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WORKING IMPEDANCE MODEL AND ITS EFFECT ON THE INTENSITY LIMITATION OF PETRA-IV STORAGE RING

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Abstract

We made sufficient progress in modeling the impedance of the PETRA-IV storage ring. The result was applied to estimate the impedance-based single and multi-bunch intensity limit. Due to the extremely small emittance of the beam the intrabeam scattering (IBS) effects will be significant unless they are reduced by bunch lengthening. The 3rd harmonic cavity was proposed to dilute the bunch density which resulted in the small synchrotron frequency with a large spread. Because of the complexity introduced by impedance and harmonic cavity we used broadband impedance up to 200 GHz to compute the parameters such as bunch length and energy spread at different currents. We found that the microwave instability started very early in current less than 0.5 mA. Even if it is small, the prediction by tracking simulation was consistent with another diffraction-limited storage ring (DLSR) when the Keil-Schnell criterion was used to predict one from the other. Then, we present the single-bunch current limit which had included the effect of geometric and resistive wall impedances of the NEG-coated chamber. Finally, we present the emittance and lifetime which can be realistically achieved in the ring with the above collective effects included.

INTRODUCTION

The proposed PETRA IV project [1] requires the total current of 200 mA (brightness mode) and the single bunch current of 1 mA (timing mode) with the lifetime greater than an hour. Because of extremely small emittance (< 20 pm), the intrabeam scattering (IBS) effects will be severe which will increase the emittance. Also, the lifetime is very short due to a small momentum acceptance of highly nonlinear lattice with strong focusing magnets. So the major effort of mitigating collective effects was to provide a long lifetime (>1.0 hr) and to store sufficient charges (>1.0 mA) in a bunch when requested. We achieved this objective by lengthening the bunch as well as by increasing the chromaticity, which was verified by tracking simulations using the full 3D impedance model. Unless otherwise stated the results presented in this paper were obtained in the RF potential formed by fundamental (500 MHz) and higher-harmonic cavities (1500 MHz) powered by the active system.

COLLECTIVE EFFECTS

Overview

In PETRA IV we expect the space-charge effects to be small because of high energy (6 GeV) and effects due to electron cloud are unlikely to be observed in an electron storage ring. However, since ion instabilities were observed in the early days of PETRA III under a poor vacuum condition, we compared the stability condition between two rings. For the same stored current in uniform fill pattern, we found that PETRA III has much more prone to accumulating ions than PETRA IV and the ion-related issue has been dealt successfully by maintaining a good vacuum and by suppressing spurious beam motion by the active feedback system. Hence, we do not expect ions to be a critical issue in the storage ring of PETRA IV.

Achieving 200 mA is critically depends on the knowledge of coupled bunch instability due to long-range wake-field effect. The experience gained in PETRA III, where 100 mA in various fill patterns has been delivered to user operations, will be carried over to PETRA IV. Specifically, we will replace the existing 7-cell cavities with newly developed HOM-damped EU-cavities. The preliminary computation reveals that HOMs of 24 cavities will be less than the stability threshold for storing 200 mA in the uniform filling. For the transverse instability, we estimated the fastest growth rate caused by the resistive wall impedance is less than 4700 s^{-1} at the chromaticity equal to zero. If we compare this with damping rate tuned to 10,000 s^{-1} of feedback system currently used in PETRA III, the same class of feedback system will be sufficient to stabilize the coupled-bunch instability driven by the resistive wall.

However, the short-range wakefield causes sudden beam losses where the feedback system is too slow to counteract the unstable motion. The remainder of the paper will be focused on determining the single-bunch intensity limit which can be achieved without the aid of the feedback system. Also, the critical beam parameters like emittance and lifetime which we can really measure with charges in PETRA IV will be presented.

Impedance Model

During the design phase of PETRA IV, the vacuum inserts are uncertain in shape and quantity as well as its locations. So we have to make major assumptions to proceed with the impedance modeling, which are:

- Beam chamber is circular with a radius of 10 mm and ID chamber is elliptical with the full gap of 6 mm; the inner surface will be coated with non-evaporable-getter (NEG) material for vacuum.
- Many components will be similar to the scaled version of PETRA III.
- The injection will be on-axis; a bunch or a train of bunches in full intensity from 6-GeV booster will be swap-in the empty buckets.
- The number and tentative location are consistent with the latest lattice that is represented in Table 1.

