Estimation of Collective Effects for the EUTERPE Ring

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Abstract

In low energy storage rings with a high current, collective effects can make the real bunch length, transverse emittances and beam lifetime notably different from the ones designed on the basis of single particle dynamics. The storage ring EUTERPE is a low energy ring with a nominal beam energy of 400 MeV and with an injection energy of 75 MeV. The estimation of collective effects in this ring is reported in this paper. The dependence of several collective effects on various machine parameters, limiting effects on the bunch size and current for several optical options and possible improving measures are discussed. The results indicate that an equilibrium transverse emittance of 8.5 nm.rad with a beam current of 100 mA in a high brilliance mode is achievable, which is near the natural emittance. Collective effects have no obvious adverse effects on low energy injection in the EUTERPE ring.

I. INTRODUCTION

A beam current is expected of more than 100 mA for the storage ring EUTERPE with a nominal beam energy of 400 MeV and an injection energy of 75 MeV. Collective effects can not be ignored in that case. With the demands of studies on particle beam dynamics and applications of synchrotron radiation, the realization of different optical options, such as the HBSB (high brightness, small beam), the SBL (short bunch length) and the HLF (high light flux) modes, is required in the EUTERPE ring [1]. In this paper, we examine the dependence of collective effects on various machine parameters and the performance limitations caused by collective effects, especially by the turbulent bunch lengthening, the intra-beam scattering and background gas scattering, in the different modes. Since the EUTERPE ring will operate with a single bunch or up to six bunches, we concentrate the discussion on the single bunch instability effects.

II. BUNCH CURRENT THRESHOLD AND BUNCH LENGTH

On the basis of single particle dynamics, the natural bunch length σ_{L0} can be calculated by [2]

$$\frac{\sigma_{L_0}}{R} = C_{qe}\left(hV_0\cos\phi_s\right)^{-1/2}\left(\frac{\alpha}{\rho_0 J_E}\right)^{1/2}\gamma^{3/2}, \qquad (1)$$

where $C_{qe} = 1.11\times10^{-3}(meter.volt)^{1/2}$, R is the average machine radius, h the RF harmonic number, V_0 the peak RF voltage, ϕ_s the synchronous phase angle, α the momentum compaction, J_E the damping partition number for energy oscillations, ρ_0 the bending radius of magnets and γ the normalized energy.

Considering the "turbulent bunch lengthening effect" [3], the energy spread and the bunch length will both increase with the stored current in the bunch above a threshold bunch current $I_{b_{th}}$. It can be determined by [4]:

$$I_{b_{th}} = \frac{\sqrt{2\pi}\alpha\,(E/e)}{|Z/n|_{eff}}\left(\frac{\sigma_E}{E}\right)^2\left(\frac{\sigma_{L_0}}{R}\right), \qquad (2)$$

where σ_E/E is the energy spread and $|Z/n|_{eff}$ the effective longitudinal broad band impedance which represents the interaction between the bunch and the surroundings. Above the threshold, the bunch length will be given by[4]:

$$\left(\frac{\sigma_L}{R}\right)^3 = \frac{\sqrt{2\pi}I_b}{hV_0\cos\phi_s}\left|\frac{Z}{n}\right|_{eff}, \qquad (3)$$

where I_b is the bunch current. The parameters of the bunch character with the bunch current below and above the threshold have been examined separately for the EUTERPE ring. There, a value of 3 Ω for the total broadband impedance $|Z/n|_0$ has been taken for the sake of simplification. For getting a good estimation, we have taken the SPEAR scaling of the effective impedance [4] and the limitation of the free space impedance [5] into account. The results indicate that the single bunch current can not be larger than 1 mA if several mm bunch length is required with a 45 MHz RF frequency and with 100 kV RF voltage. However, if a RF system with 300 MHz and 400 kV is used, a single bunch current can be achieved of several mA at a bunch length of the order of 1 mm.

From Eq.1, it seems no problem to get a very small bunch length by selecting a very small momentum compaction factor. However, in practice, when a bunch current is beyond the limitation given by Eq.2, the bunch length will mainly be determined by the effective longitudinal broad band impedance and RF parameters, but will not be influenced by the momentum compaction.

III. SELECTION OF RF VOLTAGE AT 45 MHZ FREQUENCY

What is a suitable RF voltage at a certain RF frequency? This issue concerns the assurance of several hours of beam lifetime with 100 mA beam current under 400 MeV operating energy.

