BUNCH LENGTH MEASUREMENTS AT BESSY*

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Abstract

In the range from 2 ps to 40 ps the rms bunch length and the bunch shapes have been measured with a streak camera as a function of the beam current. Short bunches were produced by reducing the momentum compaction factor of the storage ring lattice. An attempt is made to distinguish between vacuum chamber and radiation impedance effects.

INTRODUCTION

BESSY is a high brilliance VUV to soft X-ray synchrotron light source [1]. After 3 years of operation 13 out of 16 straight sections are equipped with insertion devices (ID) with gaps of the vacuum chamber down to 11 mm. Four IDs are strong superconducting devices which have an impact on the bunch length. The storage ring is operated usually at 1.72 GeV. The low emittance double bend lattice already produces short bunches due to the small momentum compaction factor, α. In addition, the bunch length can be reduced even further by nearly a factor of 10 by changing the optics and reducing α by a factor of 100. The shape and the length of these short bunches have been measured with a streak camera (SC) as a function of beam current. The technique, analysis, and very little interpretation of the observations will be presented. For comparison results will be given of further measurements related to the longitudinal dynamics of high current bunches in a storage ring like the current dependent energy spread and the current dependent shift of the longitudinal quadrupole mode.

EXPERIMENTAL SETUP

For the bunch length measurements the Hamamatsu dual sweep SC model C5680 connected to a stand alone PC is used. Bending magnet radiation (± 1 mrad in both planes) is guided out of the radiation safety area, passes through a colour glass filter which transmits radiation below 420 nm, and is focussed with a single quartz lens onto the 30 µm entrance pin hole of the camera. The camera's static time resolution was found by operating the SC in the focussing mode. Depending on the sweep speed the resolution with a 30 µm pin hole can reach 1.5 ps. The fast 250 MHz sweep voltage for the SC is taken from the RF master oscillator frequency of 500 MHz divided by two. The long term phase stability is thus assured. Short term phase noise reduces the time resolution of the SC operated in the dual sweep mode. The contributions stem from the phase noise of the master oscillator, the fast sweep voltage, and the noise in the accelerating RF voltage. In addition, the RF voltage contains small spikes which induce coherent synchrotron oscillations of the bunch. Therefore, the slower sweep speed of the SC is always chosen such that these coherent bunch oscillations occurring between 1 and 10 kHz can be resolved. A full sweep takes 1 to 10 ms. With a bunch revolution time of 800 ns many images of the bunch are superimposed in order to collect sufficient intensity. Usually a single bunch is stored, however, at extremely low beam current of the order of 1 µA, corresponding to N=5 10^6 electrons in the bunch, all 400 buckets are filled as equally populated as possible.

ANALYSIS OF THE STREAK CAMERA DATA

In the top of Fig. 1 raw data from the CCD camera at the end of the SC is shown. The slow horizontal time span is 1ms and the fast vertical time span is 275 ps. There are 640 pixels in the slow sweep direction and 512 in the fast direction. Slices of pre-chosen horizontal width are analysed and the data is averaged horizontally over the slice first. Then the background is substracted based on the signal at the beginning and the end of the fast sweep (top and bottom of Fig. 1).

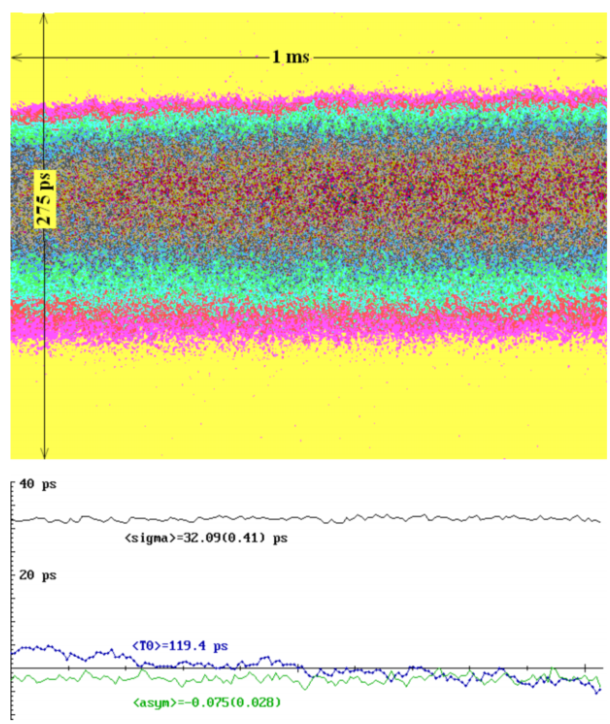

Fig. 1: Streak camera taken image in dual sweep mode (top) and results of the data analysis of the sliced image along the slow sweep direction.

