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STUDY OF COLLECTIVE EFFECTS IN A LOW-EMITTANCE PEP LATTICE*

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Introduction

A number of high-energy, high-brilliance x-ray synchrotron light sources are being proposed around the world.[1-3] These machines will enter a new frontier in high-power beam x-ray optics and will permit experiments never before possible in x-ray material studies. The possibility of operating time on several high-energy electron-positron colliders could provide the opportunity to develop the beam-line optics and to perform initial experiments that would enhance the initial scientific utilization of these future machines.

In 1986, a new low-emittance tune was developed and tested on the PEP machine.[4] As predicted, the emittance was reduced by a factor of three compared with the standard collider optics, and the installed undulators produced an x-ray beam with the lowest emittance ever achieved in a synchrotron radiation source.

Based on these encouraging results, additional calculations were performed and presented at a workshop[5] on extending the performance of PEP as a synchrotron radiation source. Following this workshop, additional operating time of PEP in the low-emittance mode was made available. During this period, PEP operated at 7.1 GeV with a measured natural emittance of $5.3 \pm 0.8 \times 10^{-9}$ π m-rad (83% of calculated) and a 4% emittance coupling.[6]

This paper summarizes the work on the collective effects studied during the previously described low-emittance operation of PEP and presented in detail in Ref. 7. These studies looked at the single bunch and multi-bunch current limits consistent with stable beam operation. The lower than expected current limits and observed coherent beam oscillations, together with methods of countering them, were considered at a recent SSRL workshop.[8] A result of these studies has been that the lower momentum compaction factor and large beta function variations of the low-emittance lattice (a common feature of all proposed high-energy radiation sources) contribute to enhanced collective effects, limiting the early achievable beam intensity to less than the desired 100 mA. The calculational models, especially because of the uncertainty of the beam impedance models, have limited predictability for these effects and will benefit from continued studies of this kind.

Single Bunch Current Limits

Table I summarizes some of the properties of PEP for the collider tune and the two low-emittance tunes studied. The emittance and the momentum compaction factor are both reduced by about a factor of three in the low-emittance case, and the horizontal tune and beta functions are increased. Previous studies[9] of the single-bunch current limits in the collider lattice were consistent with a high frequency, broadband impedance model having shunt impedances of

$$\frac{Z_{\parallel}}{n} = 2.5\ \Omega \text{ and } Z_{\perp} \approx 0.4 \text{ to } 0.6\ \text{M}\ \Omega/\text{mm}$$

with $f_r = 1$ GHz and $Q = 1$. Based on this model a single bunch current of $I_b \approx 2.5$ mA and a factor of three bunch lengthening was predicted[9] at 8 GeV. During this initial study, bunch length measurements were not available, preventing direct measurements of the longitudinal impedance. Initial measurements showed a bunch current limit (injection rate going to zero) of 1.2 mA at 5 MV RF voltage. This current increased with RF voltage as shown in Fig. 1, and the current limit agreed well with a power law dependence on the synchrotron frequency of $\nu_s^{0.79}$. At the maximum current, the bunch showed clear signs of turbulence, with a large number of synchrotron frequency harmonics in the transverse beam position monitor signal, as well as large coherent motion observed in the synchrotron light monitor.

The coherent motion appeared to be greatest in the horizontal plane, despite the fact that both the horizontal and vertical betatron tune measurements showed a similar current dependence, see Fig. 2(a). Clear evidence of transverse mode coupling (TMC) was not present, since the measured tune shift of the m = 0 mode was less than half the synchrotron tune. Fitting the measured tune shifts to a linear dependence with current yielded slopes of

$$\frac{d\nu_x}{dI_b} = -\ 0.0072 \quad \text{and} \quad \frac{d\nu_x}{dI_b} = -\ 0.0073\ (\text{mA})^{-1}$$

