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ISOCHRONOUS OPTICS AND RELATED MEASUREMENTS IN EPA

R. Corsini, J.P. Potier, L. Rinolfi, T. Risselada

Abstract

The time structure of the CLIC (Compact Linear Collider) drive beam is obtained by the combination of electron bunch trains in rings using RF deflectors [1]. The rings must be isochronous, in order to preserve the bunch length and separation during the combination process (4-5 turns). A first isochronicity test has been performed in the CERN EPA (Electron Positron Accumulator) ring. The calculated isochronous lattice can be obtained by changing the strength of existing quadrupole families without hardware modifications. Measurements of the synchrotron frequency and of the beam's time structure have been made for both the normal and the isochronous lattices. Streak camera measurements of the bunch length have been used to tune the lattice around the isochronous point. The bunch length increases rapidly over a few turns in the normal case, while no appreciable bunch lengthening is observed over 50 turns in the isochronous case. A quantitative evaluation of the momentum compaction is obtained by measuring the bunch separation in a train when close to, and far from, the isochronous condition. Plans for future tests in the EPA ring are also outlined.

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The time structure of the CLIC (Compact Linear Collider) drive beam is obtained by the combination of electron bunch trains in rings using RF deflectors [1]. The rings must be isochronous, in order to preserve the bunch length and separation during the combination process (4-5 turns). A first isochronicity test has been performed in the CERN EPA (Electron Positron Accumulator) ring. The calculated isochronous lattice can be obtained by changing the strength of existing quadrupole families without hardware modifications. Measurements of the synchrotron frequency and of the beam's time structure have been made for both the normal and the isochronous lattices. Streak camera measurements of the bunch length have been used to tune the lattice around the isochronous point. The bunch length increases rapidly over a few turns in the normal case, while no appreciable bunch lengthening is observed over 50 turns in the isochronous case. A quantitative evaluation of the momentum compaction is obtained by measuring the bunch separation in a train when close to, and far from, the isochronous condition. Plans for future tests in the EPA ring are also outlined.

1 LATTICE

The dispersion in the normal EPA lattice, used for LEP operation, is shown in Fig. 1. The dispersion is zero in the straight sections, and positive (up to 2.2 m) in the arcs. The momentum compaction is $\alpha = 0.034$. To first order, the momentum compaction is linked to the dispersion D_x and the bending radius in the magnets by the expression:

$$\alpha = \frac{1}{C} \oint \frac{D_X}{\rho} \, ds$$

where the integral is over the ring circumference *C*. In order to reduce α to zero, D_x has to be forced to negative values in some of the bends. This can be obtained by increasing the strength of quadrupoles located in a region where $D_x \neq 0$. In the EPA ring it is not possible to do so while keeping $D_x = 0$ in the straight sections, without re-cabling the existing quadrupole families. Therefore a compromise solution (shown also in Fig. 1) has been found [2], in which the dispersion oscillates in the straight sections. The injection line is, in this case, badly matched to the ring and the larger beam envelopes give rise to beam losses in the first few turns. The two central quadrupoles in the arcs (QFL family) contribute most to the change in α, while the other quadrupoles in the arcs are used to trim the tune values. The strength of quadrupoles in the straight sections has been kept unchanged in order to keep the injection bump closed.

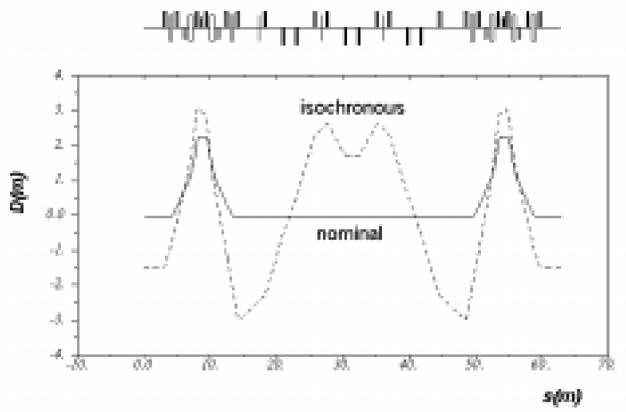

Figure 1: Dispersion in EPA different optics (half ring shown).

