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ION EFFECTS IN THE SLC ELECTRON DAMPING RING *

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Abstract

We report on the ion-related beam behavior in the electron damping ring during unusually poor vacuum conditions in the weeks that followed a catastrophic kicker chamber failure that contaminated the ring vacuum system. The vacuum gradually improved over several months of beam operation, during which time the vertical emittance remained blown up by a factor of 2. The emittance blowup was accompanied by a transverse instability that produced jitter in the extracted beam size. Both the characteristic spectrum of self-excited betatron sidebands and the emittance blowup exhibited a threshold behavior with beam current and vacuum pressure. This behavior depended strongly on the betatron tune and it was found that the ion effects could be minimized by operating just below the 1/2 integer resonance.

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Abstract

We report on the ion-related beam behavior in the electron damping ring during unusually poor vacuum conditions in the weeks that followed a catastrophic kicker chamber failure that contaminated the ring vacuum system. The vacuum gradually improved over several months of beam operation, during which time the vertical emittance remained blown up by a factor of 2. The emittance blowup was accompanied by a transverse instability that produced jitter in the extracted beam size. Both the characteristic spectrum of self-excited betatron sidebands and the emittance blowup exhibited a threshold behavior with beam current and vacuum pressure. This behavior depended strongly on the betatron tune and it was found that the ion effects could be minimized by operating just below the 1/2 integer resonance.

1 INTRODUCTION

The SLC damping rings damp 1.19 GeV beams of either electrons or positrons at a 120 Hz repetition rate with transverse damping times of approximately 3.5 ms. Under normal operating conditions the extracted beams have a $3 \cdot 10^{-5}$ m normalized horizontal emittance by $0.2 \cdot 10^{-5}$ m normalized vertical emittance. The high-voltage kicker magnets for injection and extraction of the beam use ceramic vacuum chambers to allow for fast, pulsed operation. In the electron ring one such ceramic chamber fractured as a result of arcing around the chamber and combustion products from magnet insulation were drawn into the vacuum system as it vented to atmosphere.

In order to proceed with the SLC operation as quickly as possible no general cleaning of the vacuum system was done, apart from replacing vacuum chambers in the proximity of the failed magnet. To aid in the lengthy beam processing of the vacuum system that followed, several additional pumps were added to the system, bearing in mind that the ring was already closely packed with components.

Even after the ring vacuum reached acceptable pressure to operate at full current and at the full repetition rate, it was found that the emittance had increased considerably, especially in the vertical plane and that the extracted beam size fluctuated wildly from pulse to pulse. The exact nature of the beam degradation depended on an interrelation between such factors as beam intensity, number of bunches, tune and coupling parameters, duty cycle and recovery from trips in the machine protection interlocks.

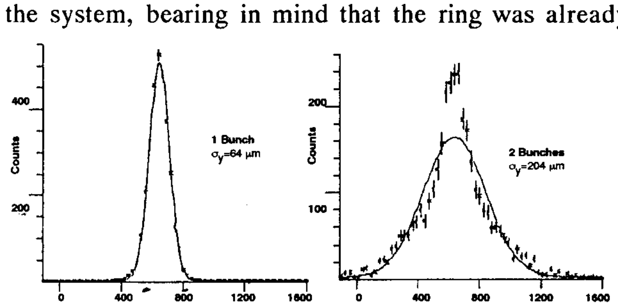

Figure 1: Extracted beam profiles measured with a vertical wire scanner for 1 bunch (left) and 2 bunch operation (right).

2 EMITTANCE AND BEAM LIFETIME

The extracted beam can be profiled on a wire scanner and figure 1 shows the vertical beam profiles in the cases of one and two bunches in the ring. The intensity per bunch is $3.5 \cdot 10^{10}$ electrons in each case but the vertical beam size increases from 60 μm for one bunch to 200 μm and very non-Gaussian for two bunches. This is to be compared to the 40 μm beam sizes that were obtained under good vacuum conditions, independent of the number of bunches.

The poor vacuum also reduced the beam lifetime to around 150 s, and had some dependency on the total beam current, but not on the number of bunches.

