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Collective Effects Associated with Ultra-High Beam Intensities in Factories

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COLLECTIVE EFFECTS ASSOCIATED WITH ULTRA-HIGH BEAM INTENSITIES IN FACTORIES

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Abstract

The beam currents at the new e^+e^- factories exceed those of conventional colliders by more than an order of magnitude. To achieve high luminosities the multi-bunch, high-current beams must be both longitudinally and transversely stable. Commissioning of the e^+e^- factories has provided a wealth of new experimental data on beam stability in the regime of extremely high beam intensities. Many high-current effects have been studied including ion and dust trapping, issues relating to heavy beam loading, and positron beam emittance dilutions due to electron cloud instabilities arising from photoelectrons and/or multipacting inside the vacuum chamber. This paper will review the new experimental data on high intensity issues with emphasis on new effects.

1 INTRODUCTION

The interaction of high current, charged particle beams with the local environment, whether it be with the immediately surrounding vacuum chamber or with foreign particles contained within the chamber, was of foremost concern while designing modern e^+e^- factories. Impedance budgets were developed on the basis of both single and multiparticle beam stability and the beam environment was carefully designed to minimize the impedance. In addition, technological advances including heavily damped cavities, higher-order-mode compensation, and bunch-by-bunch feedback systems have also been designed, tested, and successfully commissioned. For the most part, experimental data has proven consistent with expectation yet new effects have also arisen [1]-[4]. Here after briefly discussing conventional beam stability issues, recent experimental observations relating to high beam currents in the factories will be presented.

2 CONVENTIONAL BEAM STABILITY ISSUES

Ion trapping has been observed in many electron accelerators (see for example [5]-[8]). As opposed to the fast ion instability, which is a single-pass effect (see section 3), the conventional ion instability pertains to ions which accumulate over multiple beam passages and interact with the electron beam. An example is shown in Fig. 1 which shows time-dependent pulsations of the vertical beam size measured with a photodiode array detecting synchrotron radiation [5]. Gaps in the bunch fill pattern allow ions to escape as they become overfocussed. Therefore 5-10% gaps in the fill patterns are used at high current factories.

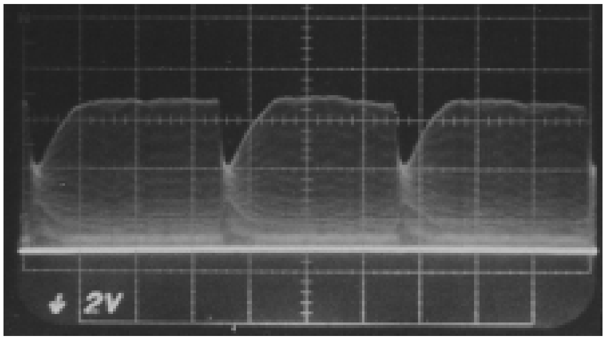

Figure 1: Vertical beam size versus time showing emittance blowup caused by ion trapping in the KEK photon factory (courtesy S. Sakanaka).

Such ion clearing gaps, however, introduce a synchronous phase change along the bunch train which becomes larger the larger the total beam current. At PEP-II for example the synchronous phase may vary by as much as 15° along each beam at high beam currents. The phase variation of the two beams must be well matched to ensure high luminosities. With 1.1 A positrons and 0.7 A electrons, the phase difference between the PEP-II beams is routinely less than 3° or equivalently 5 mm which corresponds to a 10-15% beam size increase at the shifted interaction point due to the clearing gap.

Coupled-bunch instabilities in e^+/e^- factories were of major concern as the growth rate of coupled-bunch modes scales with total beam current. Longitudinally, new innovations such as damped cavities and very broadband bunch-by-bunch feedback were developed. Another design consideration entailed the possibility that the fundamental accelerating mode itself could drive coupled-bunch instabilities due to the strong detuning required for high current beam loading compensation. At KEKB beam stability is achieved using both superconducting rf cavities and energy storage cavities coupled to normal conducting cavities [9]. At PEP-II multiple feedback loops [10] are used (see Fig. 2). Bunch-by-bunch feedback, which by itself has insufficient power to combat the large growth rates of those modes supported by the cavity bandwidth, is used together with a so-called woofer link to feed back on the klystron phase. These efforts have been very successful as evidenced by longitudinal beam stability at currents of up to 1.7 A at PEP-II and about 1 A at KEKB. In particular there is no evidence of longitudinal coupled-bunch instabilities driven by the accelerating mode of the rf cavities.