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The remaining signal is analysed in terms of centred statistical moments, M_i. This starts with the determination of $<T_o>$, the centre of gravity (COG), of the intensity distribution in the slice, I(t). In the next step up to the forth centred moment of I(t) is calculated. The final results are the averages of the following quantities:

- $<To> = M_1/M_0$
- $\sigma = sqr(M_2/M_0)$
- Asymmetry = $(M_3/M_0)/\sigma^3$

Since each image contains up to 640 slices a corresponding number of results is obtained. With these samples, averaged values and their standard deviations are calculated. Channel numbers are translated into time with the scaling factors provided by the manufacturer of the camera. The slice wise results of the above analysis are shown at the bottom of Fig. 1.

The time resolution of the SC in the dual sweep mode is not only determined by the static time resolution which depends on the size of the entrance pin hole and the quality of the streak tube. There is an even larger uncertainty introduced by the phase noise and the fact that many images are superimposed. The phase noise of the master oscillator and of the 250 MHz fast sweep voltage was measured with a Rohde & Schwarz spectrum analyser FSE30. The analysis showed that these noise sources add a random contribution of ≈2.4 ps to the bunch length. The measured bunches appear enlarged due to the statistically independent effects and the actual bunch length can therefore be obtained by:

$$\sigma_{act} = \sqrt{\sigma_{meas}^2 - \sigma_{ph.noise}^2 - \sigma_{stat.res.}^2}$$

In order to check this approach the bunch length was measured with the SC as a function of the synchrotron frequency, F_{syn}, by changing the optics and reducing the momentum compaction factor. This can be done without beam loss at very low beam current. The measured as well as the corrected results are shown in Fig. 2 and these values agree well with the theoretical expectations:

$$\sigma(F_{syn}) = const \cdot F_{syn}$$

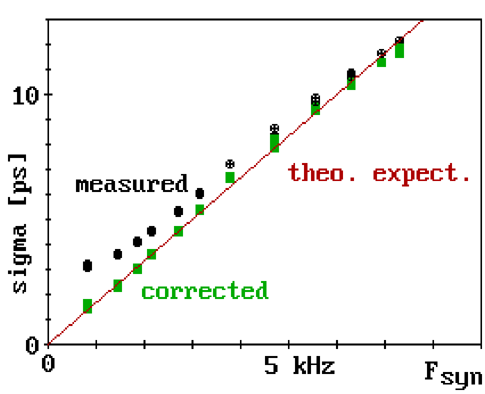

Fig. 2 Result of bunch length measurements as a function of the synchrotron frequency F_{syn}.

At small synchrotron frequencies the directly measured uncorrected bunch length saturates around 3 ps and the resolution limitations of the SC become dominant. The simultaneously observed increased shift of the COG, the synchronous phase, as a function of bunch current is however a clear indication that the bunch length really is shorter than observed. The accuracy of the COG determination is not influenced by the resolution limitations of the SC.

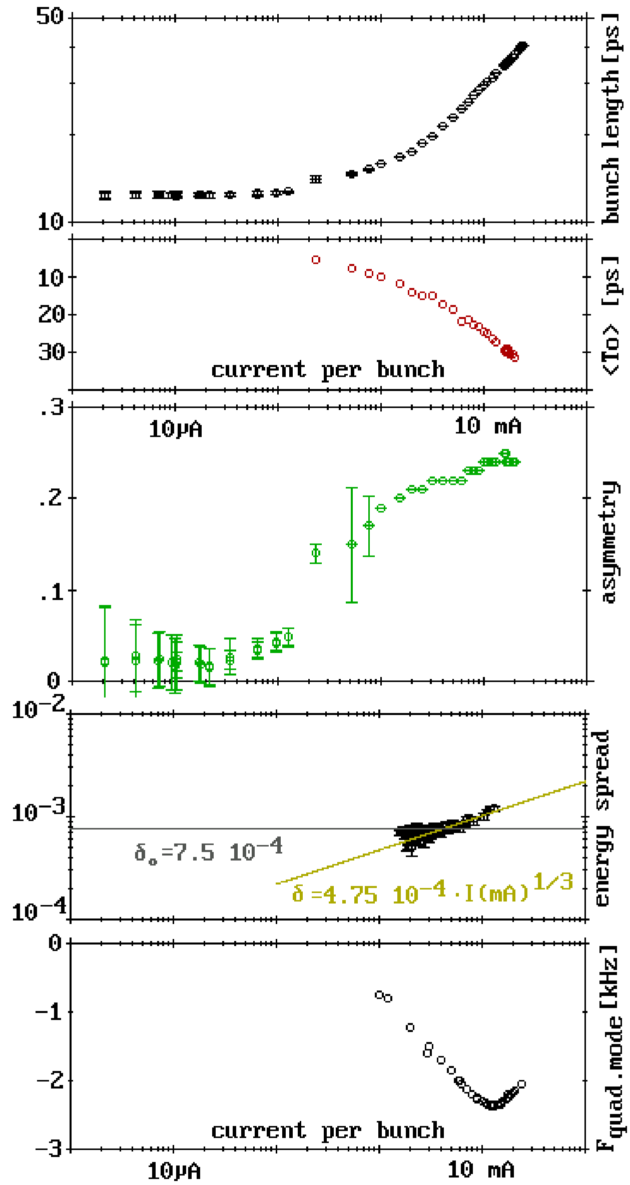

Fig. 3: Results of measurements with the nominal BESSY optics.