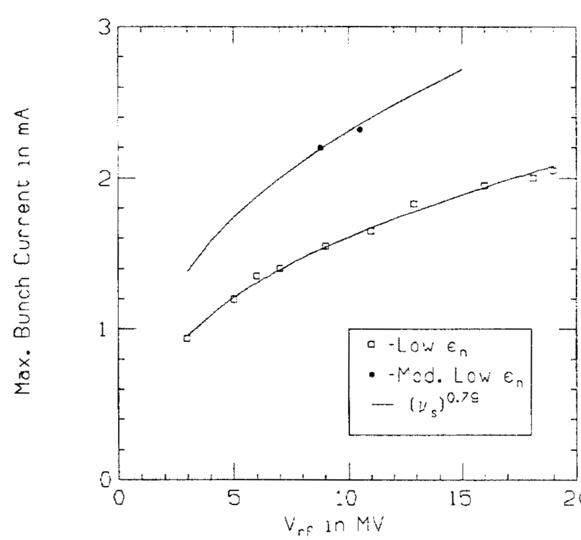

Fig. 1. The maximum single bunch current measured as a function of RF cavity voltage for the low-emittance tune (squares) and the modified low-emittance tune (dots). The curves are the result of a fit to a power law dependence on the synchrotron frequency of $\nu_s^{0.79}$.

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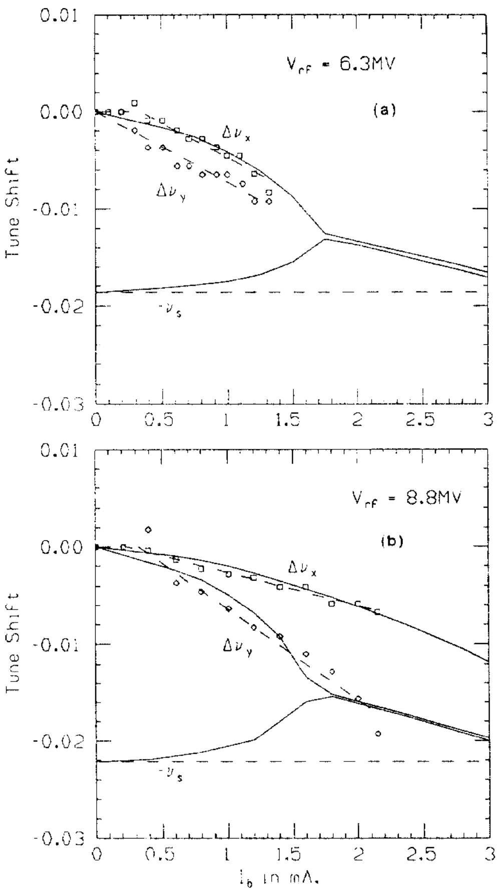

Fig. 2 Horizontal (squares) and vertical (diamonds) coherent tune shift as a function of bunch current for (a) the low-emittance lattice and (b) the modified low-emittance lattice. The dashed lines are the result of a linear fit to the measured data. The solid curves are the calculated tune shifts of the m = 0 and m = -1 modes calculated with BBI/MOSES.

as shown by the dashed lines in Fig. 2(a). Calculation of the expected tune shift, taking into account the longitudinal bunch lengthening with a $Z_{\parallel}/n = 2.5\ \Omega$, was performed using the BBI/MOSES[10] program. This calculation was unable to account for the observed tune shift, without increasing the $Z_{\perp}$ to 1.05 M Ω/m, in the previously defined model. For this case, the calculated TMC current limit is $I_b = 1.6$ mA with a bunch lengthening factor of 2.2 times (not measured). This current limit agreed well with the measured limit of $I_b = 1.4$ mA measured.