Transverse impedances were also carefully minimized by a tight impedance design budget. With the exception

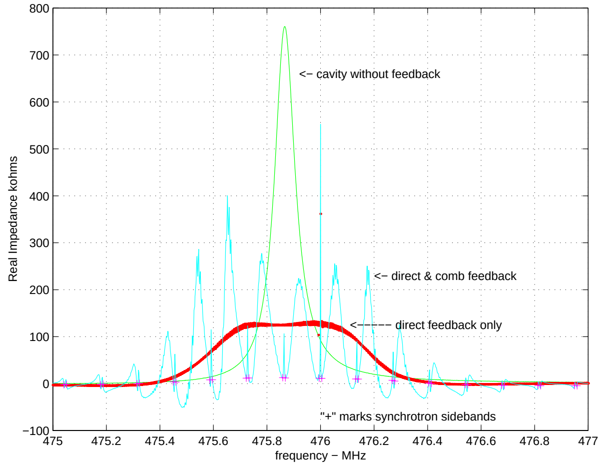

Figure 2: Measured cavity impedance at PEPII with no feedback, direct rf feedback, and comb feedback (courtesy P. Corredoura).

of a few narrowband impedances suspected to arise from bellows in the interaction regions, transverse beam stability has proven to be consistent with expectation and controllable using the bunch-by-bunch feedback systems. Interestingly, the large beam-beam tune shifts resulting from the high single-bunch beam currents are very useful in enabling additional damping of the beams when in collision. An example from ref. [11] is shown in Fig. 3.

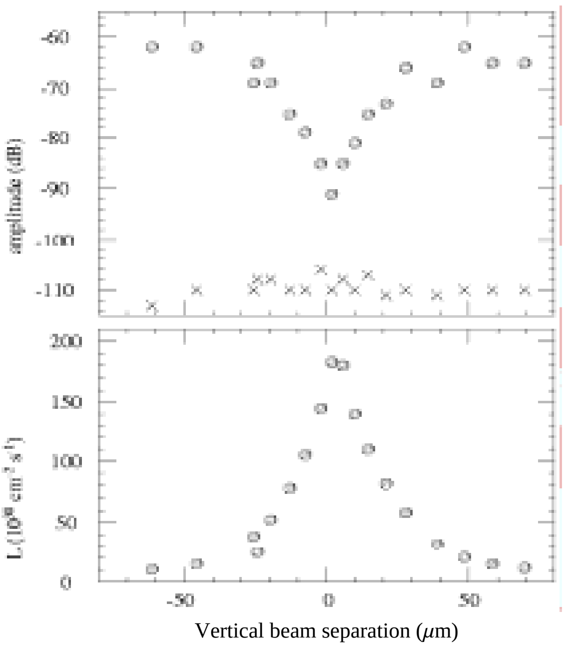

Figure 3: Landau damping of coupled-bunch instabilities by the beam-beam interaction at PEP-II. Plotted are the mode-0 betatron amplitudes (top) in x (crosses) and y (circles) and the luminosity (bottom) as a function of vertical beam separation at the interaction point.

The trapping of dust in electron rings had been observed previously [12]-[14] and newly at KEKB, during initial commissioning, and in PEP-II. At PEP-II the cause is suspected to be the emission of small positively charged particles from the NEG pumps [15]. The majority of the dust events appears to be thermally unstable, as predicted [16] in that the rate of energy deposition by the beam exceeds the rate of heat radiation. Fortunately, there is an apparent gradual decrease in the event rate with time [17].

