto 1/D^{4.28}$, where D is the aperture diameter. This indicates the steep increase in impedance if a small pipe is used in future.

As a second approach we chose the occupation factor, Φ, to be constant ; the factor is defined as the fraction of subtended angle by buttons out of 2π. Because of the constant Φ the button diameter scales linearly as the chamber aperture varies. The simulation result is shown in Fig. 4, where the kick factor depends on the aperture as $K_y(D) \propto 1/D^{2.18}$, when we used Φ equal to 0.52. This indicates moderate increase compared to the previous case with small aperture.

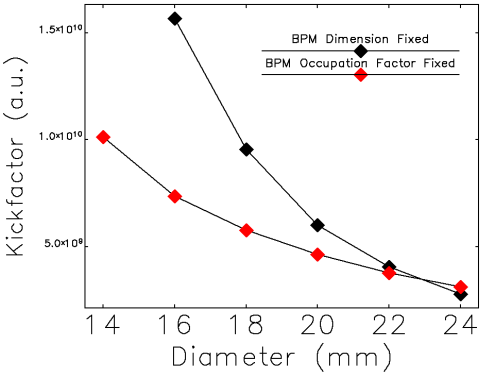

Figure 4: The transverse kick factor as a function of vacuum chamber aperture D for the constant button dimension (black diamond) as well as for the constant occupation factor (red diamond).

INSERTION DEVICE

The small gap chamber for the insertion devices in the 3rd generation light sources was the main source of vertical impedance which often limited the single bunch current. The transition angle was about 5 degree from large aperture to the small gap chamber. The dipolar component of the vertical impedance for a taper with rectangular cross section, was found to be [5]:

$$Z_y(k) = j\frac{Z_0 w}{4}\int_{-\infty}^{\infty}\frac{g'(z)^2}{g(z)^3}dz, \qquad (2)$$

where *w* is the (constant) width in the horizontal direction and *g(z)* is the (varying) gap of the taper in the vertical direction. Since the taper in PETRA IV is from circular to ellipse, we can't use Eq. (2) so that we had used the program GdfidL for the wake field computation.

The excitation of wake field occurs at the linear taper connecting 10-mm radius chamber to 10-mm by 3-mm ellipse over 20-cm length. The transition angle is about 2 degree and we will need very fine meshes to increase the signal over the numerical noise.

The empirical formula for the numerical convergence exhibits the mesh size smaller than 50 μm. Due to the limited computational resource we had tested down to 25 μm which still didn't reached the convergence. So the linear fit was extended to the zero mesh size whose result is shown in Fig. 5. Independent of GdfidL simulations we had performed the same test by using the program Echo3D [6] and its result is also included in Fig. 5. Note that both programs reached the same convergence. This reveals that we need to make about 25% correction toward the standard GdfidL simulation. The result shown in Fig. 1 had that correction included.

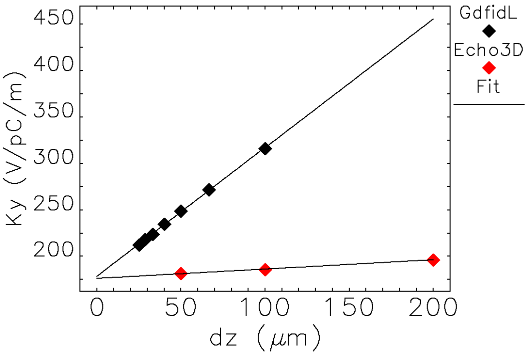

Figure 5: The convergence test of 6 mm gap ID chamber by two programs GdfidL and Echo3D.

RESISTIVE WALL IMPEDANCE

For the resistive wall the impedance of multi-layer structure can be accurately computed by the program ImpedanceWake2D developed at CERN [7]. In order to test the program we computed the wake potential of beam pipe made of aluminum. The transverse wake by the program ImpedanceWake2D is compared with the ones obtained by analytic formula of long and short range wake. The analytic formula for short range is given by [8]:

$$W_y(t) = \frac{8 t_0 c}{\pi \varepsilon_0 b^4} \begin{bmatrix} \frac{1}{12} e^{-t/t_0} \cos(\sqrt{3}t/t_0) \\ -\frac{1}{4\sqrt{3}} e^{-t/t_0} \sin(\sqrt{3}t/t_0) \\ -\frac{\sqrt{2}}{\pi} \int_0^\infty dx \frac{e^{-x^2 t/t_0}}{x^6+8} \end{bmatrix}, \qquad (3)$$

where t_0 is the characteristic time and b is the radius of beam pipe. The short range wakes are shown in Fig. 6 where the program produced the excellent agreement with Eq. (3).

