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HIGH CURRENT EFFECTS IN THE PEP-II SLAC B-FACTORY*

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Abstract

Wake fields defining beam stability affect also the beam optics and beam properties in high current machines. We present observations and analysis of the optical effects in the PEP-II SLAC B-factory, which has the record in achievement of high electron and positron currents [1]. We study the synchronous phase and the bunch length variation along the train of bunches, and overall bunch lengthening.

INTRODUCTION

The wake fields generated by the beam in the beam pipe are recognized as the cause of the beam instabilities in the high current machines [2]. The wake fields are also the cause of numerous optical effects, which do not lead to bunch instability but may be important for optimization of the beam dynamics and luminosity. Quite often, the optics of a machine is studied and optimized at low currents. However, the tunes and Twiss parameters vary with current, and the optics at collision can differ from the optimized optics at low current. Therefore, optimization of optics at low currents does not necessarily mean optimization of the luminosity. More than that, in the multi-bunch machines the wakes affect different bunches differently. Some such effects were observed and discussed in the context of the harmonic rf systems [3] but still colliders with conventional rf systems deserve more detailed analysis at higher currents. The second reason is given by the need for study of the machine impedance. There are three main contributions to the impedance budget: the rf cavities, resistive wall impedance, and the impedance generated by small vacuum components of the ring such as bellows, beam position monitors, tapers, masks, vacuum ports, etc. In our experience, analysis of the current dependence of the tunes, measurements of the synchronous phase, and the bunch length were crucial to extract impedance parameters from the measurements. We analyze some of the current dependent effects. Results are obtained for PEP-II low energy ring (LER) but may be relevant for other projects such as Super B factories and the ILC project.

VARIATION OF THE BUNCH LENGTH AND SYNCHRONOUS PHASE ALONG THE TRAIN OF BUNCHES

We used beam spectra for the bunch length measurement [4]. To resolve bunch length along the bunch train, we used a spectrum analyzer in the gated regime. Results of measurements are shown in Fig. 1.

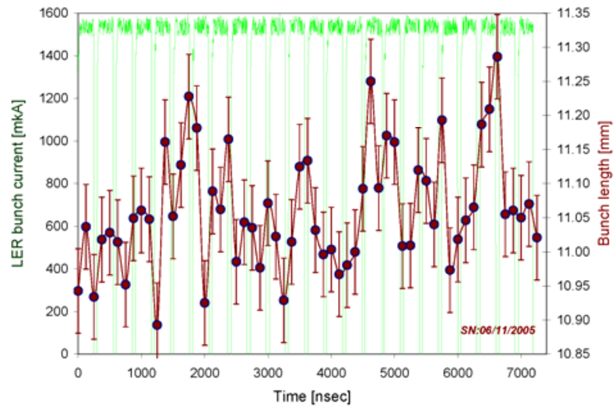

Figure 1: Variation of the bunch length (brown) and the bunch current (green) along the 24 mini-trains of the LER current. Total number of bunch is 1440. Total current is 2.2 A.

The variation shown at Fig. 1 is caused by the gaps between mini-trains and one large ''ion'' gap. The ion gap in the LER matches the ion gap in the electron high-energy ring (HER) and is needed also for the beam abort due to the finite rise time of a kicker. One can expect that a gap with the length s_g would generate transients of the rf voltage of the order of $1-\exp\left(-\frac{\omega_{rf}s_g}{2Q_l c}\right)$. Effect, actually, is larger. A small 2% gap gives substantial variation of the wake affecting different bunches and, as result, of the synchronous phase along the train. The variation of the synchronous phase contributes to variation of the slope of the voltage and, therefore, causes variation of the synchronous frequency f_s.

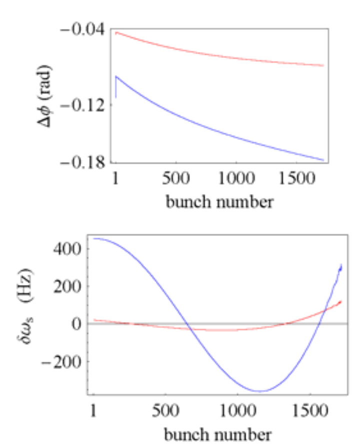

Figure 2: Synchronous phase (top) and synchrotron frequency (bottom) along the train caused by the ion gap for the beam current 0.5A (red) and 1.0 A (blue).

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Calculated variations of the synchronous phase and synchrotron frequency along the bunch train for LER parameters at the total voltage $V_{tot} = 4.5MV$ are shown in Fig. 2. These variations are due, mostly, to the fundamental mode of the rf cavities. Other higher order modes give a smaller contribution to this effect. Results of calculations for the bunch length along the train are shown in Fig. 3. The amplitude and the period of the variation depend on the beam current I_b. The amplitude and the modulation frequency depend on the detuning of the cavity and the effect is maximum when the detuning is equal to the revolution frequency which takes place for PEP-II parameters at, approximately, I_b=2.5 A.

