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CONF-880695-15

DE88 012740

BUNCH LENGTHENING IN THE SLC DAMPING RING*

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Abstract

In this paper we present the results of measurements of bunch length and bunch shape as a function of current in the SLC e^- damping ring. After extraction, the SLC bunch is compressed by means of an RF compressor and a subsequent high dispersion section. By inserting a video screen at a point of large dispersion and by using the correlation between bunch length and energy spread induced by the compressor, we have measured not only the bunch length but also the longitudinal charge distribution of the bunch in the damping ring as a function of beam intensity. At 3×10^{10} particles per bunch with a peak ring RF voltage of 800 KV, the FWHM of the bunch length in the ring doubles over the nominal value. To measure the energy spread of the bunch in the damping ring, the optics of the extraction line was modified to produce a large dispersion but small horizontal β function at the video screen. At 3×10^{10} particles per bunch, the relative energy spread in the ring is increased by about 30%. Finally, these data are compared with calculations of bunch lengthening in the SLC damping rings.

Introduction

The electron ring operates at the energy of 1.15 GeV with the betatron tunes of $\nu_x \sim 8.2$ and $\nu_y \sim 3.2$, and provides the SLC project with intense small emittance bunches. The ring is run fully coupled, and the design value for the normalized equilibrium emittance of the beam with the present set of operating parameters is $\gamma \epsilon_{x,y} = 1.5 \times 10^{-8}$ m-rad. The momentum compaction factor is 0.0147, and the low current equilibrium energy spread is $\sigma_e/E = 7.1 \times 10^{-4}$. The typical ring RF voltage is about 0.9 MV and the bunch length at low beam intensity is below 5 mm.

A bunch length compression scheme is implemented in the Ring-to-Linac transport line (RTL) [1]. A correlation between the energy and the longitudinal position within the bunch is introduced with the help of a 5-ft S-band accelerator section immediately downstream of the damping ring. It is followed by a high dispersion section where the bunch performs a rotation in longitudinal phase space, arriving at the linac with the required short bunch length (on the order of 1 mm). The RF wave in the accelerating section is phased such that the center of the bunch coincides with a zero crossing and introduces the energy spread across the bunch of

$$\frac{\sigma_t}{E} = \frac{e\bar{V}_{RF}}{E} \sin \frac{2\pi}{\lambda_{RF}} \sigma_{t0} \approx \frac{2\pi}{\lambda_{RF}} \frac{e\bar{V}_{RF}}{E} \sigma_{t0},$$

where \bar{V}_{RF} is the peak compressor voltage, λ_{RF} is the S-band wave length and σ_{t0} is the bunch length at the extraction time. The longitudinal emittance of the beam is of course preserved; moreover, in the linear part of the compressor RF, the simple product of the energy spread and bunch length is preserved

$$\sigma_{t0} \cdot \frac{\sigma_t}{E} = \sigma_t \cdot \frac{\sigma_t}{E},$$

where σ_t is the bunch length upon entering the linac.

The required bunch length in the linac, determined by the final energy spread at the end of the linac should be below $\sigma_t = 1$ mm. The RTL transport line was designed to be able to transmit beams with rms energy spread of 1%. We reach these limits at present with

$$N \approx 2 \times 10^{10} e^- \text{ per bunch}.$$

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Contributed to the European Particle Accelerator Conference, Rome, Italy, June 7-11, 1988

This limitation is due to the bunch lengthening that occurs in the ring, since the energy spread, introduced by the compressor, grows with the length of the extracted bunch.

RTL "Streak Camera"

At the beginning of RTL, upon entering the compressor, the low current bunch length is about 5 mm, which yields an energy spread in the RTL, introduced by the compressor, of about 1%. With such a large energy spread, the beam size on the profile monitors in RTL at high dispersion points is totally dominated by the chromatic size

$$\sigma_x = \sqrt{\epsilon \beta + \eta^2 \left(\frac{\sigma_t}{E} \right)^2} \approx \eta \frac{\sigma_t}{E}.$$

Digitizing the video signal from the profile monitor TV camera, we measured the horizontal beam size as a function of bunch intensity. From these measurements we were able to extract not only the bunch length but the longitudinal bunch shape as well. It was particularly important at high currents, where we observed the bunch shape asymmetry predicted by theory. In Fig. 1, we present the measured bunch length in the ring as a function of current. These results agreed very well with the measurements of the uncompressed bunch length at the linac, using a Cerenkov radiator and a streak camera [2]. The two sets of points correspond to the FWHM of the bunch shape as well as to the rms bunch length. The curves are the results of bunch lengthening calculations, using the Green's function for the damping ring impedance [3]. The bunch lengthening