3 FAST BEAM-ION INSTABILITY

The fast beam-ion instability, predicted in 1995 [18]-[19], has been confirmed and studied in numerous recent experiments [20]-[24]. As contrasted with the conventional ion instability which is avoided with gaps, the fast-ion instability is a single-pass phenomenon in which the electrons interact resonantly with the ions whose density increases along the bunch train. Initial studies, shown in Fig. 4 from the ALS [20]-[21], showed a 10-fold increase in projected vertical emittance when Helium was added. These data taken together with the measured excitation frequencies, the broad spectrum of betatron tune lines, and the observed increase in beam size along the bunch train were in good agreement with expectation thus validating the proposition of resonant interactions of the beam with ions along the bunch train.

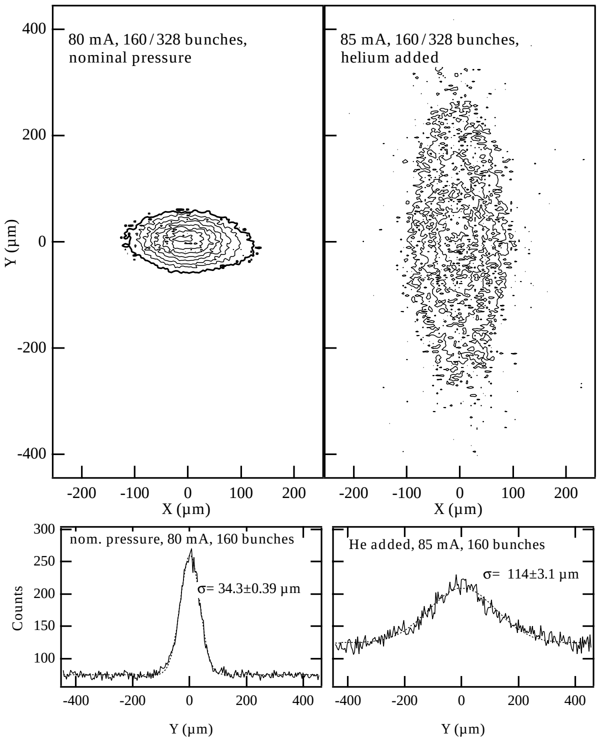

Figure 4: Transverse profiles (top) measured by imaging the beam using synchrotron radiation and their vertical projections (bottom) under nominal conditions (left) and with an intentional pressure increase (right) at the ALS.

Measurements from ensuing studies at the PLS are shown in Fig. 5 from ref. [23] which shows the vertical beam motion across the bunch train measured every four turns using a streak camera. As the pressure was increased a coherent beam-ion oscillation was observed as the ion density increased along the train. Separate measurements made with both a spectrum analyzer and single-pass beam position monitors under the conditions of Fig. 5, top right, confirmed that the wavelength of oscillation seen in the electron beam was equal to that of the ions [23].

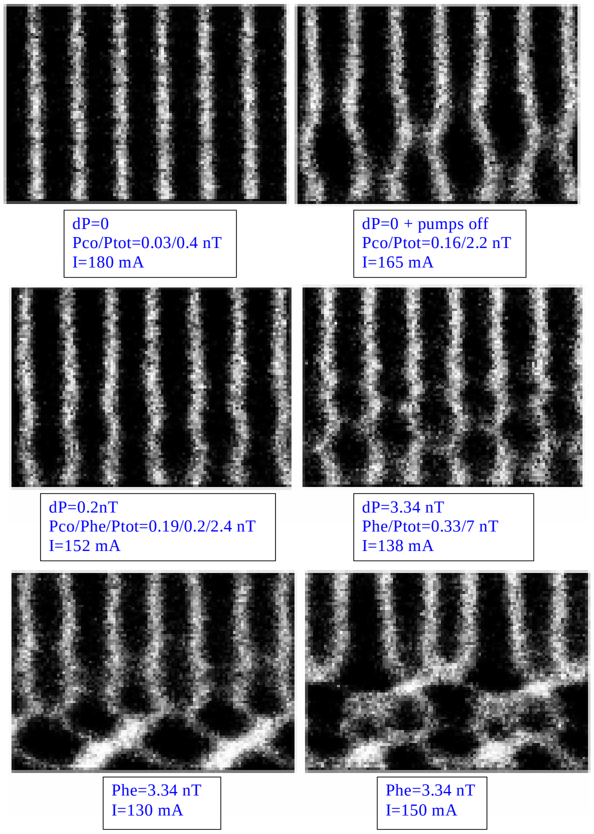

Figure 5: Streak camera data showing vertical motion along the bunch train under various conditions at the PLS. The head of the train is at the top of each subfigure. Successive traces (left to right) are spaced by 25μs or 4 turns (courtesy M. Kwon).

