SUB-PICOSECOND ELECTRON BUNCHES IN THE BESSY STORAGE RING*

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Abstract

There is an increasing interest in ultra short electron pulses for x-ray experiments. Dedicated electron accelerators are suggested and studied [1]. To explore the potential of a third generation storage ring for sub-ps bunches, the momentum compaction factor of BESSY was tuned to values of $\alpha \sim 10^{-6}$. Sub-ps bunches of currents $\sim 1\mu$A could be generated and their length measured. The bunches have several hours life time.

INTRODUCTION

The BESSY II low alpha optics is applied for bunch shortening to produce coherent THz radiation [2]. Recently experiments were started to reduce further the momentum compaction factor, α, to produce sub-ps bunches. The current in these bunches has to be low, otherwise bunch lengthening starts, which is a smooth process and starts slowly. To get a defined starting point, the threshold current of the bursting instability was measured and calculated [3].

The produced bunches are about 40 times longer than those expected from 'femtoslicing' (20 fs rms)[4] at about 10 times the charge per bunch. The bunch repetition rate could be choosen from 1.25 MHz (for single bunch) to 500 MHz (400 bunches) compared to ~1 kHz for 'femtoslicing', yielding several orders more integrated intensity.

The present results might be of interest for users of sub-ps x-rays pulses. Other aspects are to produce stable bunches as short as possible and to measure the quantitative relation between their lengths and currents. This requires also to explore the conditions and to get experience in operating a machine with such an ultra low alpha. Results of producing sub-ps bunches and the operation of the machine in this mode are discussed.

THE MACHINE OPTICS

BESSY is a double bend 16-cell low emittance storage ring. The length of stored electron bunches depends beside other parameter on the momentum compaction factor. By reducing α, the bunch length becomes shorter in proportion with $\sqrt{|\alpha|}$. This is performed by an appropriate quadrupole setting, which changes the dispersion function at fixed transverse tunes. Quadrupoles control only the α_0 term of alpha expanded with respect to momentum deviations, $\alpha = \alpha_0 + \alpha_1 \frac{dp}{p_0} + \alpha_2 (\frac{dp}{p_0})^2 \cdots$.

If α_0 approaches zero, higer order terms become important. These terms have to be controlled in such a way, that $\alpha \neq 0$ in the required momentum acceptance range of about 2 %. Higher order terms can be controlled at BESSY by an appropriate sextupole setting. (For the presently constructed MLS storage ring [5] a combination of sextupoles and octupoles are foreseen for controlling α). Instead of α, which is not directly measurable, we use the dipole mode of the synchrotron oscillation $f_s \sim \sqrt{|\alpha|}$ detected by a stripline. To achieve a good life time, f_s should increase if the rf-frequency deviates from the nominal value, as shown in Fig. 1, by controlling slope and curvature of the longitudinale chromaticity. From the measured f_s as a function of rf-frequency the nonlinear terms of α can be extracted [6], Fig.1. For small values of α this sextupole setting can only be applied if $\alpha < 0$, because of the special curvature of α as a function of dp/p_0. For $\alpha > 0$ the frequency will hit the $f_s = 0$ axis and strongly limit the bucket size.

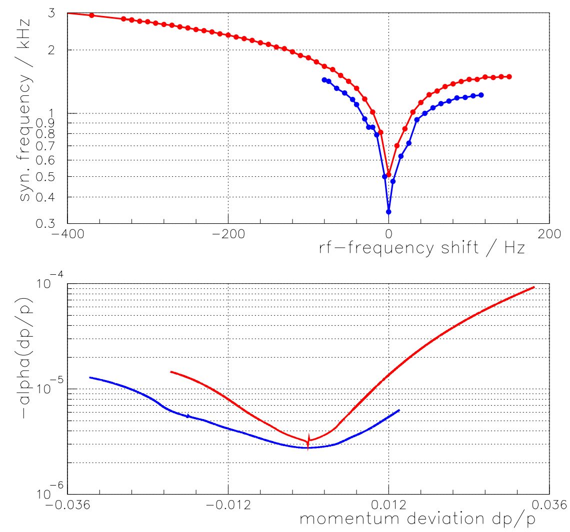

Figure 1: The upper part of the figure shows two measurements of the dipole mode of the synchrotron frequency f_s as a function of the rf-frequency for an ultra low alpha optics. From this measurements α as a function of the momentum was derived, lower part of the figure (vertical axis shows $-\alpha$).

Within the bunch rms-momentum spread of $\sigma_e = 7 \cdot 10^{-4}$ the value of α can be considered as constant.