The ion densities that are reached in the ring can be calculated from an ionization rate

$$\dot{\lambda}_{ion} \approx 4 \times 10^{11} \mathrm{m}^{-1} \mathrm{s}^{-1} \frac{p}{100\mathrm{nTorr}} \qquad (1)$$

taking carbon monoxide as a typical species with a 2 mbarn cross section. If full neutralization were to occur a line density of $\lambda_{neut} \approx 1.6 \cdot 10^{9}$ m^{-1} would be achieved after about 6 ms store time at a pressure $p = 10^{-7}$ Torr. However, doubly ionized ions, whose production cross section is about the same as for singly ionized, are lost from the beam so the

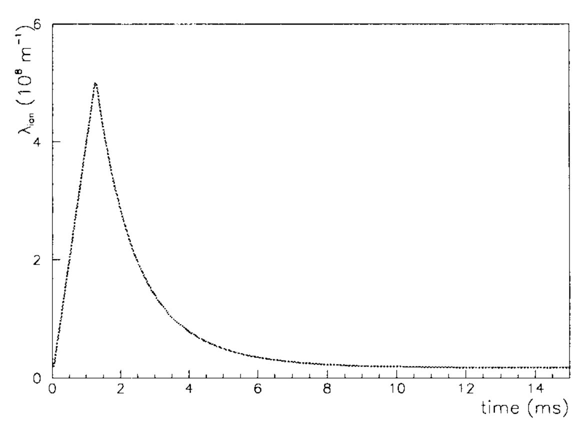

Figure 2: Predicted ion line density, increasing linearly with time then decreasing with the beam size.

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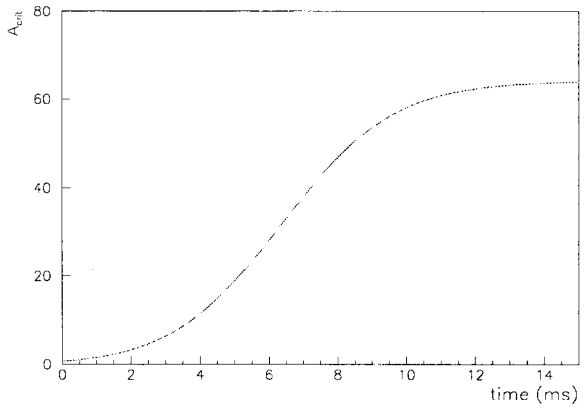

Figure 3: The critical ion mass (a.m.u.) above which ions can be trapped, increases during the store as the beam size shrinks.

equilibrium ion density will not exceed the neutral gas density [1]. The resulting line density depends on the shrinking beam size during the store, as seen in fig. 2.

The critical mass above which an ion is trapped

$$A_{crit} = \frac{N_{tot} C r_p Q}{n_b^2 2\sigma_y(\sigma_x + \sigma_y)} \tag{2}$$

also depends on horizontal and vertical beam sizes σ_x and σ_y, and in fig. 3 it is seen that the lighter ions can only become trapped immediately after injection. Here we have a total number of electrons, N_{tot}=8•10^{10}, the number of bunches, n_b=2, ring circumference C=35 m, ion charge Q (in units of e) and classical proton radius r_p. The calculated beam size assumes an injected emittance $\gamma\varepsilon_{x0}=\gamma\varepsilon_{y0}\approx 20\cdot10^{-5}$ m and energy spread $\delta\approx0.01$ and final emittances of $\gamma\varepsilon_x\approx3\cdot10^{-5}$ m and $\gamma\varepsilon_y\approx0.2\cdot10^{-5}$ m and $\delta\approx7\cdot10^{-4}$. Also assumed are $\beta_x\approx0.7$ m and $\beta_y\approx2.5$ m, $\eta_x\approx0.1$ m, $\tau_{x,y}\approx3.1$ ms $\tau_\delta\approx1.5$ ms.

The ions can reduce the beam lifetime through either bremsstrahlung or single-Coulomb scattering [2]. A combination of these at an ion density of 2•10^8 m^{-1} is consistent with the observed beam lifetime.

