EXPERIMENTS WITH LOW AND NEGATIVE MOMENTUM COMPACTION FACTOR WITH SUPER-ACO*

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Abstract

The aim of these experiments was to produce short light pulses by reducing the momentum compaction factor. These experiments show that the correction of the second-order term, using sextupole magnets, is essential in order to successfully reduce the momentum compaction by a large factor. By this technique, a factor of 100 reduction was obtained.

In addition, experiments with negative momentum compaction factor are currently being performed in order to test the predictions of beam stability with natural chromaticities (Head Tail effect) and variation of bunch length and energy spread versus bunch current (potential well effect and microwave instability). The results of these experiments are presented here.

1. INTRODUCTION

There is a great interest in decreasing the bunch length and increasing the peak current of electron or positron bunches in a storage ring. Such short bunches, if obtained at operational beam current, would lead to an increase in gain for free electron laser operation [1], would be very useful for time resolved experiments, and would provide the possibility of observing coherent radiation [2]. The natural bunch length is proportional to the square root of the momentum compaction factor (α). The reduction of α would permit a reduction of the natural bunch length. Nevertheless, it is well known that in the turbulent bunch lengthening regime, bunch length becomes independent of α [3]. However, the threshold of this effect depends on the impedance of the machine leaving open the possibility of obtaining high peak currents in future machines by this technique. In addition, it is interesting to study collective beam dynamics at low α as well as to probe the high frequency machine impedance.

There is also a growing interest in operating with negative momentum compaction factor. The head-tail instability effect does not exist when both α and the chromaticity are negative. Therefore, one could avoid strong chromatic sextupoles. In addition, simulations by S. X. Fang et al. [4] based on the resonator impedance model show that the longitudinal bunch shape is less deformed and bunch lengthening is less serious with negative α. Calculations by G. Besnier et al. [5], 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.

This paper reports on the results obtained during low and negative momentum compaction factor experiments performed on Super-ACO.

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2. LOW ALPHA EXPERIMENTS

2.1. Optics

The optics calculation giving variable momentum compaction lattices has already been published elsewhere. Lattice parameter sets were calculated for first order momentum compaction values between $\alpha_1 = 0.015$ and $\alpha_1 \approx 0$ [6].

2.2. Experimental results and discussion

2.2.1. Measurement of α_1

The quadrupole gradients calculated for each different α_1 lattice were introduced into a control program. The beam was injected at the initial point ($\alpha_1 = 0.015$) and the momentum compaction factor was reduced step by step by changing the quadrupole strengths. This allowed us to study the effects occuring during the process of reducing α_1. The experiment was performed with a single bunch at the nominal energy of 800 MeV. The peak RF cavity voltage was adjusted to 170 kV.

The synchrotron frequency was measured for each point of the path. In each case, at the operating point corresponding to the calculated value of $\alpha_1 = 0.003$, difficulties occured in terms of various instabilities, large closed orbit distortion, poor beam lifetime and sudden beam losses [7].

The variation of the experimental synchrotron frequency (f_s) versus the square root of the calculated α_1 departs from linearity below $\alpha_1 = 0.003$ (fig. 1).

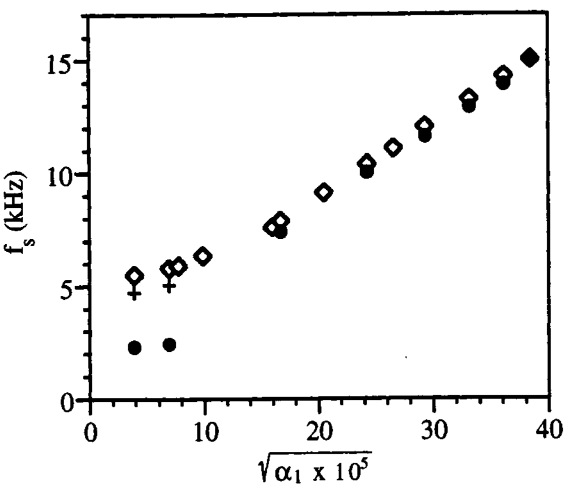

Figure 1. Measured synchrotron frequency versus calculated α_1 for three different sets of sextupole strengths.

This behaviour is consistent with the expression for f_s including the second order term of the momentum compaction factor, α_2 [7] :

$$f_s = f_{REV}\sqrt{\frac{h\ \ eV_{RF}\cos\ \phi_s}{2\pi E_o}}\left(\alpha_1^2 - 4\alpha_2\frac{\Delta f_{RF}}{f_{RF}}\right)^{1/4} \quad (1)$$

The curves of figure 1 correspond to three different sets of sextupole strengths. One of these sextupole configurations (dark circles) reduced α_2 to a near-zero value leading to a much lower synchrotron frequency for the same calculated α_1. At the lowest point, $\alpha_1 = 0.00015$ (100 times smaller than the initial value) the single bunch current was 0.1 mA. This should correspond to a reduction of the natural bunch length by a factor of 10.