In these calculations the tune shift is given by[8]

$$\frac{d\nu}{dI_b} \approx \langle\beta\rangle\ \mathrm{Im}[Z_{\perp}(\mathrm{eff})],$$

where $Z_{\perp}$(eff) is the transverse beam impedance averaged over the bunch current power spectrum. Assuming that the RF cavities have the largest effect on the transverse impedance, the average beta function was taken from that region as in Ref. 8. However, the large change in β_x in the Interaction Regions (IRs) (from collider to low-emittance lattice), where synchrotron radiation masks are installed, could increase their contribution to the effective impedance

Table I. Summary of PEP Lattice Properties for the Different Tunes

Parameter	Collider	Low Emitt.	Modified	Units
Horiz. tune, ν_x	21.28	29.28	29.19	
Vert. tune, ν_y	18.22	13.20	13.15	
Moment. Compact, α_p	2.55	0.97	1.05	x 10^{-3}
Natural emittance, ε_n	27.7	6.4	7.3	nm-rad.
Energy spread, $\sigma_{E/E}$	0.047	0.047	0.047	%
Synchrotron tune, $\nu_s[V_{rf}=8.8$ MV]	0.0358	0.0221	0.0229	
Bunch length, $\sigma_{\ell}[V_{rf}=8.8$ MV]	1.18	0.72	0.75	cm
Beta function, β_x/β_y[IR]	4.5/0.2	79/97	40/97	m
Average Beta, $\langle\beta_x\rangle/\langle\beta_y\rangle$[RF]	34/20	69/24	38/25	m
		Common Properties		
Ring Energy, E_0		7.1		GeV
Synchrotron energy loss, U_0		1.35		MeV/turn
Longitudinal damping time, τ_e		35		ms
Horizontal damping time, τ_x		70		ms
Revolution frequency, f_0		136.3		kHz
RF Voltage range, V_{rf}		2-39		MV
RF harmonic number, h		2592		

of the vacuum chamber. To test this, a modified low-emittance lattice was introduced, which reduced the horizontal beta functions by about a factor of two in the RF cavities and the IRs, to the values listed in Table I.

The modified lattice showed a 42% increase in the maximum bunch current at any given RF voltage, as shown in Fig. 1. The dependence on synchrotron frequency was observed to be similar to that of the original lattice. The betatron tune shift with current, Fig. 2(b), was reduced by a factor of two in the horizontal plane and increased slightly in the vertical plane to:

$$\frac{d\nu_x}{dI_b} = -\ 0.0034\ (\mathrm{mA})^{-1} \quad \text{and} \quad \frac{d\nu_y}{dI_b} = -\ 0.0094\ (\mathrm{mA})^{-1}$$

respectively. The horizontal tune shift calculation using BBI with the horizontal beta function in the RF cavities agrees well with the previous impedance of $Z_{\perp} = 1.05$ M Ω/m. The vertical tune shift shows sufficient change to yield a TMC current limit, since $\Delta\nu_y \approx -\nu_s$ at $I_b \approx 2.2$ mA. The impedance required to fit the vertical tune shift is quite large, as shown in Fig. 2(b), where the result of a BBI/MOSES calculation is presented for $Z_{\perp} = 4.2$ MΩ/m. However, the TMC current limit for this large impedance is about $I_b = 1.8$ mA, somewhat smaller than the 2.2-mA limit observed. Several attempts at improving the fit by varying the resonant frequency were performed. Increasing the resonant frequency to 2 GHz reduces the transverse impedance to about 1.2 MΩ/m, but still the disagreement between slope of the tune shift and the TMC current limit exists. The source of this large vertical impedance is not known, but it may result partly from the significant residual closed orbit distortion and vertical dispersion observed. This resulted from the substantial increase in phase advance between the installed correction magnets, which had difficulty correcting the closed orbit for the low-emittance lattice.

Multiple Bunch Current Limits

The goal of achieving high circulating current (≈100 mA) was studied by attempting to understand the differences between a small number of bunches filled to the maximum current per bunch, compared with many bunches filled to a much lower bunch current. Since PEP allowed filling any one of the 2592 RF buckets, an initial study compared the total current obtained for a pair of bunches filled to the single bunch limit as a function of the time between the bunches. No significant difference was observed in the total current stored at the different bunch spacings, which ranged from adjacent buckets to a maximum interbunch spacing of h/3.