Evidence of fast-ion effects have also been observed in the electron ring at KEKB, as shown in Fig. 6 from ref. [25], and at PEP-II during initial operations under possibly poor vacuum conditions. Any persisting transverse motion of the electron beams has to date been successfully suppressed with bunch-by-bunch feedback.

4 ELECTRON CLOUDS

Electrons attracted by the potential of the positron beam may cause significant emittance dilutions. Electrons can be produced by beam-gas scattering, multipacting, or by the photoelectric effect induced by synchrotron radiation.

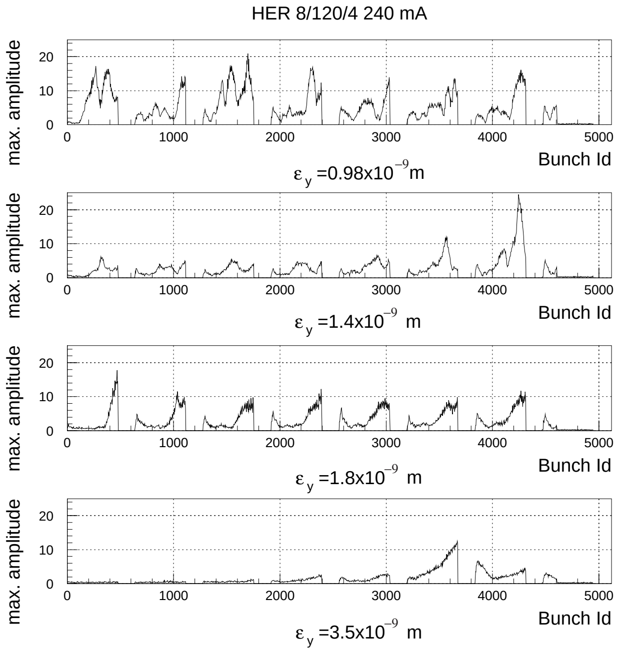

Figure 6: Oscillation amplitude along the electron beam fill pattern consisting of 8 bunch trains for different equilibrium beam emittances at KEKB (courtesy H. Fukuma).

The first direct observation of beam-photoelectron interactions was made in the KEK photon factory [26]. Notable findings included a low positron current threshold, spectra that were considerably wider than those obtained in the same accelerator but with electron beams, a dependence on the fill pattern, and an accompanying vertical emittance growth. Electron cloud effects, initially proposed by Ohmi [27] to explain these data, have been studied in detail both experimentally [28]-[30] and theoretically [31]-[36]. At KEKB vertical positron beam blowup seems to limit the achievable luminosity to date. As shown in Fig. 7 from ref. [28], the instability threshold is seen to depend on the charge density. The main source of electrons in the KEKB positron ring is believed to be photoelectrons and commensurate measures have been tried to suppress them. Application of C-Yoke magnets proved very effective for large bunch spacings however became less effective as the bunch spacing was decreased [28].

The beam size blowup is substantially reduced at KEKB by increasing the vertical chromaticity as shown in Fig. 8 from ref. [28]. It has been postulated that the observed beam size increase is a single-bunch effect driven by the presence of multiple bunches (which generate the cloud) [35]. This measurement and an accompanying measurement, in which the beam size of a test particle placed behind the bunch train depended on its own bunch current, seem to support the single-bunch instability hypothesis.

