Measurement of the Bunch Lengthening on the 1.3 GeV Electron Synchrotron

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Abstract The bunch lengths in the accelerating stage of 1.3 GeV electron synchrotron (ES) of the Institute for Nuclear Study, University of Tokyo, were measured. The observed bunch length reduction from 1.0 ns to 0.35 ns during the rf acceleration and the variation of its peak position corresponding to the synchronous phase of the rf voltage, are described well by the calculation with a tracking method. A bunch lengthening as a function of the circulating beam current at a certain voltage pattern of the rf accelerating field is observed. Neither the our tracking method nor other known bunch lengthening mechanisms can explain the data.

I. Introduction

Many experimental studies related to the bunch length have been carried out on the electron storage rings. These bunch formation mechanism are understood well.[1] In the electron synchrotron, since the amplitude of synchrotron oscillation just after the injection is very large and the rf over-voltage factor changes large at the accelerating stage, no simple analytic formula is available in order to estimate the bunch length, which is the case of the ES ring.

The first measurement of the bunch length variation in the accelerating stage of the ES was reported previously by Mutou et al.[2] In the study, the gross feature of the data is proved to be reproduced by a tracking simulation method.

Recently, the measurements on the bunch length as a function of the circulating beam current at the KEK-AR ring[3] and the UVSOR ring of the Institute for Molecular Science[4,5] clearly show bunch lengthenings. In order to search for such a bunch lengthening in the ES, we measured the bunch length variation as a function of circulating beam current. This paper reports the measurement and an anomalous bunch lengthening effect observed in the study.

II. Theory

At the low-beam-current limit, the bunch length (σ_B) of an electron storage ring is determined by the equilibrium of quantum excitation and radiation damping due to synchrotron radiation (SR), and can be expressed by a formula for the natural bunch length (σ_0),[1]

$$\sigma_B = \sigma_0 = \frac{\alpha}{2\pi f_s}\left(\frac{\sigma_E}{E}\right), \tag{1}$$

where α is the momentum compaction factor, f_s the synchrotron oscillation frequency, σ_E/E the relative energy spread of the beam, and E the beam energy.

There are two known effects which elongate the bunch length depending on the circulating beam current. One is the behavior of the bunch lengthening due to the microwave instability including the scaling low[6,7] is given by

$$\sigma_B \propto \left(\frac{\alpha I}{\nu_s^2 E}\right)^{1/(2+a)}, \tag{2}$$

where I is the beam current, ν_s (= f_s/f_{rev}) the synchrotron oscillation wave number, f_{rev} the revolution frequency, and a a constant which is independent of the electron energy.[6] The bunch begins to lengthen when the beam current exceeds the threshold current for microwave instability. On the other hand, the potential-well distortion caused by an inductive coupling between the beam and the longitudinal impedance of various components of the vacuum chamber.[6] The behavior can be described as

$$\left(\frac{\sigma_B}{\sigma_0}\right)^3 - \left(\frac{\sigma_B}{\sigma_0}\right) = \frac{e\alpha I}{\sqrt{2\pi}\,\nu_s^2 E}\left(\frac{R}{\sigma_0}\right)^3 [Z/n]_{eff}, \tag{3}$$

where e is the electron charge, R the mean radius of the ring, and $[Z/n]_{eff}$ the effective longitudinal coupling impedance of the vacuum chamber. There is no clear threshold current for bunch lengthening due to potential-well distortion.

III. Experiment

An electron beam of 1.5 μs pulse width from a 15 MeV electron linac is injected into the ES ring by the multi-turn injection method. Since the linac is operated asynchronously to the synchrotron rf phase, the injected

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electrons distribute continuously on the orbit. The rf accelerating field (133.989 MHz) applies to the beam, and a bunch structure is formed; some electrons are captured in the rf bucket for further acceleration and others are lost from the orbit in 10 μs. Along with the acceleration, the shape of the bunch varies according to those effects of the voltage pattern of the rf accelerating field (V_{rf}–pattern), adiabatic damping, radiation damping, and quantum excitation. The rf acceleration starts at the injection timing and the maximum energy is attained in 20 ms as depicted in Fig. 1 for an operation energy (E_0) of 0.6 GeV.

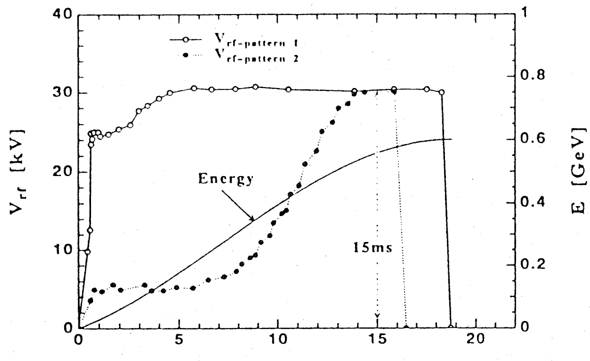

Fig. 1. The solid curve shows the relationship between the time from the zero–field timing and the electron energy E for E_0 = 0.6 GeV (solid curve). Two extreme V_{rf}–patterns used in the current–dependence measurements at 15 ms are shown.