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Table 1: Impedance Elements Table

Element	Number	β_x	β_y	Remarks
Ring Common				
BPM	1190	6.0	8.8	
Bellow	375	2.2	5.37	
Flange	375	2.23	5.37	
Absorber	3.75	2.23	5.37	
Arc with Insertion Devices				
ID6mm	25	7.8	5.0	5-m ID
P06mmR	50	7.8	5.0	ID BPM
ID6mm	4	10.3	10.3	10-m ID
P06mmR	4	7.8	5.0	ID BPM
Bellow	125	2.2	5.37	
Flange	125	2.23	5.37	
Absorber	125	2.23	5.37	
Long Straight Section (LSS)				
RF1	24	7.9	7.8	Fundamental RF
RF3	24	7.9	7.8	Harmonic RF
LFB	8	7.9	7.8	Longitudinal Feedback
FCT	4	7.9	7.8	Fast Current Monitor
Short Straight Section (SSS)				
TFBV	2	11.0	8.4	Transverse Feedback
TFBH	2	11.0	8.4	Transverse Feedback
HSCR	1	7.4	9.3	Scraper
VSCR	1	7.4	9.3	Scraper
VCOL	4	7.4	9.3	Collimator
Injection Straight				
InjKicker	4	11.0	8.4	Kicker
ExtKicker	4	11.0	8.4	Kicker

The total wake potential of the ring is obtained by summing the wake potentials in Table 1 as

$$W_{x,y,z} = \frac{\sum_{Elements} (N \times \beta_{x,y,z} \times W_{x,y,z})_j}{\langle \beta_{x,y,z} \rangle},$$

where N_j is the number of each element in the ring, $\beta_{x,y,z}$ is the lattice function at the location of the wake W_j, and <…> is the average over the ring. For each component, the wake-potential excited by the 1-mm (rms) bunch was computed by using the software GdfidL [2]. For the case of the transverse wake, the dipole and quadrupole wakes are computed separately and the salient points of the impedance modeling were described in [3]. Due to the space limitation, we only report the total impedance of the ring which is shown in Fig. 1. Due to the importance of low-frequency impedance, we showed the imaginary part of impedance with geometric and resistive-wall combined. For resistive wall impedance, we assumed 1-µm thick NEG-coated inside the aluminum chamber.

The effective emittance of the bunch (after bunch-lengthening close to 60 ps) is estimated as 0.5 MΩ/m for horizontal and 1.5 MΩ/m for vertical plane, respectively, for the chromaticity range of one to five. The longitudinal impedance is estimated as 0.15-0.3 Ω. If we use Panofsky-Wentzel theorem,

$$Z_{\perp}(\omega) \approx \tfrac{2c}{b^2\omega} Z_{\parallel}(\omega),$$

the effective radius of the chamber, b, is 15-21 mm for horizontal and 8.5-12 mm for vertical plane, respectively.

Together with the real part of impedance the charge dependent kick will be computed inside the bunch when we use the program elegant for multi-particle tracking simulation reported in this paper.

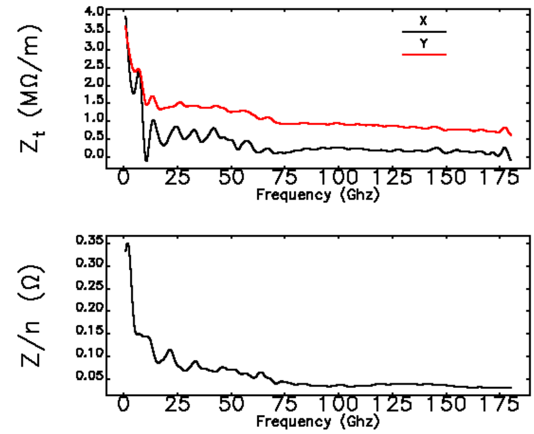

Figure 1: Total impedance of the ring (imaginary part) with geometric and resistive-wall combined.

Bunch Lengthening Cavity

Due to the extremely small emittance, the intra-beam scattering (IBS) will be significant unless they are reduced by bunch lengthening. Also, the single-bunch current will be lower than the required 1 mA with the fundamental RF system alone. Hence, we plan to use bunch-lengthening cavities as described in [4]. The difference is that we use the new lattice parameters and found new cavity voltages consistent with the project status [1]. To be complete we write the RF voltage as

$$V(\tau) = V_{rf}[\sin(\omega_{rf}\tau + \phi_s) + k\sin(n\omega_{rf}\tau + \phi_n)],$$

where ω_{rf} is the fundamental frequency, ϕ_s is the synchrotron phase, k is the voltage ratio, and n is the harmonic number. For optimum bunch lengthening, k should satisfy

$$k = \sqrt{\frac{1}{n^2} - \frac{(U_0 / eV_{rf})^2}{n^2 - 1}}.$$

With 29 IDs closed the energy loss of PETRA IV storage ring is U_0=4.0 MeV. If we use the fundamental RF voltage V_{rf}=8 MV which provides 7.1 % of the momentum acceptance, the optimum harmonic voltage and phase for n=3 are V_3=kV_{rf}=2.26 MV and ϕ_s=-12.8°, respectively. The equilibrium bunch length within the ideal quartic potential is estimated to be σ_z=9.8 mm.

The above condition as a guide we tracked 200,000 particles with the impedance effect included. Through tracking, we found a set of optimum conditions at V_{rf}=8.0 MV, V_3=2.3 MV and ϕ_3=0. The null phase of a harmonic cavity will minimize the beam power seen by the generator without compromising the bunch lengthening.