2.2.2. Measurement and compensation of α_2

Systematic measurement and control of α_2 were performed for the point corresponding to $\alpha_1 = 0.00119$. The synchrotron frequency was measured as a function of the RF frequency for different strengths of the SX4 focusing sextupole family (each quadrupole has extra coils which can be powered to produce a sextupole field) [7]. Experimental values of α_1 and α_2 were then deduced by fitting equation (1). Reducing the SX4 strength by approximately 6 % from its nominal value brought the measured α_2 to nearly zero (fig. 2.a). At this point, the measured synchrotron frequency was 4.2 kHz which, compared to the 15 kHz synchrotron frequency at the injection point, confirms the reduction of α_1 by a factor 13. The crossing point which is independent of the value of SX4 strength defines the central frequency of the machine.

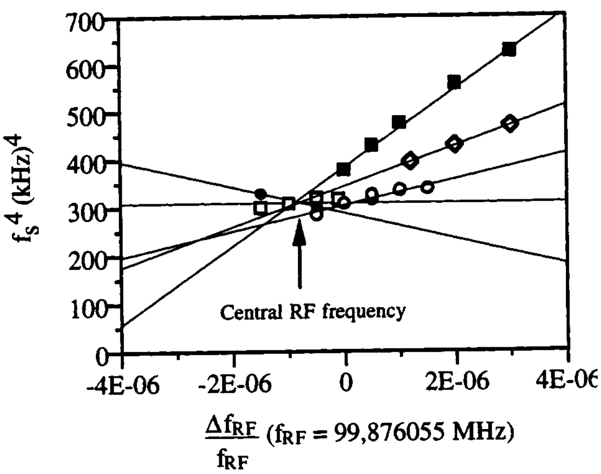

Figure 2.a. Measured synchrotron frequency versus RF frequency for different sets of sextupoles for $\alpha_1 = 0.00119$.

The variation of α_2 with the SX4 sextupole strength is linear as predicted by the calculation, and the value of the slope is in good agreement with the calculated one (fig. 2.b).

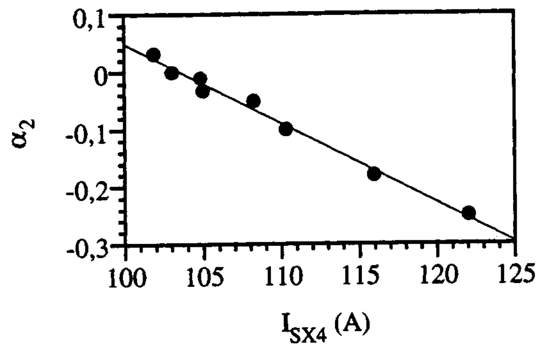

Figure 2.b. Experimental variation of α_2 versus sextupole strength SX4 for $\alpha_1 = 0.00119$.

The compensation of α_2 at this point of the path allowed us to store 5 mA in a single bunch with corrected chromaticities and beam lifetime longer than 10 hours.

No bunch length measurements were performed for this particular value of α_1. At that time there was no streak camera available and the short electrode we use routinely for bunch length measurements is not reliable for bunch lengths below 50 ps. Measurements performed at $\alpha_1 = 0.015$ and $\alpha_1 = 0.0036$ show that the bunch shortening is only clear at very low current [6].

3. NEGATIVE ALPHA EXPERIMENTS AND COMPARISON WITH POSITIVE ALPHA

3.1. Optics

Using the technique already described in [6], the dispersion function is made more negative in the bending magnets and the momentum compaction factor can then become negative.

3.2. Experiments

The beam was successfully injected and stored in a lattice where α_1 is negative and equal to - 0.012. Because no head-tail instability exists when both α_1 and the chromaticity are negative, all the sextupoles were turned off leading to negative chromaticity in both plans (ξ_{xo} = - 3 ; ξ_{zo} = - 11). The stored beam current in a single bunch was above 100 mA.

3.3. Bunch lengthening with beam current

Figure 3 shows the variation of the measured bunch length as a function of current for the positive and negative α_1 configurations.

At negative α_1 the lengthening is lower than at positive α_1. The difference in length is about 60 % at 100 mA bunch current.