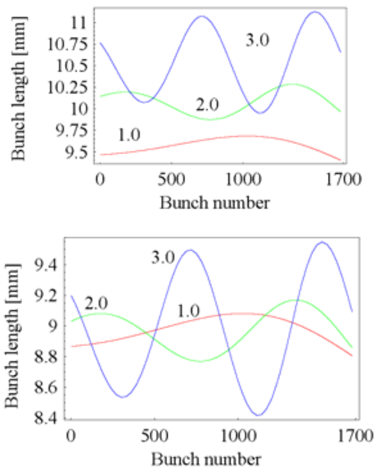

Figure 3: Calculated variation of the bunch length along the train for LER V=4.5 MV and the beam currents (indicated in the figure) I=1.0, 2.0 and 3.0 A. Bottom plot: results of only gap transients. Upper plot: variation due to the gap transients and the potential well distortion.

Synchrotron Frequency Variation with Current

The current dependence of synchrotron frequency of the train of bunches $\omega_s = \omega_s(I)$ is due to the short and long-range wake fields. It is worth noting, that synchrotron frequency measured by different methods can give different results. The actual situation is quite complicated because each bunch centroid oscillates with different frequencies. Fortunately, the frequency spread is not that large. The preferred method of determining f_s is by measuring the frequency of the second synchrotron sideband of the rf frequency which is less affected by the feedback system. However there are actually two $2\,f_s$ lines in the spectrum. One is due to the nonlinearity of the oscillations of the bunch centroid, another one is the coherent quadrupole longitudinal coupled-bunch oscillations of the bunch profile. These frequencies are, generally, different. In Fig. 4 we show the measured synchrotron frequency as a function of the beam current determined by two methods: the measurement of the first and the second sidebands of a harmonic rf frequency. Synchrotron frequency measured by the second method shows linear dependence on the beam current and deviates from the measurements by the first method due to effect of the feedback.

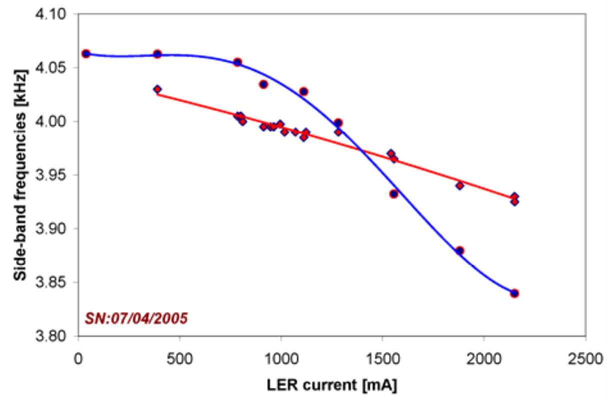

Figure 4: Synchrotron frequency measured from the first (blue) and the second sideband (red) in the beam spectrum.

Bunch Length Variation with Current

Transient variation of the rf phase and the synchrotron frequency of the bunches along the train affect the bunch length. The bunch length measured without gating on individual bunches gives the average rms over the whole train. It can be shown [5] that in linear approximation over the bunch current, the average bunch length σ_{train} in a train is deferent to the length σ_{single} of a single bunch

$$\sigma^2_{\text{train}}(I) = \left(\frac{\omega_s(I)}{\omega_{s,0}}\right)^2 \sigma^2_{\text{single}}(I) \qquad (2)$$

where $\omega_{s,0}$ is the zero-current synchrotron frequency.

Equations (2) can be verified experimentally. Comparing with experiment, we have to remember that both potential well distortion and the synchrotron frequency change with current. The first effect can be defined keeping the synchrotron frequency fixed. Fig. 5 shows results of measurement in two lines. One (blue) is the direct measurement of the bunch length in a train of bunches as a function of the beam current.

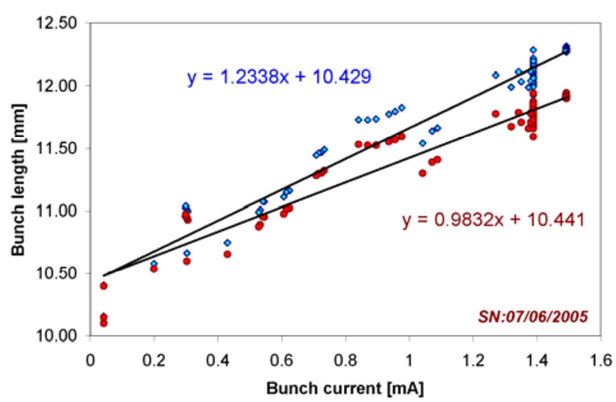

Figure 5: The measured bunch length in a train of bunches (blue) and the bunch length of a bunch with the same rf voltage and bunch current calculated from the measured synchrotron tune (red).

