Experimental observation of the longitudinal phase-space distribution in a storage-ring: influence of the beam current and the compaction factor

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Abstract

The storage ring Super ACO at Orsay offers a large agility as regards the value of the momentum compaction factor (α), i.e., under special conditions α can be set to either positive, negative or very small values. This aspect can be important for the development of new Storage-Ring (SR) based light-sources where a high electron-density is advantageous. Recently, the influence of α on the micro-bunch length and the energy-spread was investigated experimentally. The diagnostics are described in detail. Results, regarding the influence of the average beam current and α on the bunch-length and energy spread, are discussed.

Table 1: Nominal operating parameters of Super ACO. Anomalous values are mentioned in the text.

beam energy	E	800	MeV
circumference	L_c	72	m
rf-frequency	f_{rf}	100	MHz
rf-voltage	V_{rf}	170	kV
horizontal emittance	ε_x	40	π nm rad
momentum comp. fact.	α	0.0148	
average beam current	I	<400	mA
number of bunches	n_b	1-24	

1 INTRODUCTION

The micro-bunch shape and the energy spread as a function of the average beam current is an important parameter to understand the dynamics of a SR, especially for the understanding of future generation storage rings where the electron density will be high. Simulations by Fang et al. [1], based on the resonator impedance model, show that the longitudinal bunch shape is less deformed and bunch lengthening is less at increasing beam-current with negative α. Hence, this could be advantageous for machines where short bunches or a high peak-current is of interest, e.g., synchrotron sources for time resolved spectroscopy, or storage ring free-electron lasers (FEL). When changing α the energy-spread needs to be considered as well. This is, for example, important for an FEL where the gain impedes with increasing energy spread. Calculations by Besnier et al. [2], assuming a mostly inductive impedance, show that even if the bunch is shorter with negative α, the energy spread may be larger than for positive α. Hence, careful examination of both the bunch shape and the energy spread is important.

Experimental observation of both the bunch-shape and the energy-spread for different values α is not straight-forward, however. Firstly the optics of the SR need to be adjusted. Secondly a set of diagnostics is required. The synchrotron light-source Super ACO, see Tab. 1, has the capability of running with positive and negative or small α [3]. Under these conditions the micro-bunch shape and energy spread were measured with a set of diagnostics installed for the Super ACO FEL: the bunch-shape was measured with a double-sweep streak-camera and a dissector, while the energy-spread was deduced from the properties of the spontaneous-emission spectrum emerging from an optical klystron (OK). A detailed motivation and description of the diagnostics is given in Sec. 2. Results are presented in Sec. 3.

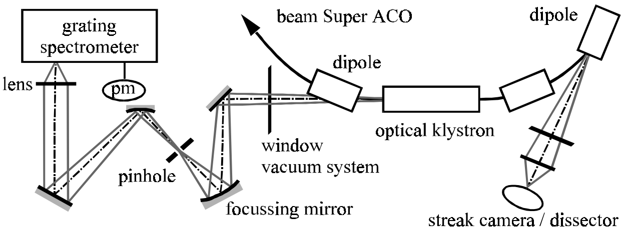

Figure 1: Experimental setup. The energy spread is derived from the spectra of the OK (left). The bunch-shape is derived from synchrotron radiation emitted from a dipole (right).

2 DIAGNOSTICS

A schematic sketch of the experimental setup is given in Fig. 1. Measurements of the bunch-shape have been done with the aid of a dissector and a double-sweep streak camera (Hamamatsu C5680) recording the synchrotron radiation from one of the dipoles of Super ACO. A schematic overview of a streak camera is given in Fig. 2a: the evolution of the synchrotron radiation is projected onto a photo-cathode. The evolution of the electrons is then transformed into a spatial distribution through a high-frequency sweep on the deflecting electrodes. Finally the signal is recorded onto a phosphorous screen. The resolution of the streak-camera used is approximately 2 ps.

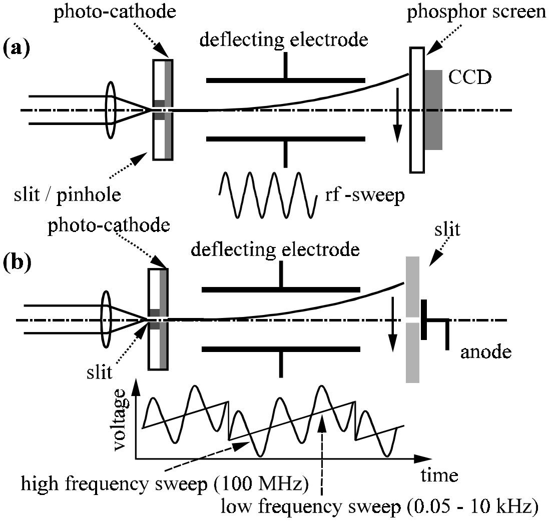

Figure 2: Schematic overview of a streak-camera (a) and a dissector (b).

