IMPURITY GROWTH IN SINGLE BUNCH OPERATION OF PF

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Abstract

Growth of the single bunch impurity was observed in the Photon Factory storage ring. The phenomenon caused by recapture of electrons that are thrown out of the main bucket by Touschek effect was analyzed theoretically. Agreement of the observed rate of the impurity growth and the theoretical estimation was fairly well. In order to cure the effect, the RF knockout method was employed. The betatron tune of a bunch depends on the number of electrons in it. If the knockout frequency is adjusted to that corresponds to weak bunches to remove them, the betatron motion of the main bunch is scarcely affected. This method is routinely used in the single bunch operation of Photon Factory.

I. INTRODUCTION

In the single-bunch-mode operation of a synchrotron light source, it is highly necessary to establish a 'pure' single bunch because undesirable bunches cause unwanted reactions in the time resolved experiments such as photoluminescence or light absorption. The single-bunch impurity, which is defined as the ratio of the number of electrons (positrons) in undesirable bunches to that in the main bunch, is the order of 10^{-4} and the increase of the ratio is much smaller. Then the measuring system with very wide dynamic range is essential. We have constructed a single photon counting system in the beamline 21 in the KEK-PF. An excellent dynamic range is obtained when enough events are collected and high time resolution is achieved because of the fast photomultiplier with microchannel plate.

The increase in a single-bunch impurity with the lapse of time after injection was previously studied in the UVSOR storage ring at Institute for Molecular Science and was explained as the recapture of electrons that are thrown out the main bucket by Touschek effect[1],[2]. The effect was estimated to be small enough for high energy storage ring such as PF ring because the Touschek effect decreases rapidly with the energy increase. However when we have measured the change in the impurity, unexpected growth was observed clearly in the PF ring. We show the theoretical treatment which takes into account of the relativistic effect on electron-electron scattering and the local machine parameters at the position where the scattering occurs. The agreement between our calculation and the observed growth rate of the impurity was fairly good[3].

In order to cure the effect, we have employed the RF knockout method. The large difference of bunch current between the main bunch and the unwanted bunches enables us to kick only unwanted bunches because the betatron tune of a bunch depends on the bunch current. This system is used not only the time just after an injection but also during the users' time routinely without affecting the beam quality. Related parameters of the KEK-PF storage ring is listed in Table. I.

Table I
Main Parameters of KEK-PF ring

Energy [GeV]	E	2.5
Circumference [m]	C	187
RF frequency [MHz]	f_{RF}	500.1
Harmonic number	h	312
Revolution period [ns]	T	624
Synchrotron tune	ν_s	0.0227
Betatron tune	ν_x/ν_y	8.45/3.30
Momentum compaction	α	0.0157
Peak RF voltage [MV]	$\hat{V}_{RF}$	1.7
Synchrotron radiation loss [kV]	U_0	399
Radiation damping time [ms]	τ_x	7.79
	τ_y	7.82
	τ_e	3.92

II. PHOTON COUNTING SYSTEM AND INCREASE IN IMPURITY

The photon counting system installed in the beamline 21 in KEK-PF and the increase in impurity measured with the system have already been described in ref.[3] in detail, therefore only a brief outline is explained here. The system is shown schematically in Fig. 1.

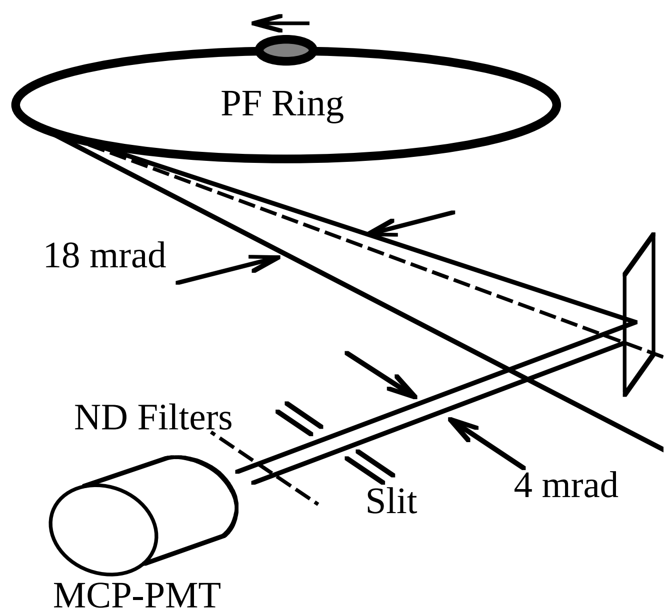

Figure 1. The photon counting system

The SR from a bending section is led to the beamline, and Phe visible part is reflected by a mirror made of SiC. Photons reach a microchannel-plate type photomultiplier (MCP-PMT, Hamamatsu R2809U-06) through an ICF-70 view port. The intensity of the photons is reduced to the level of one photon detection per about a hundred revolutions of a bunch.

