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Recent Experiments on the Fast Beam-Ion Instability and a Study of Potential Cures at ALS and PEP-II[*]

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RECENT EXPERIMENTS ON THE FAST BEAM-ION INSTABILITY AND A STUDY OF POTENTIAL CURES AT THE ALS AND PEP-II*

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ABSTRACT

We report our latest experiments on the fast beam–ion instability (FBII) 1, 2) at the Advanced Light Source (ALS). In October 1997, we studied the pressure dependence of the instability, and tested the effectiveness of two proposed cures: a large chromaticity and additional gaps in the bunch train. We also describe a very preliminary observation of increased rms motion along the PEP-II electron bunch train, which is tentatively attributed to the FBII.

1 Introduction

With the advent of the next generation of electron-positron factories, linear colliders and light sources, all operating with many bunches and small emittances, novel types of instabilities may become important. One such instability is the fast beam-ion instability (FBII) 1, 2). This is a transient ion instability driven by single-turn ions, which are cleared by a gap at the end of the train. Theories describing this instability have been presented elsewhere 1, 2, 4, 5, 6). An overview including rise-time predictions for many existing and proposed accelerators was given in Ref. 7).

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Table 1 compares relevant machine parameters and predicted exponential FBII rise times at the end of the bunch train, for a typical ALS experiment and for the PEP-II High Energy Ring (HER). The estimated rise times take into account the effect of ion decoherence and the variation of the lattice functions around the ring. In order to create experimental conditions where the fast beam-ion instability should definitely occur, we raised the vacuum pressure in the Advanced Light Source from the normal operating pressure of 0.3 nTorr to about 80 nTorr. At this pressure, the predicted rise time exceeded the damping time of the transverse coupled-bunch feedback (TFB) 8) by a significant factor. The vacuum system was vented with helium gas, since, for helium, the expected rms emittance growth due to beam-gas scattering is small (a few percent at 100 nTorr).

Comparing the estimates for the ALS experiment with those for the PEP-II design parameters suggests that the instability rise times should be very similar. The large error in the rise-time predictions reflects a theoretical uncertainty as to how precisely the variation of the beta functions should be treated. For a typical light-source optics, *e.g.*, a Chasman-Green cell, the larger number for τ_e may hold, while for a FODO cell, such as for the PEP-II design optics, the smaller number will give a better estimate. It is, of course, always possible to intentionally introduce a beta beating, thus detuning and slowing down the instability. Indeed, for chromatic correction purposes the PEP-II design optics already includes a large beta beat in 2 of the 6 arcs.

Table 1: *Parameters and predicted oscillation growth rates for the ALS machine experiment compared with those for the design values of the PEP-II High-Energy Ring;* ‡*for helium atoms;* **assuming carbon-monoxide or nitrogen molecules.*

parameter	symbol	ALS experiment	PEP-II HER
norm. emittance	$\gamma\epsilon^N_{x,y}$ [μm]	12, 0.4	500, 25
no. of bunches	n_b	1–320 (240)	1658
bunch population	N_b [10^{10}]	0.5	3
av. beta function	$\beta_{x,y}$ [m]	2.5, 4	25, 20
rms beam size	$\sigma_{x,y}$ [μm]	200, 20	1250, 200
bunch spacing	L_{sep} [m]	0.6	1.2
beam energy	E [GeV]	1.5	9
pressure	p [nTorr]	$80^{\ddagger}$	5^{*}
pred. rise time	τ_e [μs]	28–280	74–740

2 Recent Experiments

Our main diagnostic is an image of the transverse beam profile at one location of the storage ring using light from synchrotron radiation 9). The transmitted soft

X-rays are converted to visible light by a scintillator and then focused onto a CCD camera. Unfortunately the response time of the scintillator is long—300 ns, about half the revolution period—, so that it does not allow beam-size measurements of individual bunches within the bunch train.