The dissector [4], see Fig. 2b, is a stroboscopic device and, hence, can only be used to analyze reproducible signals with a fixed period. The phosphorous screen is replaced by a slit/anode which permits the recording of only a small part of the micro-bunch distribution. The specific part of the distribution changes gradually through the aid of a low-frequency sweep of the bias-voltage on the deflecting electrodes which enables the registration of the whole distribution on multiple passages of a micro-pulse. The resolution of the dissector used is approximately 10 ps. A main advantage of the dissector is its capability to process an analogue output signal directly. However, due to its stroboscopic nature it is not possible to follow fast fluctuation phenomena.

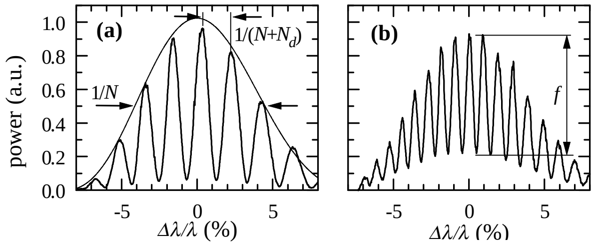

Figure 3: Measured spectrum of the Super ACO OK SU7 (N=2×10): (a) with a low magnetic field-strength in the dispersive section ($N+N_d$=55) and (b) with a high magnetic field ($N+N_d$=110).

In a SR the energy spread can be derived from the transverse beam-dimension in a section of the SR with non-zero dispersion. However, the method is not always accurate, especially when other parameters, such as the emittance, play a more prominent role in determining the transverse beam dimension. We note that, though it is possible to operate Super ACO with negative α, the machine was not designed for this purpose and the flexibility of the optics is limited. At present, one of the consequences is approximately 10-fold increase in the horizontal beam emittance[5].

It is more accurate to derive the energy spread from the spontaneous emission of an undulator or, even better, from a so-called optical klystron (OK) [6]: a set of two (small) undulators separated by a drift- or dispersive section. Similar to a regular planar undulator the central wavelength of the OK radiation is given by:

$$\lambda_R = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right) \qquad (1)$$

where λ_u is the undulator period, γ the Lorentz factor corresponding to the electron-beam energy and θ the angle of the off-axis radiation. The parameter K expresses the field strength of the undulator (K=0.93 B_u λ_u [T][cm]). Since the radiation of both undulators is generated by the same electrons, both sources are coherent. Hence, the radiation of the two undulator sections interferes and the spectral distribution of the undulator radiation is modified to [6]:

$$\begin{aligned} I(\nu) &\propto \mathrm{sinc}^2(N\nu)\left[1+f\cos\left((N+N_d)\,\nu\right)\right] \\ \nu &= 2\pi(\lambda_R-\lambda)/\lambda_R \end{aligned} \qquad (2)$$

where the parameter N_d denotes the number of wavelengths of light that pass over the electrons as they traverse the dispersive section. In Fig. 3a an example of such a spectrum is given. The modulation rate and thus the homogeneous line-width of one fringe depends on the phase-delay between the two undulators and can be adjusted by changing the magnetic field strength of the dispersive section. In the case of a finite energy spread the spectrum deteriorates and the modulation depth of the spectrum is reduced, see Fig. 3b. For a Gaussian distribution of the energy-spread one finds for the modulation rate [6]:

$$f = f_0\, e^{-2\left(2\pi(N+N_d)\frac{\sigma_\gamma}{\gamma}\frac{\lambda}{\lambda_R}\right)^2} \qquad (3)$$

where σ_γ denotes the absolute rms energy spread in terms of the Lorentz factor γ and f_0 denotes the reduction in modulation rate due to other inhomogeneous effects, e.g., emittance. It is with the aid of Eq. (3) that the energy-spread can be determined, i.e., by recording the modulation depth of the power spectrum as a function of the gap of the dispersive section. For the experiment the emission of the SU7 OK was focused down to a spot of $\approx$100 mm^2 on a pinhole with a diameter of 100 μm in order to select the on-axis radiation only, see Eq. (1). The radiation passing through a grating spectrometer was recorded with a photo-multiplier. The spectral resolution of the spectrometer was of the order of 0.03 nm at a wavelength of 410 nm, i.e., the longest possible wave-length at the nominal beam energy of 800 MeV. This wavelength was chosen in order to minimize the line-width broadening due to emittance. The value of N_d could be varied by means of a change of the gap of the dispersive section of SU7.