Pulses from a PMT are amplified by a two-stage wide-band amplifiers with a total gain of 49dB, then shaped by a constant fraction discriminator (CFD) which detects the peak of the pulse. The time interval between the output of the CFD and the timing signal synchronized to the revolution of a bunch is converted to the pulse height by a time-to-amplitude converter and analyzed with a multichannel analyzer. An example of the measured longitudinal bunch structure is shown in Fig. 2.

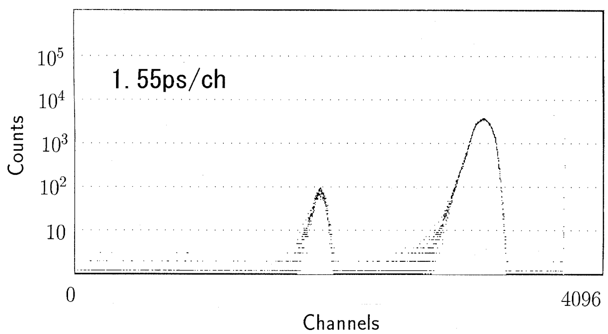

Figure 2. Longitudinal bunch structure measured by the photon counting system.

Figure 3 shows the measured increase in impurity at the bunch

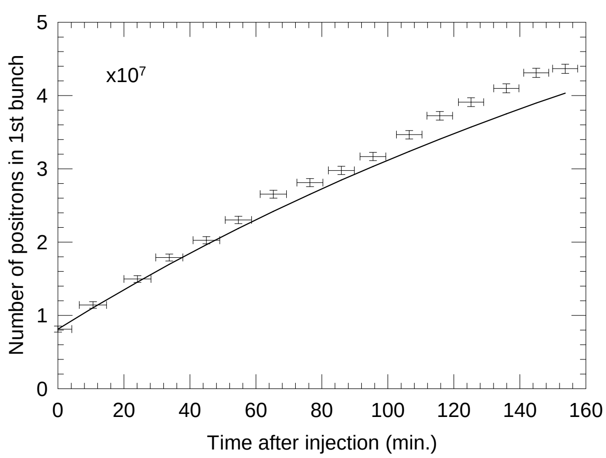

Figure 3. Increase in the population in the first bunch. The horizontal bars represent the time interval during each measurement.

The increase in impurity is not negligible small for users' experiments.

The mechanism of increase in impurity is the followings. The synchrotron motion of an electron with a momentum of $p_0 + p$, where p_0 is the design momentum, in longitudinal phase space is described as

$$\frac{d\epsilon}{dt} = \frac{1}{TE} e\hat{V}_{RF} \sin(\phi_0 - \phi) - \frac{1}{TE} U_0 - \frac{2}{\tau_e}\epsilon \quad (1)$$

$$\frac{d\phi}{dt} = -h\omega_0 \alpha \epsilon \quad (2)$$

where $\epsilon = p/p_0$, ϕ_0 and ϕ are the synchronus phase and the phase of the RF, respectively. Owing to the radiation damping term in eq. (1), the separatrixes have an opening shown in Fig. 4.

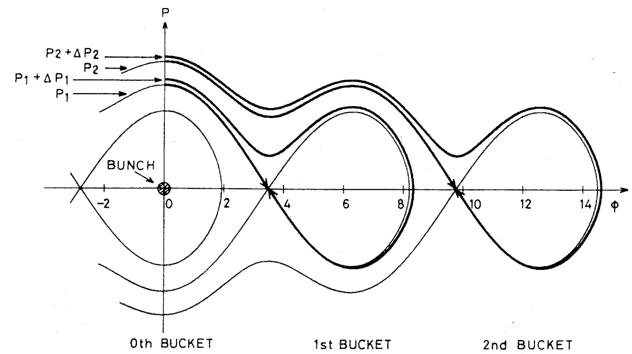

Figure 4. Trajectory of an electron thrown out from the main bunch in longitudinal phase space

If there are electrons which thrown out of the main bunch with momenta corresponding to the aperture, they are recaptured. Only the Touschek scattering mechanism can produce such electrons with significant probability.

Since it is not applicable for non-relativistic approximation for the PF ring, we used the Völkel's formula[5] with the approximation of small RF bucket height and rectangular momentum distribution. Because the result depends linearly to the bunch volume, we included the local beam size for horizontal and vertical, and the bunch lengthening effect also measured by the photon counting system simultaneously. Additionally, the effect of intrabeam scattering was also included. The growth rate $\Delta N_i/\Delta t$ of the single-bunch impurity for i-th bucket is then

$$\frac{\Delta N_i}{\Delta t} = \frac{N_0}{2}\left(\frac{1}{\tau_T(p_i)} - \frac{1}{\tau_T(p_i + \Delta p_i)}\right) \quad (3)$$

where $\tau_T(p)$ is the Touschek lifetime for bucket height p and N_0 is number of electrons in the main bunch. Note we need the coefficient $1/2$ because one of two electrons that take part in the collision loses momentum and is never captured by the backward buckets. The solid line in Fig. 3 shows the calculated result.

