

# STUDY OF SINGLE BUNCH EFFECT IN PETRA-IV STORAGE RING

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## Abstract

The H6BA lattice has been adopted as the baseline design for the PETRA-IV storage ring. To ensure operational flexibility, the ring must operate effectively both with and without damping wigglers (DWs), resulting in two distinct sets of natural equilibrium beam parameters. This study investigates single-bunch effects arising from impedance in the H6BA lattice under both operational scenarios. We analyze the influence of impedance on the electron beam and demonstrate that, with the inclusion of a third-order harmonic cavity and a chromaticity setting of 6, the single-bunch current threshold exceeds 2 mA. Additionally, at the nominal coupling value of  $\kappa = 0.1$ , the Touschek lifetime is found to exceed 10 hours.

## INTRODUCTION

Table 1 in Ref. [1] presents a comparison of the nominal lattice parameters for the H6BA lattice. The main storage ring of PETRA-IV is designed to support two operational modes: timing mode, which requires high single-bunch charge, and brightness mode, which prioritizes beam brightness. Both modes must be available with the DWs either turned on or off. In particular, the timing mode necessitates delivering at least 1 mA of single-bunch current. This paper focuses on analyzing the collective effects impacting single-bunch beam dynamics in the H6BA lattice.

Beam impedance can lead to instabilities when the bunch current exceeds a certain threshold [2]. This single-bunch current threshold can be increased through several mechanisms, including natural synchrotron radiation damping, chromaticity adjustment, and bunch lengthening via a harmonic cavity, among others. In the following sections, we first introduce the impedance model adopted in our study. The results of particle tracking simulations are then presented and discussed. Finally, conclusions are summarized in the last section.

## IMPEDANCE MODEL

Table 1 lists the types and quantities of impedance elements, together with the local betatron function values at their locations<sup>1</sup>. The resistive wall (RW) impedance originates from the insertion device (ID) chambers and the remaining sections of the storage ring. All other elements contribute to the geometrical impedance. For each geometrical component, the wake potential is computed using GdfidL simulations [3–5], with a 1 mm-long Gaussian bunch used as the excitation source. For the transverse wakefields, dipole and quadrupole contributions are evaluated separately. The

total wake potential of the ring is computed by:

$$W_{x,y,z}^{tot} = \frac{\sum_j (N_j \times \beta_{x,y,z}^j \times W_{x,y,z}^j)}{\langle \beta_{x,y,z} \rangle}, \quad (1)$$

where  $N_j$  is the number of each impedance element,  $W_{x,y,z}^j$  is the wake potential of the  $j$ th impedance component,  $\beta_{x,y,z}^j$  is the local transverse betatron function.  $\langle \beta_{x,y,z} \rangle$  is the average betatron function weighed by element length.  $\langle \beta_z \rangle$  is set as 1. Noticeably, the average betatron of the round ring chamber is obtained by  $\sum l_i \beta_i / \sum l_i$  from the twiss output in elegant code. Compared to  $R/v_{x,y} = (2.71, 4.25)$ , it roughly overestimates the average betatron function by a factor of 2 at the round ring chamber section. As a result, the vertical impedance contribution from the round chamber is overestimated by a factor 2 as well, giving a more pessimistic threshold current limit.

The program ImpedanceWake2D [6] is used to generate the RW impedance of chambers from the IDs and the rest of the ring. The standard ring chamber is made of Cu and with a 10 mm inner radius with a round shape. The ID chambers are made of Al with different full gap depths as 5 mm, 6 mm, and 7 mm. All vacuum chambers are coated with NEG (resistivity of  $2 \mu\Omega m$ ) of thickness not exceeding  $1 \mu m$ .

Figure 1 shows the wakefields and impedance in the longitudinal, horizontal, and vertical direction of the 1mm leading electron Gaussian bunch. Here, the wakes and impedance are related to  $(W^{tot} * \langle \beta \rangle)$  so that the units shown are different from conventional ones. Qualitatively, the wakefields from the geometrical impedance and RW impedance are comparable. Noticeably, the quadrupole wake counteracts the dipole wake in the horizontal direction, whereas the vertical ones are added up. It indicates that the wake field in the vertical direction dominates the transverse beam dynamics. The second row in Fig. 1 shows the longitudinal, horizontal dipole and vertical dipole impedance<sup>2</sup>, which is adopted in the beam particle simulation.