2 SYNCHROTRON FREQUENCY MEASUREMENTS

In order to estimate the values of α, the synchrotron frequency f_s was measured for different optics, corresponding to calculated values of α ranging from 0.034 to –0.01. The measurement requires a stored e^- beam and the use of the RF cavity, and therefore excludes α values too close to zero. Unfortunately, all attempts to measure f_s for negative α values failed. Fig. 2 shows that the measured values do not coincide with the theoretical ones (solid line) for small values of α, pointing to an imprecision of the theoretical model. A similar observation [3] was reported in an earlier experiment in 1992. The reason for this discrepancy is not yet understood.

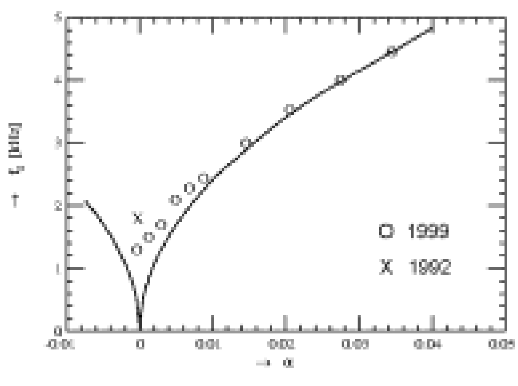

Figure 2: Calculated and measured synchrotron frequencies.

3 STREAK CAMERA MEASUREMENTS

3.1 Experimental apparatus

In order to measure the bunch length over many turns in the EPA, the synchrotron light emitted [4] has been observed with a streak camera. The source of the synchrotron light is located 192.5 mm upstream of the centre of the third dipole of the last arc. The dispersion at this place is 1.5 m for the normal optics and 1.7 m for the isochronous optics. The source length is limited by the optical aperture to about 50 mm. The light can be divided using a movable beam splitter in order to monitor its intensity on-line with a diode, while using the streak camera, and to set up the proper timing.

3.2 Measurements

The beam was injected axially, and lost on the septum after the desired number of turns by firing the second injection kicker. The pulse was composed of several bunches, spaced by 333 ps, corresponding to the 3 GHz accelerating frequency. The total intensity of the pulse, measured at injection, was 2.4×10^{10} electrons. The beam energy was 500 MeV, and the FWHH energy spread was 1.8 %. Streak camera images were recorded for different turns (up to the 40^{th} for the isochronous optics). In Fig. 3 the streak camera image of the pulse is shown. The abscissa is time (about 5 ns full scale), while the ordinate corresponds to horizontal particle position. The bunches in the pulse are visible (about ten can be counted). The FWHH pulse length was about 4 ns. The light source is located in a dispersive region, therefore the horizontal beam position and size depend on the beam energy and momentum spread, respectively. This is evident in the image, where the momentum-time correlation due to beam loading along the pulse is clearly visible. In Fig. 4 and Fig. 5, corresponding to a faster sweep-time (2.25 ps/pixel), the time profile of the individual bunches can be seen. The FWHH bunch length at injection, evaluated using a Gaussian fit, was about 60 ps.

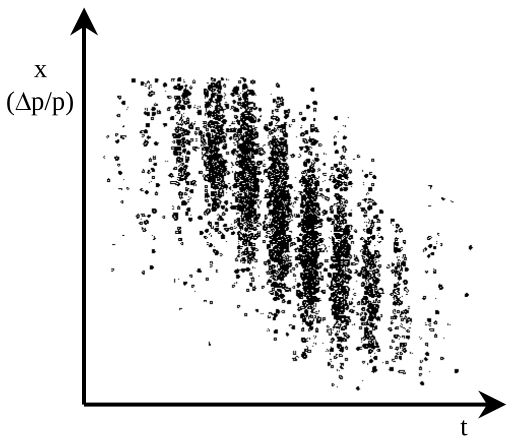

Figure 3: Streak camera image of the electron pulse.