The longitudinal electron density distribution in a bunch was given as the distribution of the time interval between an rf phase and a SR photon emitted in a bending section. We used the ES–SOR beamline of the Institute for Solid State Physics (ISSP), University of Tokyo. The SR is led out of the vacuum chamber of the beamline through a quartz window, then it is deflected through 90° with a mirror and is detected by a fast photomultiplier (PMT) with a double–stage micro–channel plate. In front of the PMT, neutral density filters and a pinhole are positioned such that the counting rate is maintained a few kcps throughout the experiment.

A signal from the PMT started a time–interval measurement with a CAMAC Time–to–Digital Converter (TDC) and a reference rf–timing signal stopped the TDC. A frequency converter of 1/16 referring to the signal of rf accelerating frequency picked up the SR photons from the electrons belonging to the same bunch among the 16 simultaneously–circulating bunches. In order to select the SR photons in a certain acceleration–energy range, a delayed signal of the zero–field timing, which was generated when the field strength of the ES magnets reached zero, gated the PMT signal. Thus, we could measure the longitudinal bunch shape of the electrons which belong to one circulating bunch in an acceleration–energy range.

The time resolution of the detection system was determined to use the SR photons from the 380 MeV storage ring of ISSP. According to eq.(1), the bunch length is proportional to $1/f_s$. We measured the bunch length as a function of f_s at the beam current of less than 1 mA. The measured bunch length is given by the quadratic sum of the bunch length and time resolution of the detection system, and then the square of it is plotted against $1/f_s^2$ in Fig. 2. Therefore, the extrapolated line at $1/f_s^2$=0 gives the time resolution of the detection system. The deduced time resolution is 87.5±15.5 ps, and this value is subtracted from the measured bunch length to be obtained the bunch length.

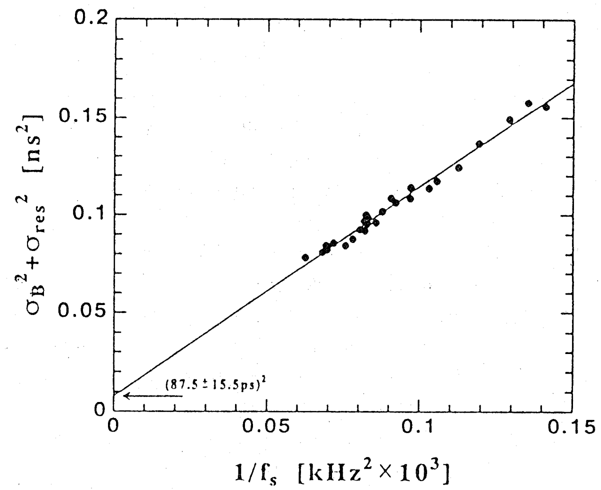

Fig. 2. The data plotted as the measured bunch length vs. $1/f_s^2$. The solid line is a fit to the data with a least square method.

IV. Result and Discussion

At first, measurements at E_0 = 0.9 GeV were carried out for a few V_{rf}–patterns. A bunch length variation over the entire accelerating stage is shown in Fig. 3, where the shape of the V_{rf}–pattern were kept constant through the measurement. The bunch lengths 0.7 – 0.9 ns at 4 ms gradually decrease to 0.3 ns at 12 ms, and they are constant up to 20 ms. A tracking simulation method taking into account the effects of the adiabatic damping, radiation damping, and radiation excitation[2)] reproduces well the data except in the range before 6 ms.

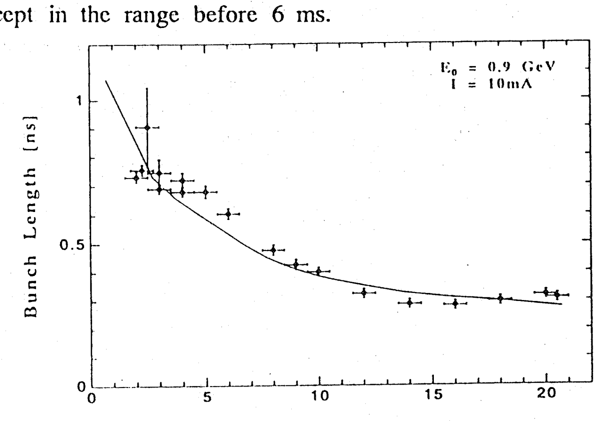

Fig. 3. The measured bunch lengths at E_0 = 0.9 GeV vs. the time from the zero–field timing. The curve is the result of the tracking simulation.