3 TRANSVERSE INSTABILITIES

Ion scattering alone does not account for the large discrepancy in beam sizes between one and two bunch operation. Evidence for a transverse instability causing pulse-to-pulse fluctuations in beam size is also seen in the form of self-excited betatron tune lines in the bunch spectrum, shown in fig. 4. When the beam is stored by disabling the extraction kicker, strong betatron sidebands can be seen around the 8.5 MHz revolution harmonics, even up to 200 MHz. The side-bands correspond to the vertical tune, with some lower amplitude activity also evident at the horizontal tune frequency. The instability can persist for over a minute as the beam intensity decays. On the shorter time

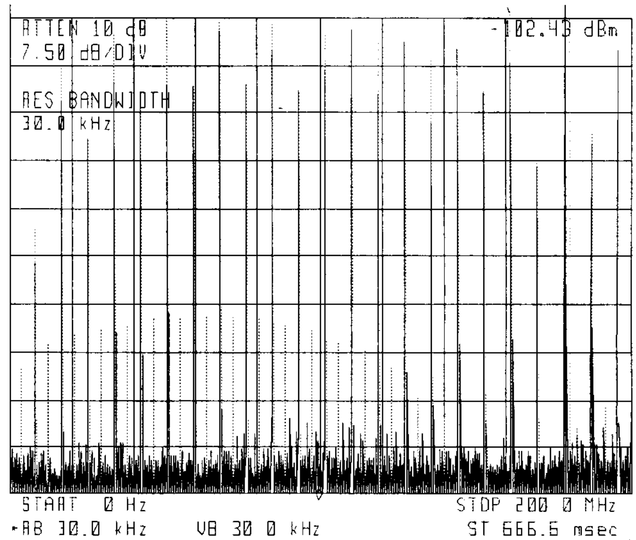

Figure 4: Bunch spectrum when 2 bunches of 4•10^{10} electrons each are stored, showing a large number of self excited vertical betatron sidebands.

scale between injection and extraction during normal ring operation the fluctuations in extracted beam size can be linked to rapid variations in the amplitude of the vertical betatron sidebands. In fig. 5 the spectrum analyzer is tuned to one such sideband frequency and the frequency span put to zero so that the sweep detects amplitude changes over a 20 ms interval, triggered at injection. After some milliseconds of damping the amplitude of the betatron motion increases with a sub-millisecond growth time until some self-limiting amplitude is reached and the beam damps once more. This process repeats itself irregularly several times during the store.

It seems reasonable to conclude that ions are captured when the beam is large at injection and remain trapped as the beam shrinks. Even though the critical mass threshold is passed as the beam shrinks, preventing further trapping of ions, the ions, once trapped, can remain in the beam potential.

The horizontal and vertical frequency at which the ions oscillate in the beam potential is given by

$$f_{x,y} = \frac{c}{2\pi}\left(\frac{N_{tot} 2 r_p \nu}{C\sigma_{x,y}\left(\sigma_x + \sigma_y\right)A}\right)^{1/2} \tag{3}$$

and is shown in fig. 6 as a function of time as the beam size decreases, for two different ion masses, A (in a.m.u.). The ion frequencies are below 30 MHz and consequently too low to account for the observed sideband frequencies in the bunch spectrum. The spectral lines observed at 100 MHz frequencies can only be due to transverse dipole modes of the bunch.

4 TUNE RELATED BEHAVIOR

The additional focusing force from the ion cloud produces an upward tune shift, $\Delta\nu$, in both the horizontal, x, and vertical, y, planes, given by

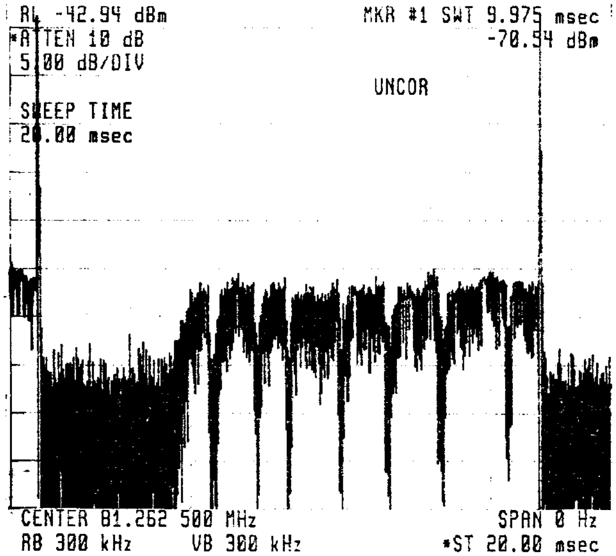

Figure 5: Time dependence of the amplitude of the vertical sideband at $10f_0-\nu_y$, over a period of 20 ms starting at injection (left hand peak).