Electron cloud effects are also observed in the PEPII positron ring. Shown in Fig. 9 is the measured single-bunch luminosity as a function of single-bunch positron current (which was proportional to the single-bunch elec-

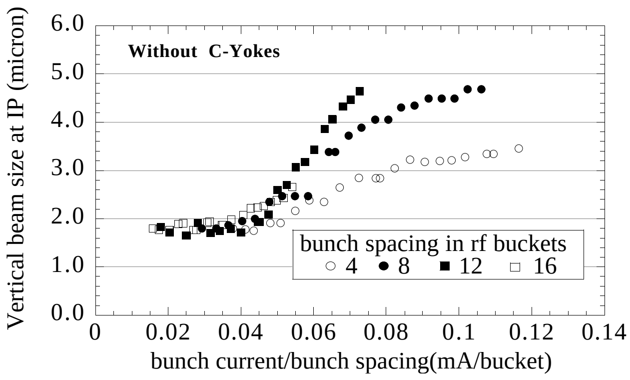

Figure 7: Interferometric measurement of the vertical beam size versus linear charge density for various bunch spacings at KEKB (courtesy H. Fukuma).

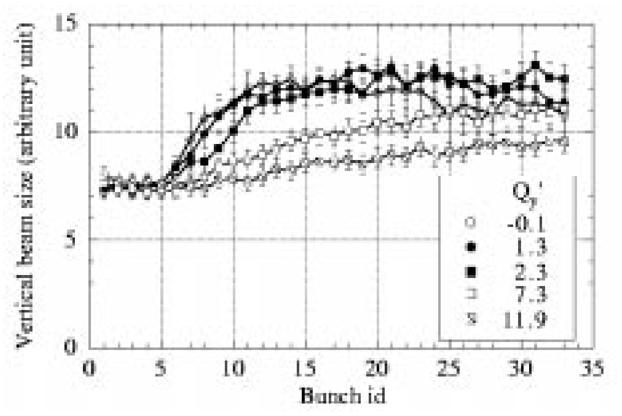

Figure 8: Vertical beam size along the bunch train measured using a fast-gated camera for various vertical chromaticities at KEKB (courtesy H. Fukuma).

tron current) for two different bunch spacings. With higher bunch numbers (i.e. smaller bunch spacings), the single-bunch luminosity did not continue to increase. This, together with measurements indicating the absence of coherent dipole oscillations, led to the conclusion of blowup of the particle beams. Interestingly, these data also showed that the beam-beam limit had not yet been reached even at single-bunch luminosities far exceeding the design value of 1.8×10^{30} cm^{-2}s^{-1}mA^{-2}.

A likely source of electrons in PEP-II is multipacting electrons [15], [37] generated in the straight sections. The measured pressure versus total beam current is shown in the arc and straight sections regions in Fig. 10. The different curves correspond to different bunch spacings as indicated. The pressure is observed to increase nonlinearly above a certain current. The case $\tau = 3\tau_d$ is not understood. To suppress these electrons, solenoidal windings continue to be added around the straight sections. As shown in the second column of Fig. 10, the current dependence of the pressure, measured under identical conditions, was significantly reduced with a single few-meter solenoid.

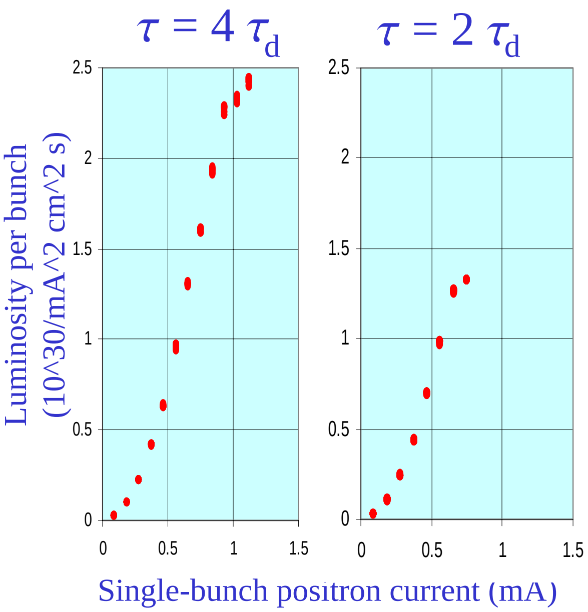

Figure 9: Single-bunch luminosity versus single-bunch beam current at PEP-II for two different bunch spacings (given in units of the design bunch spacing τ_d).