Another one (red) depicts variation of the bunch rms length at fixed synchrotron frequency calculated using measured frequency of synchrotron oscillations. The linear fit gives $\frac{d\sigma_{meas.}}{dI_b} = 1.23 mm/mA$ for total effect and for potential well distortion $\frac{d\sigma_{meas.}}{dI_b} = 0.98 mm/mA$.

The calculated averaged bunch length vs beam current is shown in Fig. 6.

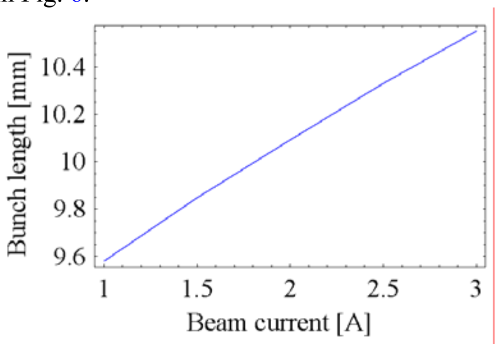

Figure 6: Averaged over the train bunch length vs beam current. Inductance L=80 nH, radio-frequency voltage is 4.5 MV.

Calculations are based on the estimate of the LER impedance [6] which gives inductance of the vacuum components L_{ind} =80 nH. The real inductance is, probably, higher partially due to vacuum components added after the estimate was carried out. The fit gives a result close to the measurement $\frac{d\sigma_{calcul.}}{dI_b} = 0.83\ mm/mA$. The few comments ought to be added. Generally, the bunch centroid motion is a superposition of harmonics of the CB frequencies, including the second harmonics $2\omega_{s,n}$. If the bunch-to-bunch frequency variation due to long gap transients is large, we can neglect bunch coupling caused by the longitudinal wake. In this case, all bunches have different frequencies and are approximately equal to $2\omega_{s,n}$. In the other extreme case, when the gap transients are small, the bunch frequencies are the frequencies of coupled-bunch modes and the set of these frequencies is the same for all bunches. The shape of the spectrum for different bunches still can be different because contributions of particular CB modes are not the same for different bunches. For PEP-II LER, the spread of the CB modes is comparable with the variation of the synchrotron frequency along the train.

EFFECT ON LUMINOSITY

Variation of the synchronous phase affects luminosity of the collider in two ways: First, through the induced variation of the bunch length σ_l which, in its turn, changes luminosity L due to the hour-glass effect. Second, the waist of the bunch shifts longitudinally and collision takes place at the point with larger β-function and, therefore, with larger transverse beam size. The effect is shown in Fig. 7.

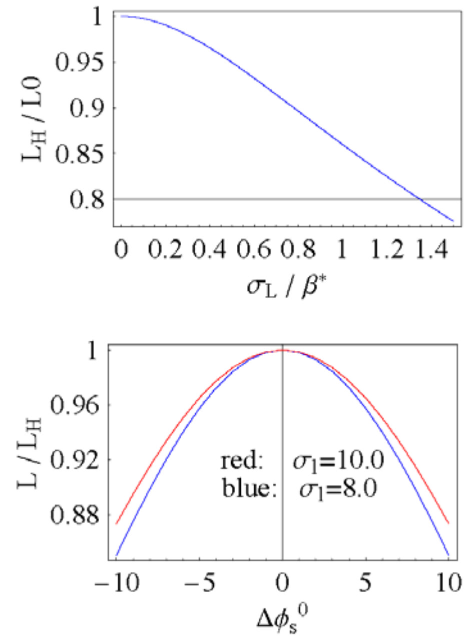

Figure 7: Upper plot: Hour-glass effect due to σ_l variation. Bottom plot: Variation of the luminosity with the phase shift due to gap transient for σ_l =10 mm (red), and σ_l =8 mm (blue). Vertical beta function β=1:0 cm.

The luminosity is normalized by the nominal luminosity of the point-like bunches. It is worth noting that, even if the rf phases of two beams are matched, the variation of the synchronous phase along the train remains and reduces the average luminosity. A special device such as dedicated harmonic cavity is needed to eliminate this adverse effect.

It is worth noting that the synchronous phase variation can be more important at large crossing angles suggested for the Super B factory [7]. The synchronous phase shift along the train can also be responsible for the variation of the tune along the train due to parasitic crossings.

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