Most extensive studies were performed with the nominal optics and the results are shown in Fig. 3. In the case of long bunches the resolution limitation of the SC is not important. The top three curves are the bunch length, the shift of the synchronous phase, and the asymmetry of the distribution as measured with the streak camera. The bunch leans forward with a steeper leading edge of the distribution and moves up the RF voltage in order to compensate for the increased current dependent energy loss. This is consistent with a resistive interaction of the bunch with its surroundings. The observed phase shift corresponds to 5 ps/mA. Other experimental results are included in Fig. 3 for comparison. The fourth trace shows the outcome of direct absolute measurements of the rms energy spread by Compton back scattering a CO_2-laser beam [2]. With this technique also the nominal momentum compaction factor was determined with high accuracy and found to be in agreement with the expectations based on the linear model of the storage ring lattice. The onset of the turbulent bunch lengthening shows up around 3 mA not as clearly as desired. The accuracy of this measurement suffers from the low rate of back scattered high energy photons obtained with a small beam current in the single bunch. At the bottom of Fig. 3 is shown the frequency shift of the quadrupole mode which is for very small beam current equal to $2*F_{syn}$. The quadrupole mode shifts down with beam current. The beam was excited by an amplitude modulation of the RF cavity voltage with a swept frequency and the quadrupole mode was detected as a sideband to the 500 MHz-component of the beam. A shift of 0.7 kHz/mA is found at low beam current. This result is close to the more direct determination of the incoherent synchrotron tune shift by looking at the shifts of the transverse m=±1-modes in the vertical plane [3]. The measured tune shift can be used to estimate the inductive impedance.

In Fig. 4 the current dependence of the bunch length is shown for different values of the momentum compaction factor (the synchrotron frequency). The asymptotic slope of the rms bunch length is proportional to $I^{3/8}$ which is close to $I^{1/3}$ as expected from a purely inductive impedance. An inductive impedance alone would however not produce energy widening.

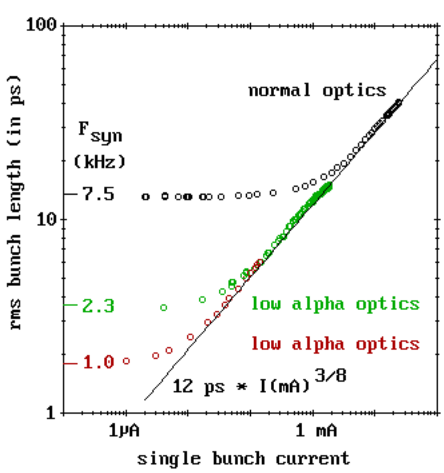

Fig. 4: Bunch length as a function of beam current for three different momentum compaction factors.

INTERPRETATION

These measurements are traditionally interpreted in terms of the vacuum chamber related geometrical impedance. Especially with very short bunches the radiation impedance can play a significant role in the longitudinal dynamics of a bunched beam. Fig. 5 shows the shielded coherent synchrotron radiation (CSR) impedance for the BESSY parameters and calculated with equ. (B7) of Murphy, et al. [4]. Included in the figure is the spectral power density of a Gaussian bunch.

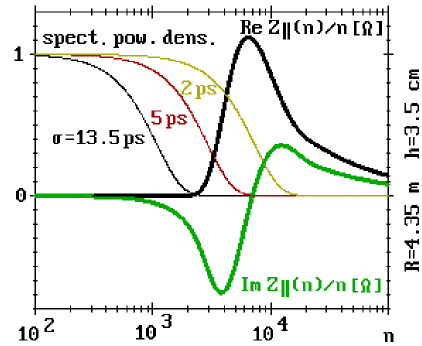

Fig. 5: CSR impedance for BESSY. The frequency is given by ω=n·R/c, with R the dipole bending radius, and c the speed of light.

There is hardly any overlap between the real and imaginary parts of impedance and the bunch modes for the nominal bunch length of 13.5 ps. Therefore, at least the shift of the synchronous phase and of the quadrupole mode presented in Fig. 3 must be attributed to the impedance of the vacuum chamber. So far only a very simple impedance model has been used to explain the observations:

$$Z_{par}(\omega) = R - i\omega L$$

It consists out of a resistive part R=850 Ω and an inductive part, L. The resulting predictions are not yet in acceptable agreement with all the measurements.

In summary, a variety of experimental results has been presented which are related to the longitudinal beam dynamics taking place in the storage ring BESSY. Comparison of these results with the estimated impedance of the BESSY vacuum chamber based on two and three dimensional calculations [5] and modelling with more advanced impedance models [6] including the shielded CSR effects will take place in the near future.

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