The effect of the solenoids on the positron beam size was also measured by imaging the beam via emitted synchrotron radiation as shown in Fig. 11. In PEP-II both transverse beam sizes were blown up due to the electron cloud. From these data, the current threshold was seen to increase when adding one few-meter long solenoid. With beams in collision, however, the positron beam size was observed to increase at a lower total current for reasons that are not yet clear. At present [15] 340 m of about 500 m total available space has been wound with solenoids around the vacuum chambers and the single-beam positron beam size is nearly constant up to at least 1.2 A.

5 CONCLUSION

The new e^+e- factories have successfully demonstrated beam stability with order of magnitude higher bunch numbers and beam currents than their predecessors giving a corresponding increase in luminosity. Data taken at ultra-high beam currents have validated many expectations regarding ion trapping, beam loading, coupled-bunch instabilities, and fast beam-ion instabilities. While electron cloud effects have generated a few surprises, rapid progress is being made as new data become available in both the understanding and in the cures.

Acknowledgements

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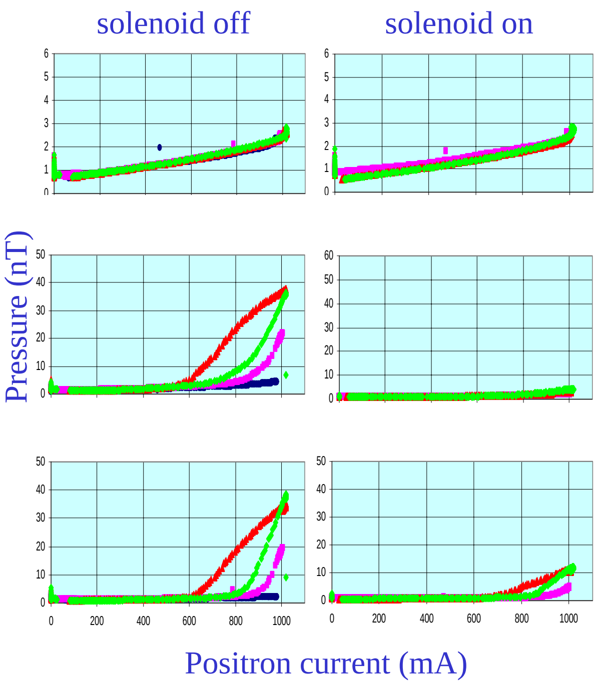

Figure 10: Pressure versus total positron current at PEP-II in the arcs (top), the start of a straight section (middle), and in the middle of the straight (bottom) with and without a solenoidal confinement field. The different curves correspond to bunch spacings of τ_d (black star), $2\tau_d$ (pink square), $3\tau_d$ (red triangle), and $4\tau_d$ (green diamond), where τ_d is the design bunch spacing.

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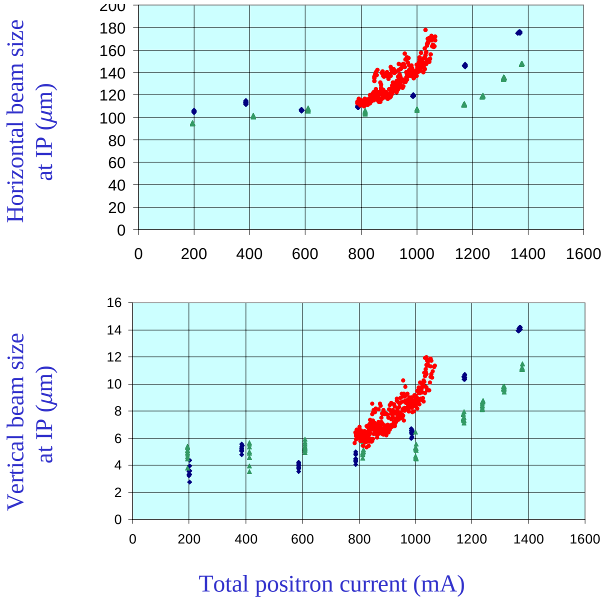

Figure 11: Beam size at the PEP-II interaction point measured with a single beam without solenoids (blue diamonds), with a single solenoid (green triangles), and with beams in collision (red circles).

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