## HARMONIC CAVITY

To increase the single bunch current threshold, a harmonic cavity is proposed to lengthen the bunches to reduce the particle densities at the core. In general, the total RF voltage in a multi-RF cavities system can be expressed as  $V(\tau) = \sum_n V_{c,n} \sin(\omega_{rf,n}\tau + \phi_n)$  where  $n$  represents the cavity harmonic number,  $V_{c,n}$  is the cavity voltage,  $\omega_{rf,n}$  is the angular cavity frequency,  $\phi_n$  is the cavity phase. The optimum bunch lengthening condition requires  $V(0) = U_0/e$  to compensate the radiation loss  $U_0$  per turn

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<sup>1</sup> This table is still in working progress and keeps updating if more details are considered in each element.

<sup>2</sup> The quadrupole impedance is not shown here

<sup>3</sup> The average betatron here is obtained by  $\sum l_i \beta_i / \sum l_i$  from the twiss output in elegant code.

Table 1: Impedance Elements

element	Number	$\beta_{x,y}$ (m)
<b>General Components (Storage Rings)</b>		
BPM	788	6.18/7.31
Absorber	576	3.80/4.73
Bellow	375	2.71/4.25
Flange	375	2.71/4.25
<b>ID ARCS (21 × 5 [m] + 5 × 10 [m] )</b>		
ID 5 mm	4	5.04/5.04
ID 6 mm	17	5.04/5.04
ID 7 mm	5	10.25/10.25
Absorber	96	5.85/4.4
Bellow	96	5.7/4.3
Flange	96	5.8/4.4
<b>Long Straight Section</b>		
RF	24	20/20
3V RF	24	20/20
FCT	6	7.76/8.44
<b>Short Straight Section</b>		
FB H.	4	12.5/15
FB V.	4	12.5/15
Collimators	4	12.5/15
<b>Injection Straight Section</b>		
Inj. Kicker	30	10/10
<b>ID Chamber RW impedance</b>		
5mm_ID	4	3.14/3.14
6mm_ID	17	3.14/3.14
7mm_ID	5	6.08/6.08
<b>Ring round Chamber RW impedance<sup>3</sup></b>		
10 mm radius	1	8.0/8.76

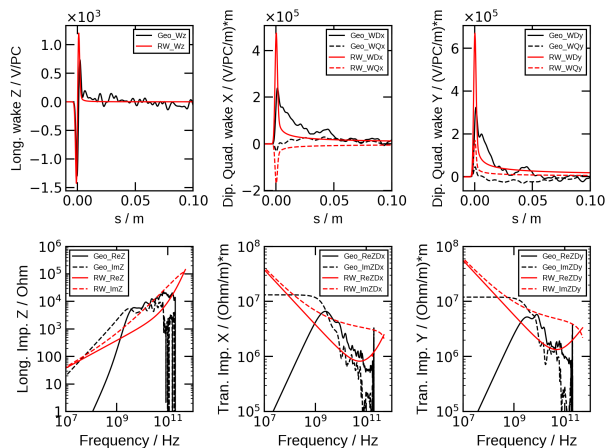


Figure 1: Above: wakefield of a 1 mm leading electron Gaussian bunch from the geometrical and the resistive wall impedance. Bottom: Impedance from the geometrical and resistive wall. From left to right, figures correspond to the longitudinal, horizontal, and vertical directions respectively.

and  $V'(0) = V''(0) = 0$  to have a flat RF potential. In PETRA-IV the main cavity voltage is set as 8 MV. A 3-order ( $n = 3$ ) harmonic cavity system is considered as the baseline for bunch lengthening.

## SINGLE BUNCH EFFECT

### Microwave Instability (MWI) and IBS Effect

In the longitudinal plane, the impedance leads to an increment of bunch length and energy spread. The longitudinal MWI instability threshold is defined as the current limit when the energy spread starts to grow. In the following, we show simulation results for 4 scenarios when DWs are closed and open respectively:

1. Single RF together with longitudinal impedance;
2. Single RF together with longitudinal impedance and IBS effect;
3. Double RF together with longitudinal impedance;
4. Double RF together with longitudinal impedance and IBS effect;

Figure 2 shows the bunch length, energy spread and vertical emittance as a function of the bunch current when DWs are closed or open from simulation with Elegant code [7]. The impedance and harmonic cavity both lengthen the bunch. At zero beam current, the bunch length is increased roughly by a factor of 4 due to the harmonic cavity. At 1 mA single bunch current, the bunch is lengthened by the longitudinal impedance to 8 mm, and further increased to around 20 mm by the 3rd harmonic cavity. The IBS has a minor effect on bunch length. The longitudinal MWI thresholds are very different when DWs are closed and opened. Without the harmonic cavity, the MWI thresholds are around 0.3/0.2 mA when DWs are closed/open. With the harmonic cavity, the MWI thresholds increased to around 0.7/0.4 mA when DWs are closed/open. The IBS effect increases the energy spread as well. The shorter the bunch, the larger the energy spread increment. Not surprisingly, the IBS effect induces a significant transverse emittance increase.