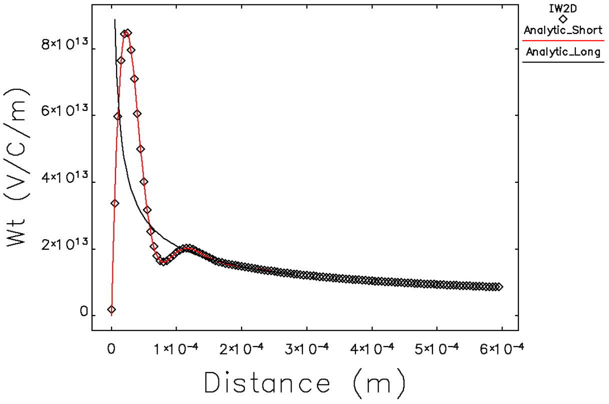

Figure 6: The short and long range wakes of resistive wall are in solid lines and the ImpedanceWake2D result in diamond.

In order to estimate the effect of NEG coating we used the same program. The NEG is a compound material consisting of (Zr, Ti, V) whose resistivity is (41.0, 55.6, 26.1)×10^{-8} Ωm, respectively. The coating is approximated as a single layer materical of 40×10^{-8} Ωm applied on 2-mm thick AL-6060 chamber. The coating thickness of 1, 2 and 3 μm was considered and the transverse impedance of coated chamber was depicted in Fig. 7. Depending on the thickness, the impedance begins to increase above certain frequency deviating from the bare chamber. If we assume the bunch length is about 20 mm, then the beam spectrum extends up to 5 GHz; hence the thickness less than 1 μm will have no effect on the beam. So we specified the thickness of NEG coating to be less than 1 μm.

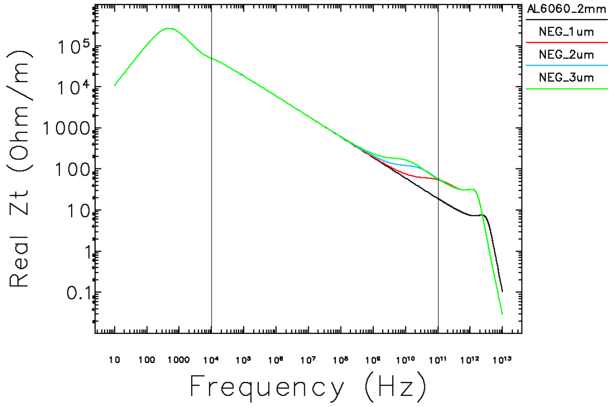

Figure 7: The resistive wall impedance of NEG coated aluminum chamber computed by ImpedanceWake2D.

CONCLUSION

In this paper we described the current status of impedance modelling for PETRA IV upgrade. For a timing mode the impedance budget is about 1.2 MΩ/m for 22-mm bunch and we plan to keep the total impedance within the budget.

ACKNOWLEDGEMENTS

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REFERENCES

[1] C. Schroer *et al.*, “The future ultra-low emittance source at DESY”, *J. Synchrotron Rad.*, submitted for the publication.

[2] A. W. Chao and M. Tigner, “Handbook of Accelerator Physics and Engineering”, 2nd Printing, world scientific, 1999, p. 212.

[3] Y.-C. Chae and J. Keil, presented at IPAC’18, Vancouver, Canada, Apr.-May 2018, paper TUPMF074, this conference.

[4] **`http://www.gdfidl.de`**

[5] G. Stupakov, *Phys. Rev. ST Accel. Beams,* vol. 10, p. 094401, 2007.

[6] I. Zagorodnov, *Phys. Rev. ST Accel. Beams,* vol. 9, p. 102002, 2006.

[7] N. Mounet, “The LHC transverse coupled-bunch instability”, Ph.D thesis, Lausanne, EPFL, 2012.

[8] J. Wu *et al.*, “Transverse effect due to short-range resistive wall wakefield”, in *PAC’07*, Albuquerque, NM, USA, Jun. 2007, paper FRPMS085, pp. 4267-4269.