For the storage ring, the beam lifetime is mainly limited by three factors: quantum fluctuations, residual gas and intra-beam scattering. Considering the effective aperture of the vacuum chamber with 2.3 cm in vertical direction in bending magnets and 4.7 cm in any transverse direction elsewhere [1], the quantum lifetime will be more than 1000 hours for the transverse oscillation. In order

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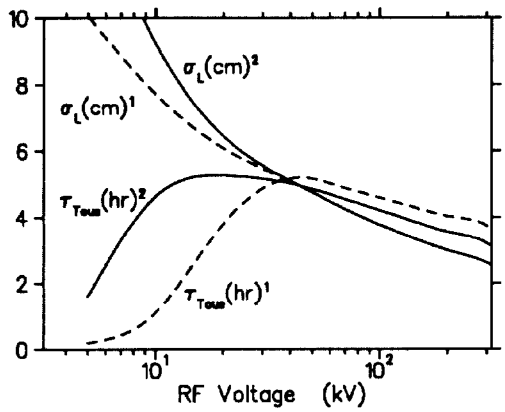

Figure 1: *Bunch length and Touschek lifetime versus RF voltage with frequence of 45 MHz. Beam current is 100 mA with 400 MeV. 1: HBSB mode; 2: HLF mode.*

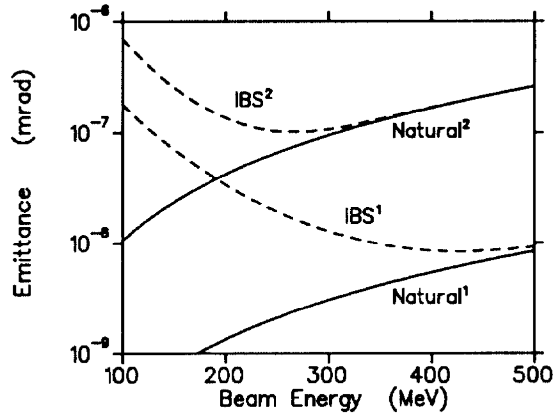

Figure 2: *Horizontal emittance versus beam energy. Beam current is 100 mA and RF voltage is 60 kV at 45 MHz. 1: HBSB mode; 2: HLF mode.*

to obtain the same quantum lifetime for the longitudinal oscillation, the RF voltage needs to be larger than 10 kV at 45 MHz frequency.

Single, large-angle Coulomb scattering within a bunch will reduce the beam lifetime by causing particle momenta to exceed the momentum acceptance, which is determined by the RF bucket momentum height, the transverse dynamical aperture and the physical aperture. Using the Touschek scattering formulae [3,4] and considering the bunch lengthening, the equilibrium emittance (resulted from a balance among the quantum excitation, intra-beam scattering and radiation damping processes) and the effect of the dispersion on the beam dimensions, we calculate the scattering lifetime in the EUTERPE ring. Fig.1 shows the bunch length and Touschek lifetime as a function of the RF voltage. The suitable RF voltage appears to be somewhere between 10~100 kV, where the Touschek lifetime can be longer than four hours and the equilibrium emittance is almost constant.

Furthermore, for a certain RF frequency, the optimum operating voltage ought to give a RF bucket height which is near the transverse momentum acceptance of the ring. In order to get a long Touschek lifetime and not to cause an obvious increase in the transverse emittance, it looks reasonable to choose 60 kV as a suitable voltage in the EUTERPE ring. This selection of the RF voltage is also good enough for getting a long gas scattering lifetime, which will be seen in later discussion.

IV. EMITTANCE GROWTH AND MINIMUM EMITTANCE

The natural emittance is 5.4 nmrad for the HBSB mode and 168 nmrad for the HLF mode [1]. We have examined the equilibrium emittance with the computer code ZAP [4]. The results are shown in Fig.2. When the energy increases, the radiation damping increases quickly and the emittance tends to the natural value. At the same time the Touschek lifetime increases up to 5 hours. The interesting thing is that the smallest emittance appears

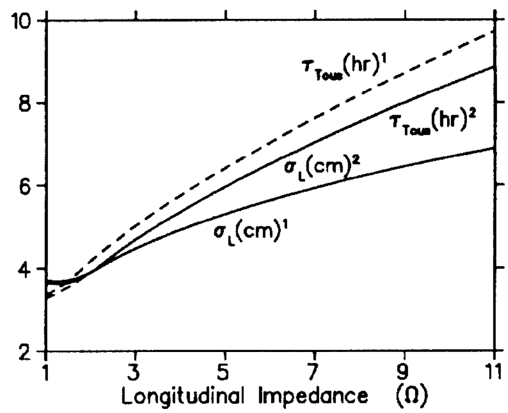

Figure 3: *Bunch length and Touschek lifetime versus longitudinal impedance. Beam current is 100 mA with 400 MeV energy and RF voltage is 60 kV at 45 MHz. 1:HBSB mode; 2: HLF mode.*

just near the 400 MeV region which is the expected operating region for the EUTERPE ring (It is favourable to a high spectral brilliance). This shows that the designed parameters of the lattice and RF cavity are reasonable. On the other hand, the beam size in the horizontal direction (injection region) is about 4 mm for the HLF mode and is 3 mm for HBSB mode when the beam energy is 75 MeV with the same RF parameters. The Touschek scattering lifetime is longer than one hour for both modes. Hence, this gives no problem for the electron accumulation and acceleration using low-energy injection.

V. EFFECTS OF DIFFERENT IMPEDANCE

From section II, we know that the influence of the turbulent bunch lengthening mainly depends on the effective impedance of the ring. As the impedance increases, the beam bunch becomes longer and wider. This results in intra-beam scattering weakening and Touschek lifetime increase. The bunch length σ_L is almost same in the two different modes except when $|Z/n|_0$ is smaller than 2 Ω, which can be seen clearly from Fig.3. On the other hand, the impedance has little influence on the emittance in transverse direction except that a short bunch length will cause more intra-beam scattering when the impedance is small. Hence, when the bunch length is not important for the synchrotron radiation, a big longitudinal impedance seems useful to get a long bunch at a certain current and to get a long lifetime.