Presently there is a limit by 300 Hz noise, visible on the longitudinal beam signal, probably generated by power supplies of the rf-cavities. If f_s approaches 300 Hz the frequency signal on the spectrums analyser is hardly visible and no longer a well defined line. Approaching these very small α values, the beam orbit becomes increasing sensi-

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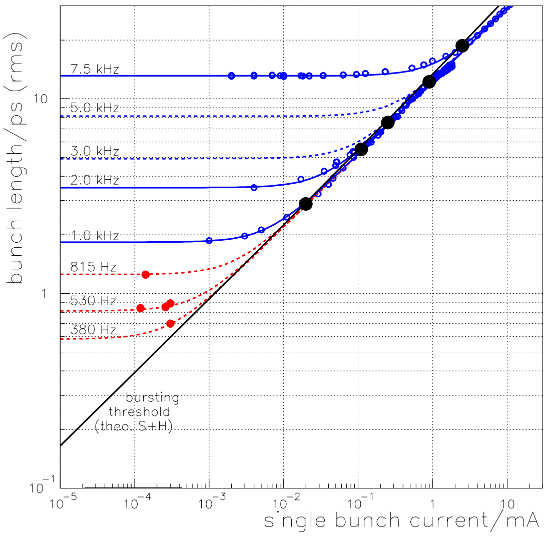

Figure 2: Measured bunch length as a function of the current, indicated by colored dots. Blue: streak camera data and empirical fit to the data; black: bursting threshold of coherent THz signals; red: coherent THz radiation based data. At the fitted data lines the rf-voltage amplitude and f_s are indicated.

tive to distortions. For example, within few seconds the orbit is drifting by about 1 mm, showing a periodic chromatic orbit pattern probably caused by thermal drifts. To correct this, an rf-frequency change of only 1 Hz (at 500 MHz), the present rf bit-resolution, would be suffcient, but leads to large and sudden orbit jumps. A smooth orbit correction is obtained by using steerer magnets. The optics up to $f_s = 350$ Hz (α=1.4·10^{-6}) is very reliable, it was reproduced several times, beam accumulation directly into this optics is possible and the life time at low currents is several hours.

It might be questionable if the relation $f_s \sim \sqrt{|\alpha|}$ is still valid for the BESSY optics. The rf-cavities are placed in a dispersive section. Longitudinal rf-kicks are exciting transverse oscillations, by shifting the chromatic orbit. These two planes are coupled and amplitude dependent orbit lengthening effects could dominate the ultra low alpha. Therefore, the transfer matrix for a double bend achromat, which couples the horizontal and the longitudinal plane, was derived. An eigenvalue analysis were performed to verify that $f_s \sim \sqrt{|\alpha|}$ holds also in the case of coupled oscillations.

BUNCH LENGTH MEASUREMENTS

For different α resp. f_s values bunches were generated and their length measured. Fig.2 shows the relation between rms-bunch length σ und bunch current I (I = 2mA/bunch $\hat{=}$ 10^{10} electrons). The measured data points can be empirically fitted by

$$(\sigma/\sigma_1)^4 = (f_s/f_{s0})^4 + (I/I_1)^{3/2},$$

where σ_1=13.1ps, I_1=1.18mA are fit parameters. The relation between α and f_s is given by α=$\alpha_0(f_s/f_{s0})^2$, where α_0=7.3 · 10^{-4}. The value f_{s0} depends on the applied rf-voltage. For bunches shorter than 1.5 ps a cavity voltage of 1.5 MV (f_{s0}=8 kHz) was applied, and for longer bunches only 1.35 MV (f_{s0}=7.5 kHz) was available. Bunches longer than 1.5 ps were measured with a streak camera [7], shorter bunches were analysed with coherent THz radiation [8]. To produce these shorter bunches the optics was tuned to $\alpha < 0$. Examples of sub-ps pulses are shown in Fig.3, were the power spectrum of the emitted radiation together with a simulated bunch shape are compared. Best agreement was found for simulated power spectra of 700 fs, 870 fs and 1.2 ps rms bunch lengths. The simulation takes into account only a current dependent bunch deformation by its own CSR field [9]. Up to now only bunch lengthening with increasing current was observed, no bunch shortening. For α <0 the current dependency needs still to be done.