With this rf setting, we tracked 200,000 particles. The longitudinal phase-space of particles is shown in Fig. 2. The first case in the top was the zero current with the fundamental only (Gaussian distribution), followed by the case with the harmonic cavity in the middle (flat beam), and finally, we included the impedance effects to simulate

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1-mA bunch in the combined rf potential. That is shown at the bottom. The impedance blows up the beam to make it longer. For current dependent bunch lengthening we tracked 50,000 turns whose results are shown in Fig. 3, where the average of last 20,000 turns is shown together with the uncertainty of $\pm\sigma$.

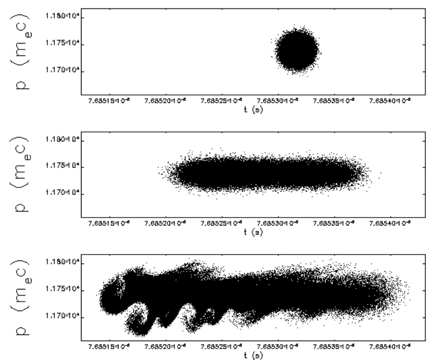

Figure 2: The longitudinal phase spaces (see text for explanation).

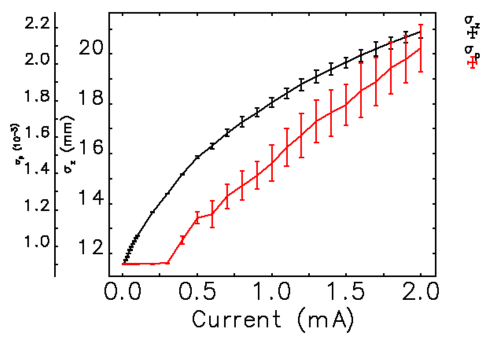

Figure 3: Bunch length and energy spread of PETRA IV with harmonic cavities and impedance effects included.

Single Bunch Intensity Limit

In PETRA IV we envision the full intensity injection. How much charge we can store is the subject of the research. The first estimate based on the TMCI threshold was $I_{th} = 0.1$ mA × F if Z_y=1.1 MΩ/m, where F is the required bunch lengthening factor which must be provided by the harmonic cavity and/or impedance effects. However, it turns out that the impedance of PETRA IV will be >1.5 MΩ/m and the harmonic cavity will reduce the synchrotron frequency such that the real threshold current will be lower than the one achieved by the bunch lengthening alone. So we explored high chromaticity option to increase the single bunch current limit.

At high current, we observed the beam loss in both planes but it was mainly vertical plane where the beam gets unstable leading into the partial or total loss. With the injection amplitude of 200 μm in both planes, the beam centroid and its beam size were plotted in Fig. 4. The current was 1 mA and the chromaticity was increased from 1 to 5. It showed that the beam is stably injected without loss when the chromaticity was set to 3.

In the present design [5], we can set the chromaticity up to 5 in both planes. The maximum current we can store in that setting was 4 mA per bunch. However, this high charge may not be suitable to be a user mode because the lifetime will be too low to be radiation safe.

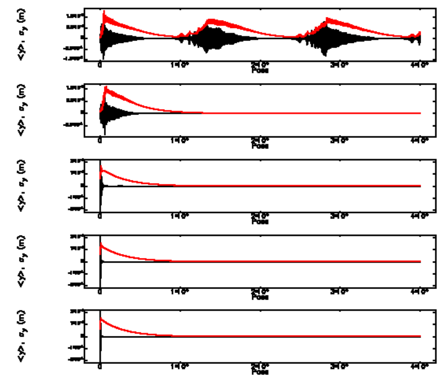

Figure 4: Transient motion of injected beam from start to 40,000 turns. The centroid is in black and the vertical beam size is in red. The chromaticity was increased from 1 (top) to 5 (bottom). At chromaticity 3, we have reached a stable injection without beam loss.

Beam Parameters

Final bean parameters including IBS, harmonic cavity and impedance effects are calculated by using the programs ibsEmittance and touschekLifetime [6]. For this computation, the bunch length and energy spread shown in Fig. 3 are input to IBS computation, whose result, in turn, was used to compute the Touschek lifetime. The results are summarized in Table 2, where we assumed all 29 IDs were closed.

Table 2: Final Beam Parameters Including the Effects of IBS, Higher-Harmonic RF System, and Impedance

	Reference	**Brightness Mode**	**Timing Mode**
Current (mA)	0.01	0.125	1.0
ε_x (pm)	7.37	11.60	19.21
ε_y (pm)	1.46	2.32	3.84
σ_z (mm)	11.7	13.7	19.3
σ_t (ps)	39.1	45.7	64.3
σ_p (10^{-3})	0.914	0.963	1,562
Lifetime (hrs)	49.4	4.7	1.2

CONCLUSION

Because of small emittance and momentum acceptance, providing an adequate lifetime is one of the challenges to meet especially in timing mode of operation. Combination of bunch-lengthening and high chromaticity would deliver sufficient charge with adequate lifetime for PETRA IV.

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