Figure 4 shows the variation of the bunch peak position corresponding to the synchronous phase of the V_{rf}; the change in the over-voltage factor causes the structure. While there are some structures which are not described by the calculation, the calculation also reproduces the wavy behavior of the data after 6 ms. From these observations, we conclude that the calculation describes the variations both of the bunch length and of the synchronous phase in the energy range of E = 0.37 - 0.9 GeV.

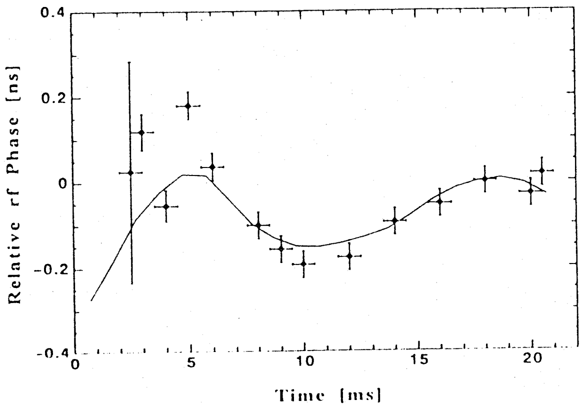

Fig. 4. The measured peak positions corresponding to the rf synchronous phase are plotted as a function of the time from the zero-field timing. The curve is the result of the tracking simulation.

In these studies on the energy-dependent bunch length variation, we found that the bunch lengths before 12 ms depend strongly on the shape of the V_{rf}-pattern, and after that timing the bunch lengths are nearly constant. These facts in mind, we measured the current dependence of the bunch length at 15 ms at E_0 = 0.6 GeV. In order to change the circulating beam current, the beam current of the linac was adjusted and accordingly the V_{rf} was modified slightly to compensate the change in beam loading. Thus the V_{rf}-pattern was kept nearly constant; the change in the bunch length due to the error in keeping the V_{rf} constant is estimated by calculation to be less than 0.05 ns. Figure 5 shows the results for the two V_{rf}-patterns. While the bunch lengths for the V_{rf}-pattern 1 are approximately constant, the data for the V_{rf}-pattern 2 change from 0.19 ns at 0.5 mA to 0.30 ns at 100 mA. A fitting to the data gives

$$\sigma_B = (0.040 \pm 0.007) \log I + (0.221 \pm 0.006) \qquad (4)$$

with χ^2 = 1.2, where I is the beam current in mA and the errors are statistical. This establishes a statistically significant bunch lengthening for the V_{rf}-pattern 2.

Now, we examine possible causes of the bunch lengthening. The current dependence of the potential-well distortion expressed by eq. (3) is approximately $I^{-1/3}$ because of $(\sigma_B/\sigma_0)^3 > \sigma_B/\sigma_0$ in the measured beam current range. The logarithmic current dependence of eq. (4) is equivalent to $I^{0.07\pm0.01}$ in the measured range, thereby these data do not agree with the prediction by the distortion. The microwave

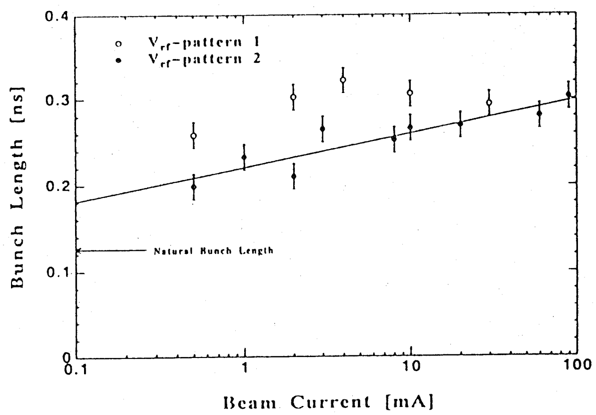

Fig. 5. The current dependence of the bunch lengths for the V_{rf}-pattern 1 (open circles) and V_{rf}-pattern 2 (closed circles) at the time of 15 ms from the zero-field timing (E = 0.56 MeV) at E_0 = 0.6 GeV. The solid line is a fit to the V_{rf}-pattern 2 data. Natural bunch length corresponding to E = 0.56 GeV is also shown.

instability by eq. (2) dose not give the correct current dependence because of the constraint to the constant a. Thus neither the potential-well distortion nor the microwave instability explain the present current-dependent bunch lengthening. The calculation which reproduces both the energy dependence of the bunch length and the peak position variation does not show current dependence.

V. Conclusion

We measured the longitudinal bunch shape of the circulating electron beam in the accelerating stage of the 1.3 GeV electron synchrotron. At E_0 = 0.9 GeV, the measured behaviors of the bunch length reduction from 1.0 ns to 0.35 ns and the variation of its peak position as a function of the acceleration energy are well described by the calculation of a tracking method which takes into account various damping and excitation effects. A bunch lengthening due to the increase of the circulating current is observed at E_0 = 0.6 GeV for a certain voltage pattern of the rf accelerating field, and the effect can not be described by neither the calculation nor other known bunch lengthening mechanisms.

VI. References

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