Filling a train of bunches to their maximum bunch current produced clear signs of longitudinal bunch instability. Injection into some buckets was not possible without using the longitudinal damping system, which worked well on six bunches (its designed value) but had little effect beyond that range. However, injecting into RF buckets ahead of the bunch train permitted filling a bunch number that was longitudinally unstable at the tail of the train, due to large wakefields. Filling in this manner achieved a total current of about 20 mA with lifetimes less than one hour. At this current, the bunches showed considerable coherent motion in the longitudinal and transverse directions. This was exhibited by a coherent betatron frequency signal dominated by many harmonics of the synchrotron frequency, rather than by the betatron tune signal. The beam profile, as observed with the synchrotron light monitor, showed considerable motion of the spot, as well as changes in the spot size and orientation.

Since the tune shift and growth rate of normal modes of oscillation of multiple bunches are directly proportional to the single bunch current, several studies of filling the RF buckets to less than the single bunch current limit were performed. The first attempt at filling every other RF bucket to 0.5 mA (1/3 maximum) yielded a total current of 15 mA with little coherent bunch motion and a lifetime of greater than 90 min. Increasing the current further resulted in significant coherent motion in the vertical plane, but very few synchrotron frequency harmonics were observed in the transverse monitors. A second attempt at filling every 20th RF bucket to 0.2 mA/bunch yielded similar total current but with less coherent motion and lifetimes greater than 100 min.

With a total of 24 (5-cell) RF cavities in PEP and only 6 cavities powered (at 7.1 GeV), a study of the impedance effects of the unpowered cavities was performed. Normally the tuners in the unpowered cavities shift the fundamental cavity mode approximately 1/2 of the rotation frequency below the h = 2592 acceleration harmonic. Calculations of the growth rates for longitudinal coupled bunch mode K_b-1 predict a longitudinal instability current limit less than 10 mA.[7] Moving the fundamental mode of half the unpowered cavities by a similar frequency above the h = 2592 RF frequency, a reduction of the K_b-1 mode growth rate by a factor of three is expected.[7] With the fundamental mode of the unpowered cavities arranged in this manner, a total 34-mA current was obtained by filling every 20th RF bucket to 0.5 mA per bunch. The beam appeared quite stable with lifetime in excess of 100 min. An additional study was performed using one pair of powered RF cavities shifted to a frequency of h = 2593, in order to spread the synchrotron tune between bunches and increase the Landau damping. No increase in total current was observed, due to a serious instability by the first normal mode of the coupled bunch oscillation. In the future, damping will be provided by shifting another pair of cavities to the h = 2591 harmonic frequency.

Conclusions

Single bunch current limits were measured for the low-emittance tunes in PEP and found to be limited by the TMC instability to less than 2.5 mA for RF voltages up to 10.5 MV. The horizontal and vertical transverse impedances appear to be

$$Z_x = 1.05\ \mathrm{M\Omega/m} \text{ and } Z_y = 4.2\ \mathrm{M\Omega/m}\ ,$$

respectively, assuming that the average beta functions are equal to those in the RF cavities. At the maximum single bunch currents, considerable coherent motion of the bunch was observed, probably resulting from the large wakefields caused by the residual closed orbit distortions.

The multiple bunch operation showed large longitudinal and transverse coherent oscillations when bunches were filled to the single bunch limit. Total currents in excess of 30 mA were obtained by filling widely spaced bunches to less than 1/3 of the single bunch limit. With this method the coherent beam motion was quite small in all dimensions.

Future studies are in the planning stage. These studies will include: improve closed orbit corrections, bunch length measurements, single bunch turbulence measurements, reduction of RF cavity impedances, and possibly coupled bunch feedback systems.

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