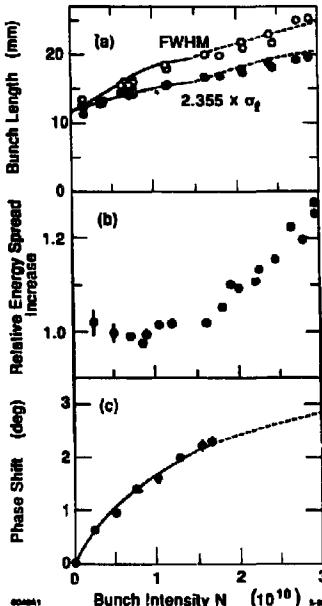


Fig. 1. Bunch length, relative energy spread increase and synchronous phase shift as a function of current.

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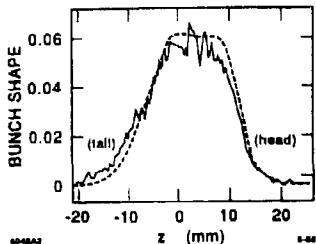


Fig. 2. Measured longitudinal charge distribution in the lengthened SLC bunch and (dashed curve) the calculated prediction for it. The bunch population is 1.2×10^{10} .

calculations above the turbulence threshold utilized the cube root scaling of both energy spread and bunch length with current. In Fig. 2, we reproduce one of the bunch shape distributions together with the predictions from the potential well bunch lengthening theory [4]. The ragged quality to the beam shape data reflects the granularity of the screen material; we hope to repeat the measurements in the near future with better screens. The agreement between the measured longitudinal charge distribution and the predictions from the dynamic theory is remarkably good.

Energy Spread

In order to measure the equilibrium energy spread in the ring, the compressor was turned off and special optics was used in the RTL to obtain a high dispersion and a low β function on the screen where the measurements were made. With the chromatic size of the beam dominating the betatron size, we were able to measure the equilibrium energy spread in the bunch as a function of current. The results are presented in Fig. 1 and illustrate that we indeed had turbulent bunch lengthening in the ring, with the threshold of approximately

$$N_{th} \approx 1.5 \times 10^{10}$$

particles per bunch. The energy distribution of the bunch over the entire range of intensities remained Gaussian, as far as we could tell, as predicted by the theory. An example data plot at $N = 3 \times 10^{10}$ is shown, with a superimposed Gaussian curve, in Fig. 3.

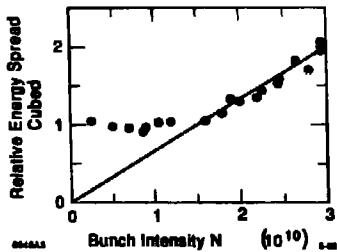


Fig. 3. A data plot of the longitudinal energy distribution, with a superimposed Gaussian curve at $N = 3.0 \times 10^{10}$.

The relative increase in energy spread raised to the third power is plotted against the intensity in Fig. 4. This allows us to use a linear fit to constrain the measured data to the well known scaling law [5]

$$\frac{\sigma_t}{E} \propto \sqrt[3]{N}$$

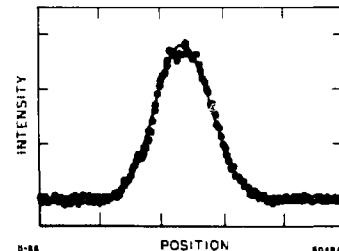


Fig. 4. Relative energy spread cubed as a function of current. The linear fit through the origin helps to determine the turbulence threshold.

We have used this fit to obtain the "effective impedance" of the ring, using the common threshold condition [6]

$$\left| \frac{Z}{n} \right| [\Omega] = 2\pi \frac{Ec}{eI_p} \cdot \left(\frac{\sigma_t}{E} \right)^2 = \frac{53.76}{I_p [A]} ,$$

where I_p is the bunch peak current

$$I_p [A] = \frac{eNc}{\sqrt{2\pi}\sigma_t} = 191.4 \frac{N [10^{10}]}{\sigma_t [\text{mm}]} .$$

Thus, for the present damping ring we obtain the result

$$\left| \frac{Z}{n} \right| \approx 1.5 \Omega .$$

If we were able to reduce the inductive part of the impedance by 25%, as we hope to do by installing the "sleeves" to shield the bellows, the effective impedance would be reduced to

$$\left| \frac{Z}{n} \right| \approx 1.1 \Omega .$$

In this case, from the scaling above, one would expect the threshold to increase to about 2×10^{10} particles per bunch.