$$\Delta\nu_{x,y} = \frac{r_p \beta_{x,y} \lambda_{ion} C Q}{\gamma 2\pi\sigma_{x,y}\left(\sigma_x + \sigma_y\right)} \tag{4}$$

assuming the ion distribution is Gaussian with the same transverse dimensions as the beam. At ion densities equal to the residual gas density the expected tune shifts are $\Delta\nu_x \approx 0.007$ and $\Delta\nu_y \approx 0.05$. If ion densities closer to full neutralization are assumed in order to be consistent with the observed beam lifetime, the expected tune shifts become quite large at 0.07 and 0.5 in x and y respectively.

Several techniques have been employed to measure the tunes and tune shifts. The self-excited betatron lines can be observed with a gated, digital-signal-processing spectrum analyzer (Tektronix 3052) over short time intervals between injection and extraction. For long store times a conventional sweep spectrum analyzer (HP 70000) was also used to measure tunes as the intensity gradually decayed. The transverse betatron modes can also be excited by a broadband rf kicker while the driving frequency is swept through the resonance. Using this technique single bunch vertical tune shifts of 0.022 have been observed with $4 \cdot 10^{10}$ electrons. A technique of using gated white noise centered around the tune frequency while observing on the gated spectrum analyzer have also been tried [3]. After the first few milliseconds of store time, when the ion density is highest according to fig. 2, the driven tune response is difficult to detect. This maybe due to the very large tune spread that accompanies the tune shift, making coherent motion of the bunch difficult to resolve.

A particularly interesting behavior of the tunes was seen when two bunches were stored and allowed to decay over several minutes. The vertical tune had been set close to the 1/2 integer at 3.44 because of the evidence for clearing of the ions from the beam at this working point. After the intensity had decayed by approximately a half from the initial $4 \cdot 10^{10}$ electrons, the vertical tune made a spontaneous upward jump of 0.022. The event history could be recalled on the waterfall display of the Tektronix 3052 spectrum analyzer, where one sees the tune line at the beginning of the store as both large in amplitude and with a small frequency spread. After the tune jump the amplitude decreases and the tune spread increases to about .002.

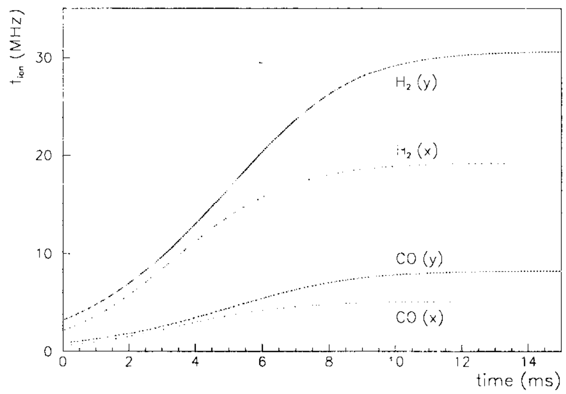

Figure 6: Expected oscillation frequencies for two different ion species as a function of store time during which the beam shrinks.

The tune jump is probably the result of a sudden change in the ion population, but it only occurs at vertical tunes just below the 1/2 integer and not at tunes just above the 1/2 integer. Coherent instabilities due to the interaction of an ion cloud and a coasting beam have been analyzed [4] and resonant clearing effects discussed in terms of changing ion frequencies at different beam size locations. In our case a clearing mechanism may be at work through transverse shaking which is discussed in terms of coupled bunch modes in a companion paper at this conference[5]. Since making this observation of clearing the ions the vertical tune has been routinely kept close to the 1/2 integer to minimize emittance growth due to ions.

5 ACKNOWLEDGMENTS

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