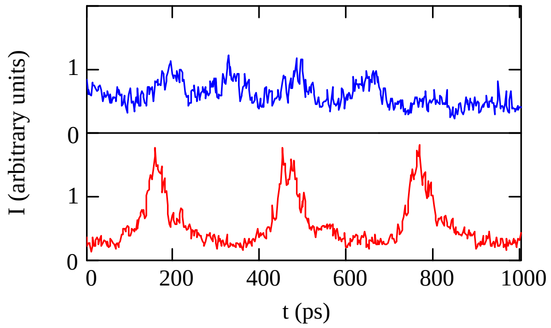

Figure 4: Pulse profile in time with normal optics at the 1^{st} turn (bottom) and 10^{th} turn (top). The loss of structure (due to the bunch length increase) and the decrease in bunch-to-bunch spacing are clearly visible.

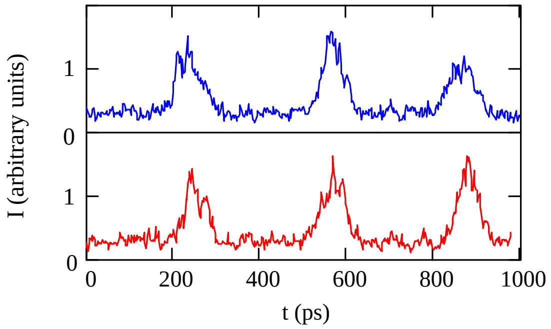

Figure 5: Pulse profile in time at the 1^{st} turn (bottom) and 20^{th} turn (top), for the isochronous optics. The time structure is virtually unchanged.

The bunch structure inside the pulse was almost lost after 10 turns in the normal machine. Also the distance between bunches decreased in the normal machine, as expected, due to the bunch-to-bunch energy variation caused by beam-loading along the pulse. The machine optics was then changed and put close to isochronicity, and the exact tuning found by changing the current in the QFL quadrupole family, while looking at the streak camera image of the bunches. The optimum value found for the QFL current was 88.5 A, to be compared to the theoretical value of 84.5 A, obtained from the MAD model simulations. In this case the bunch length and the bunch distance were essentially unchanged over at least 20 turns. A further measurement was also taken after up to 50 turns. At this point, beam losses started to limit the light intensity at the streak camera, and affect its resolution. In spite of that, it was possible to evaluate the bunch length, still unchanged. The bunch-to-bunch distance, evaluated off-line afterwards for the 40^{th} turn, was only slightly reduced (by about 7 ps). In order to make sure that the observed constant bunch length was not due to losses, a different kind of measurement was taken. The QFL current was changed by –1 A and + 2 A around the estimated isochronous condition. Streak camera images of the beam were taken.

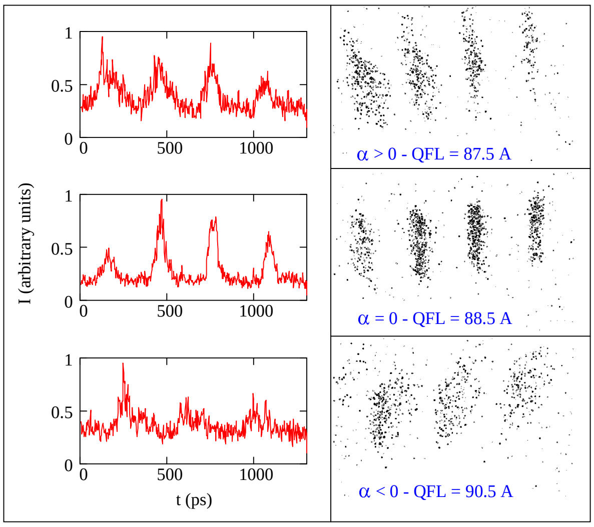

Figure 6: Streak camera images and time profiles for different settings of the QFL quadrupole family.