### Single Bunch Current Limit

The single bunch current threshold is defined by the lowest bunch current, which leads to a non-100% transmission in simulation. The lost particle is defined as those with offsets larger than (15, 10) mm in the horizontal and vertical directions respectively. In the simulation, the transverse dipole, quadrupole impedance, and longitudinal impedance are all taken into account. Fig. 3 shows the single bunch current limit as a function of chromaticity when the DWs are closed and open. As expected, the single-bunch current limit is significantly improved by the harmonic cavity. With the harmonic cavity, to cover the requirements of 1 mA bunch current for the timing mode operation scheme, the chromaticity has to be set larger than 4 for both open and closed DW scenarios, which is within the nominal chromaticity settings [1].

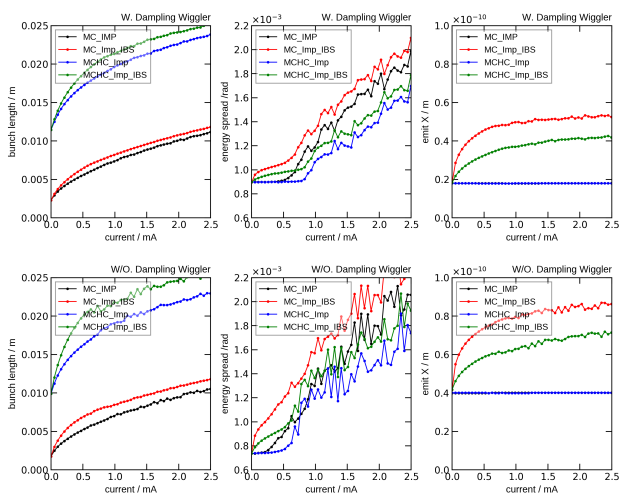


Figure 2: Single bunch length (left), energy spread (middle) and horizontal emittance (right) as functions of single bunch current. The top and bottom figures correspond to cases when the damping wigglers are closed and open respectively.

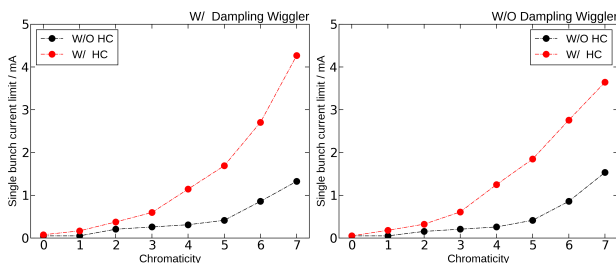


Figure 3: Single bunch current limit as a function of chromaticity when the DWs are closed (left) and open (right).

### Touschek Lifetime

The code package TouschekLifetime [7] is applied to evaluate the Touschek lifetime, where the bunch lengthening, emittance growth due to the impedance, harmonic cavity, and IBS effect are all included. Fig. 4 shows the results of the Touschek lifetime when DWs are closed and open, the 3rd harmonic cavity is turned on and off. At 1 mA single bunch current in the single RF system, the Touschek lifetime is around 7 hours. It can be roughly increased to 17 hours by turning on the harmonic cavity. In addition, the Touschek lifetime can be increased by adjusting the coupling factor, since the density of the bunch core is reduced accordingly.

### SUMMARY

With the impedance database established [4], This paper analyzed various single-bunch effects in PETRA-IV H6BA

lattice. With current impedance database, 1 mA single-bunch current with a life-time more than 10 hours, required from the "timing mode" can be guaranteed by the combination of a 3-rd harmonic cavity working at the "flatten-well potential" and chromaticity 4. In the future, studies will keep updating when our impedance model is updated.

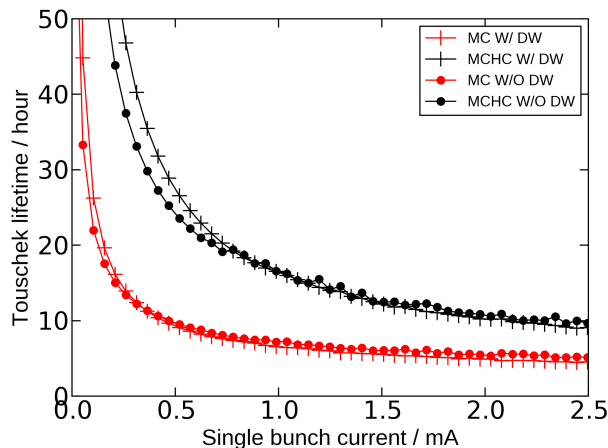


Figure 4: Touschek lifetime as a function of single bunch current.

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