We thus studied the onset of the instability by recording the projected beam size over the entire train as the length of the bunch train was slowly increased by injecting additional bunches. Shown in the left part of Figure 1 is the result of an earlier study 3, 7), where the RMS vertical beam size is plotted as a function of the number of bunches continuing up to a total of 45 bunches. Also shown are the corresponding vertical beam sizes at nominal pressure. With helium gas added, the beam size increased significantly as the train length exceeded 8 bunches. Serendipitously, for a train length of 8 bunches the theoretically predicted rise time is roughly equal to the feedback damping time of about 1 ms 7)!

The right part of Fig. 1 shows the same type of measurement performed at three different helium pressures. In this recent study, the transverse feedback (TFB) was turned off, for two reasons: first, conventional HOM induced instabilities are not important for short bunch trains, and, second, the feedback was suspected to drive the FBII by introducing a noise excitation. In accordance with our expectation, at the higher pressure the beam-size blow up was more pronounced and already visible for shorter trains. Indeed, during the pump-down from 6 nTorr to the nominal pressure (0.3 nTorr) we were able to watch, over a few minutes, how the vertical beam size of the 180-bunch train decreased and the beam finally fully stabilized at an intermediate pressure of about 0.5–1 nTorr.

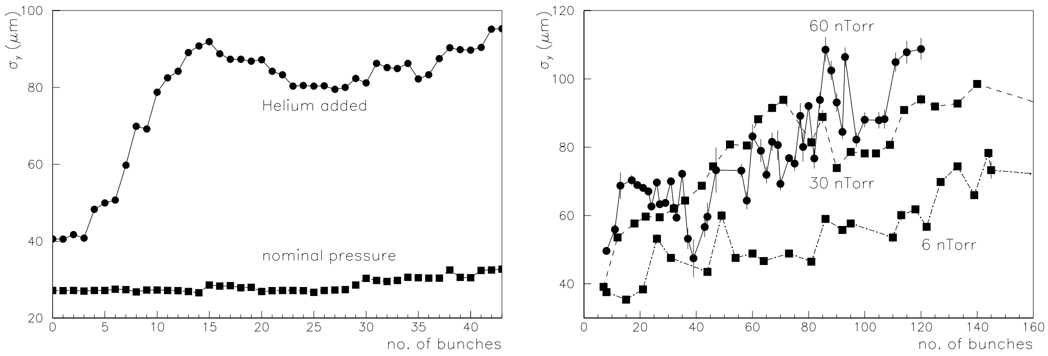

Figure 1: *RMS vertical beam size versus the number of bunches at a current of 0.5 mA/bunch: (left) for nominal and elevated pressure conditions, TFB on; (right) for three different values of the average helium pressure, TFB off.*

We have also studied two proposed cures for the FBII. The left picture of Fig. 2 shows the reduction of the beam-size blow up by a strong increase of

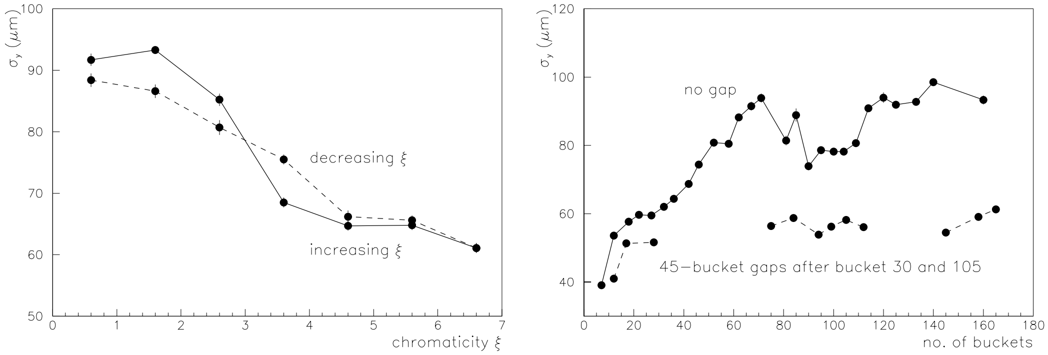

Figure 2: *RMS vertical beam size: (left) versus the vertical chromaticity ξ_y (the horizontal chromaticity $\xi_x \approx 1.5$ was held constant, the helium pressure was about 30 nTorr, and the total current of the 160-bunch train was 75 mA); (right) versus the number of bunches, or buckets, in the train with and without two additional gaps of 45 empty buckets each; the helium pressure during this measurement was about 30 nTorr, and the current about 0.5 mA/bunch.*

the ring chromaticity, which was varied by changing the strength of two sextupole families. The suppression of the instability by a large chromaticity was effected either by the increased head-tail damping and/or by the enhanced Landau damping. This experimental result might explain why the ESRF, which reportedly operates with a high positive chromaticity, does not observe the FBII. Unfortunately, a large chromaticity will not always be a practical cure. For example, at chromaticities above 5 in our study, the beam lifetime dropped to a few minutes (the normal lifetime is several hours).