III. CURE THE SINGLE-BUNCH IMPURITY

The typical single-bunch impurity just after the injection is about a few per cent and of course is not acceptable for users. To cure the impurity in the ring, we applied the RF knockout method. Under the single-bunch mode, huge bunch current deviates the betatron tune from the zero-current tune. The measured vertical betatron tune shift with the current is shown by the solid line in Fig. 5, it was about -3×10^{-4}/mA.

As the bunch current of neighboring bunches is a few percent of the main bunch current, we are able to only excite a betatron oscillation of the unwanted bunches sweeping the knockout frequency without disturbing the main one.

In the 'purification' process, we measure the vertical betatron tune just after the injection and determine the frequency range of the knockout, that the frequency slightly higher than that of vertical betatron frequency of the main bunch to 490 kHz. The

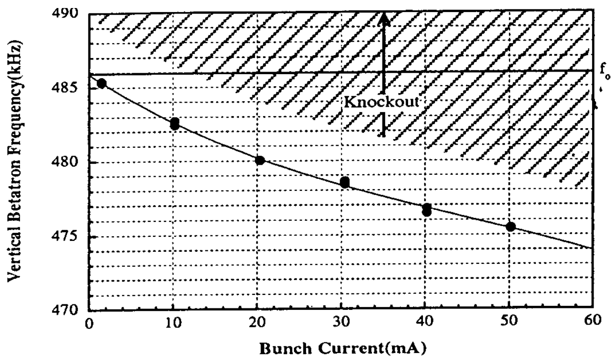

Figure 5. Measured vertical betatron tune in single-bunch mode with bunch current (solid line) and the RF knockout frequency range (shaded area).

frequency range is shown by the shaded area in Fig. 5. We sweep the frequency using the computer-control system shown in Fig. 6. The knockout frequency range is automatically controlled with the beam current from a DCCT.

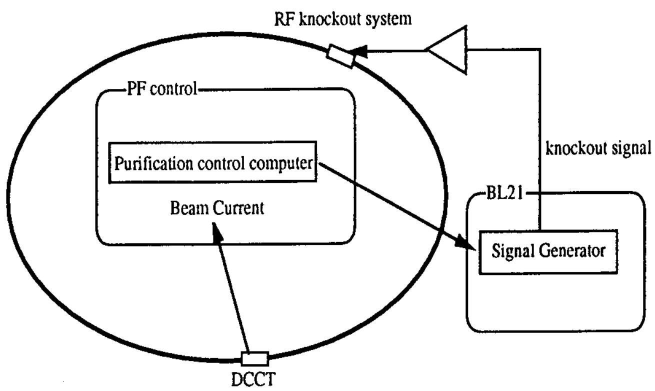

Figure 6. Automatic RF knockout system to keep the single bunch purity.

In the users' time for the single bunch operation, we enlarge the x-y coupling by exciting skew qadrupole magnets to make the Touschek lifetime long. Nevertheless, there remains unacceptable increase in impurity. Though we use the RF knockout system continuously during the users' time, the betatron amplitude growth with the system is acceptably small. Figure 7 shows an example of the change in impurity measured during a users' time using a photon counting system.

We used the avalanche photo diode in the X-ray region as the detector to improve the signal-to-noise ratio[6]. The impurity is kept small enough compared with the requirements from users.

IV. SUMMARY

We have measured the increase in single-bunch impurity in the Photon Factory positron storage ring with the photon counting system installed in the beamline 21. The electrons thrown out of the main bunch by the Touschek effect were recaptured by the following bunches by the radiation damping effect. With employing the relativistic formula for the Touschek effect and evaluating the beam size properly, we have reconstructed the measured growth in good agreement.

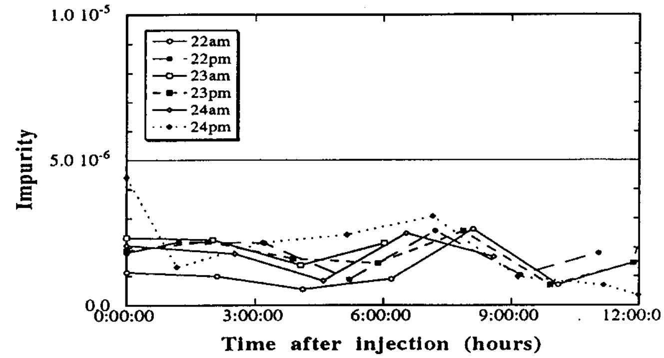

Figure 7. Increase in impurity during the users' time. The measured impurity has been kept less than 5×10^{-6}.

To cure the impurity, we have constructed computer-control RF knockout system. Using the betatron tune shift with the bunch current, the unwanted bunches are swept out clearly. This system is routinely used during the users' time without bothering the beam quality.

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