The results are shown in Fig. 6, and demonstrate clearly the transition from a positive to a negative value of α. From top to bottom, the bunch length reaches a minimum, then increases again while time-momentum correlation along each bunch changes sign.

4 ANALYSIS OF MEASUREMENTS

When α is close to zero, the measured variation in bunch length is too close to the resolution limit to obtain a reliable evaluation of α. In addition, the increase of bunch length should be quadratic rather than linear, and depends both on the initial time-momentum correlation within each bunch and on its charge distribution. The non-zero momentum compaction of the injection line ($\Delta L/L$ / $\Delta p/p$), that cannot be tuned to be isochronous, is an added complication. On the other hand, the variation in bunch-to-bunch distance is both relatively large and linear with the number of turns:

$$\Delta t(N) = \alpha \frac{C}{c}\frac{\Delta p}{p} N + \Delta t(0)$$

where N is the number of turns, C the ring circumference, c the speed of light and $\Delta p/p$ the bunch-to-bunch energy variation. The bunch distance is easier to use than the bunch length for comparison with the normal case (see Fig. 4), where the bunches are mixed after a few turns, while the distance between bunch centres is still measurable. We know that Δt = 333 ps (corresponding to the RF period) at the end of the linac.

At injection, Δt is reduced by the momentum compaction of the transfer line. It can be evaluated using a linear fit to the data taken with the normal optics, obtaining $\Delta t(0)$ = 320 ps. In Fig. 7, the measured bunch spacing is plotted as a function of the number of turns, for both the normal and the isochronous case. A linear fit of the measured data is also shown.

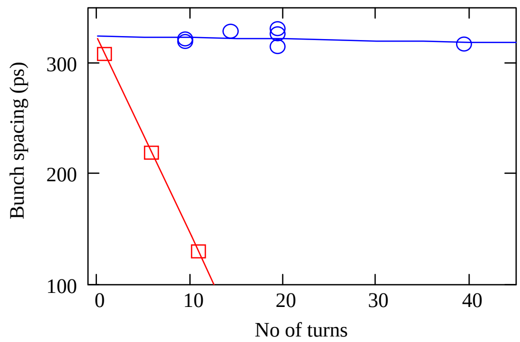

Figure 7: Bunch-to-bunch spacing as a function of the number of turns for the normal (squares) and the isochronous optics (circles).

The fit can be used to evaluate the momentum compaction in the isochronous case, equal to the ratio of the slopes, times the normal momentum compaction:

$$\alpha_I = \frac{m_I}{m_N}\alpha_N$$

Assuming α_N = 0.034, which has been confirmed by the synchrotron frequency measurement, one gets $\alpha_I = 2.3 \times 10^{-4}$ for the isochronous case. The data spread for the isochronous machine (Fig. 7) is due to re-tuning of the QFL current while the measurements were taken. Therefore the estimated value of α is rather an average than a precise value. Nevertheless, such evaluation is valid for the last data point taken, where the sensitivity is higher.

5 CONCLUSIONS

The preliminary tests on EPA have demonstrated the possibility of obtaining and measuring values of α as small as 2.3×10^{-4}, close to the goal of the future CLIC test facility, CTF3 ($|\alpha| \leq \pm 10^{-4}$). We hope to perform further measurements this year, in order to reach such a value and check the higher orders of momentum compaction, and their compensation by sextupole tuning [2]. As a preliminary stage of CTF3, in the year 2001, we plan to modify the EPA quadrupole families and the injection line. This would allow us to obtain an isochronous lattice with D_x = 0 in the straight sections and a good matching of the line to the ring. The next step will be a first demonstration, at low charge, of the principle of beam combination with RF deflectors.

REFERENCES

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