There are few examples, were the bursting threshold was measured, shown as black dots in Fig.2. At the threshold intense bursts of coherent THz radiation are observed. The bursting threshold is used as an indication, when the bunches start to lengthen. The theoretical curve [3] (unscreened CSR impedance) is extended into the sub-ps range, as a kind of estimate, which bunch length could be expected. This still needs an experimental verification, specially because up to now all bursting values are measured at $\alpha > 0$. From our results the threshold fits best, if the ratio of bunch length to first unstable mode (expressed as wave length λ) is equal to $k\sigma = 2\pi\sigma/\lambda = 5.0$ [3], [10], [11]. A current dependent bunch lengthening based on our measurement was applied for this calculations. If $k\sigma$ is known, the rise time τ of the instability [3] can be estimated. A value of $\tau f_s = 1.4$ was found, the inverse of the bursting rise time is close to the synchrotron frequency, independent on other parameters.

At the present ultra low alpha values we are close to the range, were the synchrotron frequency approaches the inverse of the transverse synchrotron damping time of 8 ms (125 Hz). In this frequency range the application of the model starts to become questionable.

SCALING OF THE THRESHOLD CURRENT

Scaling of the threshold current seems to be presently more reliable than scaling of the bunch length to shorter values, where storage ring based data are still missing. From the bursting properties we can estimate the expected length-current relation of the bunches by simple scaling. The threshold currents are compared at equal bunch length, which needs to be preserved by an appropriate α tuning. This keeps the threshold condition $k\sigma$=5 fixed.

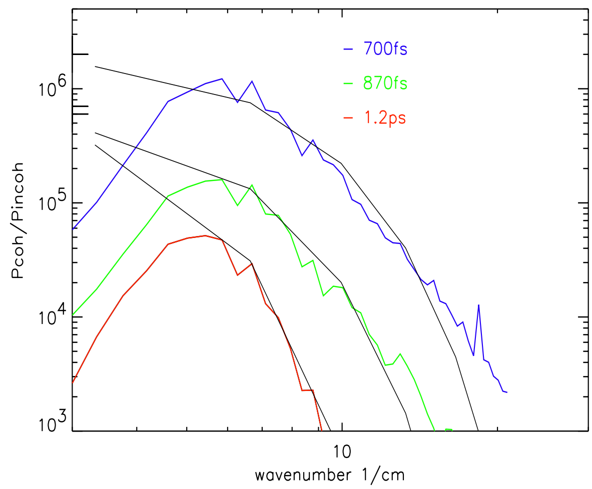

Figure 3: Ratio of coherent and incoherent THz power for three different bunches. The results are fitted by simulations, using 700 fs (0.3μA), 870 fs (0.3μA) and 1.2 ps (0.14μA) bunches. Transmission limitations become apparent below 6 cm^{-1} (values in 1/cm $\hat{=}$ 1/λ, where λ is taken in cm).

For the synchrotron frequency f_s and the bunch length σ, we use

$$\sigma = \alpha c \sigma_e/(2\pi f_s) \qquad f_s^2 = \frac{e\alpha}{2\pi R m_e \gamma}\frac{dV_{rf}}{ds} ,$$

where e, m_e are charge and mass of the electron.

Following [3], the beam starts to become unstable if the condition (for $\alpha > 0$) is satisfied

$$k\rho = 2\Lambda^{3/2} .$$

Λ=$(N r_0 \rho)/(\sqrt{2\pi}\sigma\alpha\gamma\sigma_e^2 R)$ is a parameter modified for a Gaussian bunch and N equals the number of electrons per bunch, r_0 is the classical electron radius, ρ the dipole bending radius, γ the Lorenz factor, and R the average storage ring radius. From the threshold condition and replacing $\alpha\gamma\sigma_e^2 R$ by $\sigma^2 dV_{rf}/ds$ we get

$$N \sim (\sigma/\rho)^{1/3}\sigma^2 dV_{rf}/ds$$

There is a difference in the exponent of the bunch length-current relation $\sigma \sim N^{7/3}$ compared to our bursting data, which show better agreement with $\sigma \sim I^{8/3}$. This leads to longer bunches than predicted by the simple scaling.

From the scaling relation we find, that for a given machine, with fixed bending radius and rf-voltage, the threshold for a given bunch length does not depend on the machine energy. In case of a reduced energy, the desired bunch length is achieved at larger values of α and f_s, which could be an advantage.

If one consideres a possible upgrade of the rf-voltage gradient, the threshold increases in direct proportion to the gradient. Based on our present results, a 100-times larger threshold current achieved by a 100-times increase of the voltage gradient yields $5 \cdot 10^9$ electrons resp. 0.1mA per ps-bunch at a variable repetition rate of 1.25 MHz (0.1 mA average current) to 500 MHz (50 mA average current). This could be performed, for example, with a kind of bunch-shortening, passive Landau multicell cavity running on a higher harmonics and might fit in one or two straight sections of the ring.

It is a pleasure to thank our BESSY collegues for supporting us on many aspects during developpment of this special machine mode.

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