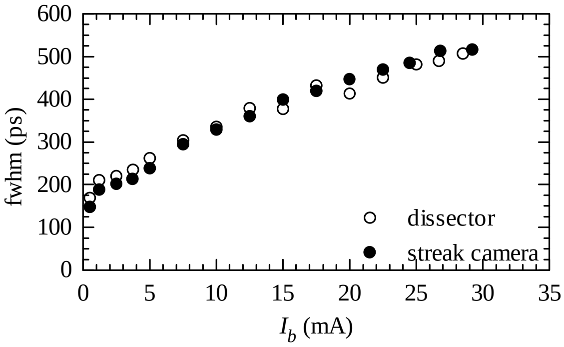

Figure 4: Bunch length vs. the current per bunch for Super ACO with E=600 MeV and α=+0.0148.

3 EXPERIMENTAL RESULTS

In Fig. 4 a comparison of bunch-length measurements with a streak-camera and a dissector is shown. The results are obtained simultanously in a 2 bunch mode of operation. The average current was kept below 35 mA/bunch in order to avoid bunch oscillations such as quadrupolar motions that occur above this current and are too fast for the dissector to be followed. During these measurements the streak-camera was also several synchrotron periods. Contrary to the results found by Clarke et al. [7] both the dissector and the streak-camera provide similar results.

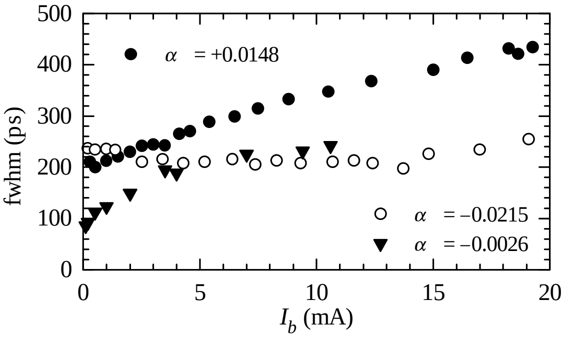

Figure 5: Bunch length vs. the current per bunch for different values of α.

In Fig. 5 a comparison, obtained with a streak camera, between the bunch-length as a function of the average beam current for three different values of α is made. It follows that the bunch-length is reduced with 40% with negative α for beam currents up to 20 mA. For very small values of α the nominal bunch length for I_b=0 mA is reduced even further. The bunch-length increases more rapidly, however.

The energy spread as a function of beam current, for various values of α, is plotted in Fig. 6. Contrary to earlier measurements [8] there is no clear treshold for micro-wave instability for the nominal value of α=0.015. Furthermore, the energy spread now increases less with increasing beam current. For this reason the results were also verified with an alternative method which derives the energy spread from the variation of the horizontal beam dimension in a section with non-zero dispersion. The results obtained are similar. For negative α the energy spread increases more rapidly with increasing beam current. Also the initial energy spread at zero current is already somewhat larger. The reason for this last effect is not clear yet. However, we should note that due to the increased beam emittance these measurements were more complicated and the estimated maximum error margins are much larger. For a more accurate measurement it is necessary to reduce the effects of emittance.

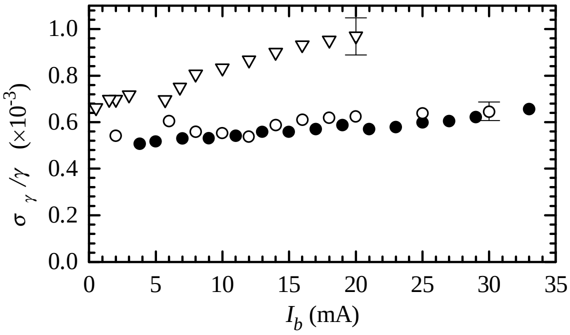

Figure 6: Energy spread as a function of bunch current for α=+0.015 (dots) and α=–0.015 (triangles). At positive α results are compared with a diagnostic based on the transverse beam dimension (solid dots).

CONCLUSIONS

The diagnostics critical for the FEL have proven to be beneficial for a better understanding of the beam dynamics. The results obtained suggest possible merits of a negative α mode of operation. The bunch-length can be reduced at the expense of a somewhat increased energy spread. For a definite answer more research is necessary. For example, preliminary calculations based on the present results already suggest an equivalent performance for an FEL with either positive or negative α. Further optimization might thus prove important.

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