A second possible cure is the introduction of gaps in the bunch train in order to clear the ions. Simulations suggested that this is effective for large gaps 10). Additional gaps have, therefore, been proposed as a fall-back option for the PEP-II HER. The right picture of Fig. 2 clearly demonstrates the beneficial effect of two additional gaps in the ALS bunch train. The gaps were introduced after bucket 30 and after bucket 105. The gap length of 45 empty buckets was slightly larger than an ion-oscillation wavelength.

Lastly, we report a study conducted at the PEP-II HER on October 12, 1997 11). A 700-bunch train was stored with 4.2-ns bunch spacing and a total current of 125 mA. The TFB was turned on, though not fully optimized. For an estimated average pressure of 5 nTorr, the predicted FBII e-folding rise time at the end of the train was about 500 μs, and, thus, significantly shorter than the TFB damping time, which, at this current, was estimated as several ms.

Figure 3 compares two measurements of the rms orbit motion along the

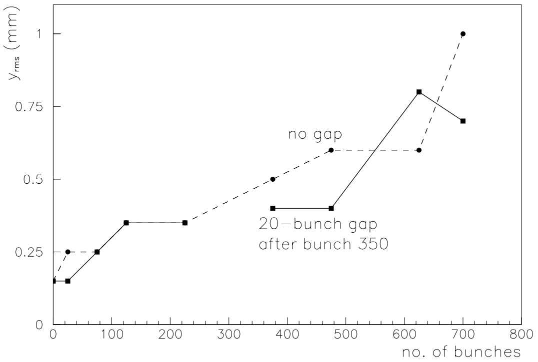

Figure 3: *RMS vertical beam motion over 1 s in the PEP-II High Energy Ring, for a 700-bunch train with and without an additional very short gap at the center of the train. Each measurement is an average over ∼10 bunches. During this study the average pressure in the ring was close to the design value of 5 nTorr and the transverse feedback system was active, though not fully optimized.*

700-bunch train with and without a short gap of 20 empty bunch places introduced after the 350th bunch. The orbit motion behind the gap appears to be somewhat smaller than in the case without gap. The gap in this experiment was short and corresponded to only about 20% of an ion oscillation wavelength. Thus, only a rather small fraction of the ions could have been lost in this gap. At this point, it is pure speculation whether this observation is related to the FBII. Unless a pressure dependence can be demonstrated in a repeated experiment, we cannot exclude that this effect was caused by conventional wakefields and not by the FBII. However, under the conditions of this experiment the FBII was expected to occur, whereas conventional instabilities were not.

3 Summary of Other Studies and Conclusions

In the ALS, the FBII is not observed at the nominal pressure. A vertical blow up was observed when 6–100 nTorr helium gas was added in a regime where multi-turn ion trapping is not expected; the tail of the bunch was driven more strongly than the head. The instability threshold (as a function of bunch no.) measured with feedback turned on occurred very close to the predicted value. We also observed betatron sidebands at frequencies consistent with the calculated ion frequencies; they scaled with current and vertical spot size (increased by approaching the coupling resonance) as expected. The growth saturated at 2–4 σ. The reported measurements of growth along the train for different pressures clearly demonstrated a pressure-dependence of the blow up, which was further confirmed by an observed spontaneous stabilization of a 180-bunch train during pump down. We have shown that a large chromaticity can reduce the vertical blow up, and that gaps in the bunch train with a length comparable to the ion wavelength are a very efficient cure for the FBII. We also reported preliminary and speculative evidence for the FBII at the PEP-II HER.

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