Parasitic Mode Loss

A circulating electron bunch in a storage ring, in addition to the synchrotron radiation losses, loses part of its energy to the resistive longitudinal impedance of the ring. The RF system compensates for the total loss, and the relative phase between the beam and the RF changes with intensity. We have measured the relative phase change utilizing a vector voltmeter. The technique has been described in more detail elsewhere [7].

The results are presented in Fig. 1, where the curve corresponds to the calculations that used the calculated Green's function for the ring impedance. This measurement allows us to check the resistive part of the calculated impedance.

Synchrotron Tune Shifts

We have measured the frequency shift of the quadrupole synchrotron oscillations over the same range of current. The results are shown in Fig. 5. We observed the saturation of the frequency shift with current above the turbulence threshold. It agrees with the expectations from theory that predict the frequency shift scaling with current as [8]

$$\Delta f \propto \frac{N}{\sigma_t^3} .$$

The data agrees with the conclusion from the energy spread measurements that the threshold current for turbulent bunch lengthening is $N_{th} \approx 1.5 \times 10^{10}$ electrons per bunch. This measurement also provided us with another check of the reactive part of the longitudinal impedance of the ring.

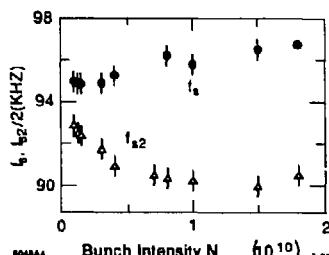


Fig. 5. Dipole and half of the quadrupole synchrotron oscillations frequencies as functions of intensity.

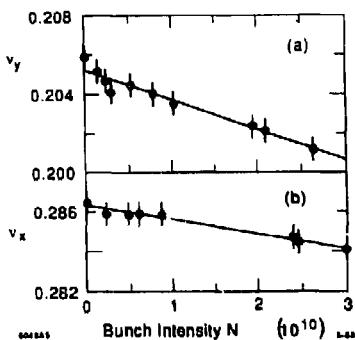


Fig. 6. Betatron tune shifts as a function of intensity.

Betatron Tune Shifts

We have also measured the betatron frequencies as a function of current and the results are shown in Fig. 6. With the present degree of bunch lengthening, we do not expect the mode coupling instability to occur up to the design current of 5×10^{10} particles per bunch.

Limitations to SLC Operation

The bunch lengthening in the damping ring has limited the single bunch intensity available for the SLC. The limitation is due to the beam losses in the RTL transport line. Because of the energy spread produced by the compressor, the horizontal beam size in regions with high dispersion is proportional to the equilibrium bunch length in the damping ring. The increased horizontal beam size leads to beam loss on the vacuum chamber walls at the maximum dispersion point in the transport line.

We have recently rebuilt the vacuum chamber in RTL near the point of highest dispersion, removing that aperture limitation. As a result we are now able to transmit beams with larger energy spread through the RTL, raising the available bunch intensities in the linac in excess of 2×10^{10} particles.

The original limit of $N \approx 10^{10}$ per bunch was overcome with the use of a bunch prerotation in the ring that we dubbed "bunch muncher." The trick consists of switching off the RF in the ring shortly before the extraction time, letting the bunch lengthen, and then switching the RF back on, inducing quadrupole bunch shape oscillations. The operation is timed so that the bunch length is at a minimum at the extraction time. This prerotation of the bunch in longitudinal phase space results in up to a factor of two higher energy spread and a correspondingly shorter bunch, the longitudinal emittance of the beam, of course, being preserved during the operation.

This scheme has been tested and a factor of two shorter bunches were obtained. Since the energy spread in the RTL is determined by the bunch length at the compressor, this allowed us to transmit bunches through the RTL with intensities greater than 2×10^{10} particles per bunch.

We are planning to install thin metal sleeves into the bellows in the ring. These sleeves should reduce the reactive part of the longitudinal impedance substantially, since the bellows make up 25% of the ring's inductance according to the calculations [3]. If the full 25% reduction is realized, we expect to be able to significantly raise the useful SLC bunch intensity.

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