However, as in the case of positive α_1, experiments with different negative α_1 values show that the bunch lengthening threshold is decreased when α_1 is reduced and for operational beam current intensities above 5 mA, the bunch length is independent of the magnitude of α_1 (Fig. 4). These bunch length measurements were made with a streak camera.

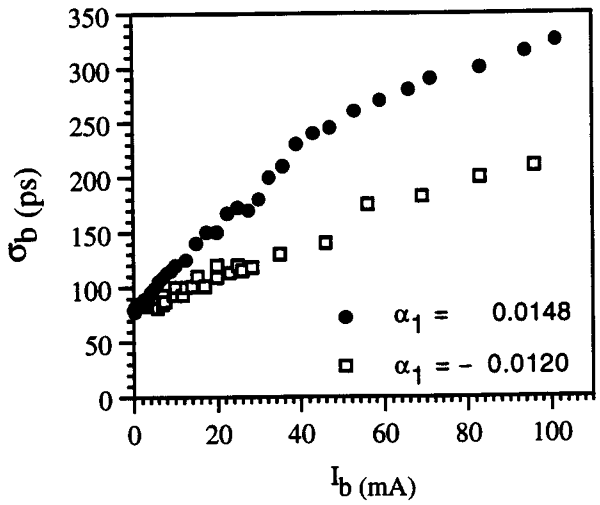

Figure 3. Experimental bunch lengthening with positive and negative α_1.

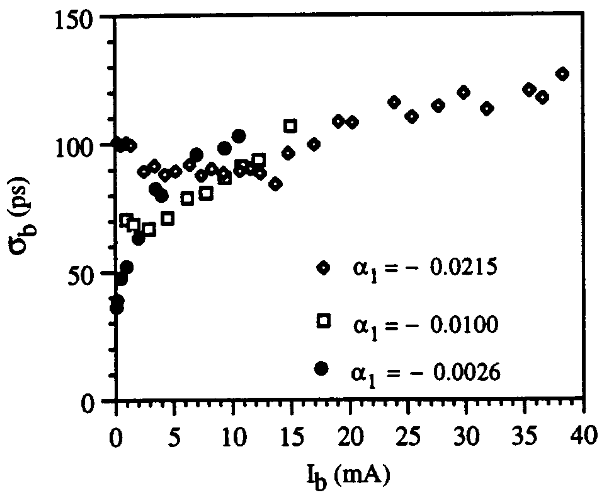

Figure 4. Experimental bunch lengthening with three different negative values of α_1.

3.4. Energy spread measurement versus current

The energy spread has been measured with two methods. The first uses the variation of the horizontal beam dimension with current at a location were the dispersion function η_x is not zero while the second is based on the spectrum of an optical klystron [8]. The result of these measurements, given in figure 5, shows that the energy spread is almost constant at positive α_1 whereas a significant increase with current is observed at negative α_1. This result is consistent with the predictions of G. Besnier et al. [5].

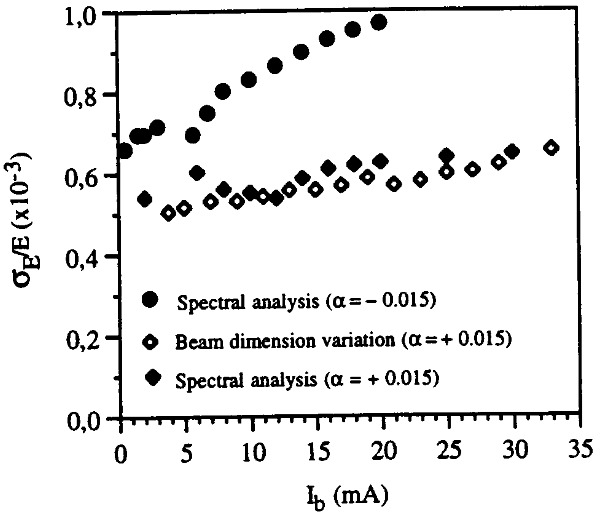

Figure 5. Measured energy spread versus current with positive and negative α.

4. CONCLUSION

The first order of the momentum compaction factor α_1 has been reduced by a factor 100 by both changing the dispersion function in the bending magnets and compensating the second order term α_2.

The bunch length was measured at two values of α_1, respectively 0.015 and 0.0036 and shows that bunch shortening is only clear at very low current.

Negative α_1 operation has achieved a 100 mA stored beam current in a single bunch with all the sextupoles turned off. The bunch lengthening with current was smaller than with positive α_1 but the energy spread was significantly larger.

Experiments with different negative α_1 values show that the bunch length is independent of the magnitude of α_1 for beam current intensities above 5 mA.

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