VI. INFLUENCE OF BEAM INTENSITY ON BUNCH CHARACTER

When the beam current increases up to the threshold I_{bth}, the beam bunch length starts to increase and the energy spread also starts to increase. For the HLF mode, the emittance is almost constant with increasing beam current, which indicates that multiple small angle Coulomb scattering is not serious in that case. However for the HBSB mode, the emittance will become large as the beam current increases, which is because the charge density of the bunch current in the HBSB mode is much higher than that in the HLF mode. The emittance with 200 mA beam current is near the double of the natural emittance. Then, the beam lifetime drops by one hour.

VII. GAS SCATTERING LIFETIME

There are essentially four processes on the beam-gas interaction [2], i.e., the elastic scattering on nuclei (ESN), the bremsstrahlung on nuclei (BSN), the elastic scattering on electrons (ESE) and the inelastic scattering on electrons (ISE). At "room temperature", the gas-scattering (GS) lifetime is given by

$$\tau_g = \frac{2.16 \times 10^{-19}}{n_z P \sigma_t} (hours), \qquad (4)$$

where P is the residual gas pressure in Pascal, n_z the number of atoms per gas molecule and σ_t the cross section for the electron losses. It tells us that the GS lifetime is inversely proportional to n_z, P and σ_t. σ_t is mainly determined by the aperture of the ring and by the atomic number for residual gas components. Fig.4 shows the relative contribution of the different types of scattering to the lifetime in the case of the HLF mode, where the RF voltage is 60 kV at 45 MHz. There, the ESN gives the main contribution to $1/\tau_g$. Because the ESN is strongly dependent on the β function of the lattice, the loss of the electron is more serious in the HBSB mode and the GS lifetime is only about half of the value in the HLF mode.

The vacuum in a running electron storage ring is limited by the photon stimulated desorption (PSD) originating from the synchrotron radiation. The vacuum design of EUTERPE is chosen in such a way that we can expect a partial CO pressure of 100 nPa at 400 MeV with 200 mA. We assume that the residual gas mainly consists of hydrogen and CO. Generally, the GS from hydrogen can be neglected. Thus, the expected GS lifetime is 10 hours in the HLF mode, see Fig.4. During the injection, the critical energy of the synchrotron radiation is far below the

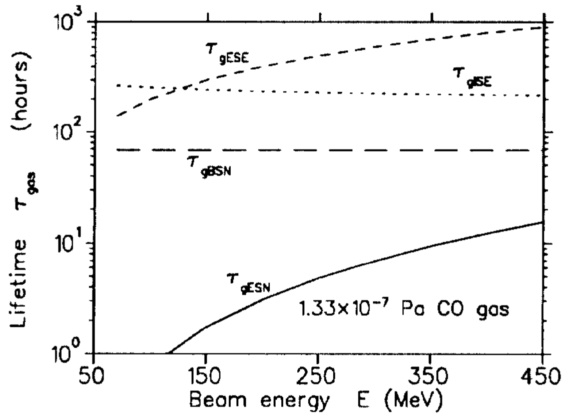

Figure 4: *Lifetime resulted from the different processes of beam-gas interactions for HLF mode.*

10 eV threshold for PSD. Then, the pressure in the machine will be limited only by the thermal gas desorption of the chamber walls with the expected CO partial pressure lower than 10 nPa corresponding to about 4 hours GS lifetime in the HLF mode. At present, experiments are carried out in our laboratory to find the best material and surface treatment for the vacuum chamber.

VIII. CONCLUSION

The estimation of collective effects in the EUTERPE ring indicates that:

1. Using a 45 MHz and 20-100 kV RF cavity and taking the designed parameters of the lattice, the value of the horizontal emittance at 400 MeV with 100 mA beam current is near the value of the natural emittance and the smallest emittance is 8.5 nmrad in the high brilliance mode.
2. Under these conditions, the Touschek lifetime is longer than four hours in the high light flux mode and high brilliance mode.
3. It is necessary to take a 300 MHz RF system if a high intensity single bunch (with single bunch current more than 1 mA) with a length of the order of 1 mm is needed.
4. When the beam energy is 75 MeV, the gas scattering lifetime and Touschek lifetime can be more than one hour. Therefore, collective effects have no obvious adverse effects on low energy injection in the ring.

IX. REFERENCES

[1] Boling Xi, J.I.M. Botman, C.J. Timmermans and H.L. Hagedoorn, Nucl. Instr. and Meth. B68 (1992) 101.

[2] M. Sands, SLAC-121, may, 1979.

[3] J. Le Duff, Nucl. Instr. and Meth. A239 (1985) 83.

[4] M. S. Zisman, S. Chattopadhyay and J. J. Bisognano, "ZAP User's Manual", LBL-21270, Dec., 1986.

[5] A. Faltens and L. J. Laslett, Particle Accelerators, 4 (1973) 151.