The Effect of Beam Excitation on the HERA Electron-Beam Lifetime Disruption

D. R. C. KELLY, DESY, Hamburg, Germany

Abstract

The electron beam of HERA is subject to disruptions of the beam lifetime. The prevailing conjecture is that this is due to dust particles trapped by the beam within quadrupoles magnets. Good lifetime can be recovered temporarily by beam excitation. This has been predicted by theory and simulation and was confirmed by experiment for HERA and PETRA electron beams. During HERA electron machine studies in Dec 1995 the lifetime was increased from 2 h to 9 h with an injection kicker at a kick rate of 10 Hz over a period of 10 minutes at energy 27.5 GeV and at current > 30 mA. Similarly, the lifetime was improved from 3 h to 7.5 h with a feedback kicker sweeping from frequencies near or above the beam tunes $f_x \approx 10$ kHz, $f_y \approx 15$ kHz to low frequencies ≈ 100 Hz at a sweep period of ≈ 200 ms.

The local *discrete* decrease of electron loss rates in loss monitors located near arc quadrupoles and of global loss rates in background and electron detectors at experiments H1 and ZEUS correlated with *discrete* beam lifetime improvements during the beam excitation procedures - providing further support for the trapped dust particle explanation of the HERA electron beam lifetime problem. The frequency of all loss monitor and detector events was greatly reduced during the excitation procedures. Further lifetime disruptions were however observed to recur after the excitation "cleaning" procedures were concluded, especially at desired operation currents > 20 mA. The kicking procedure, loss rate observations, and agreement with theory are presented.

1 THE EQUATION OF MOTION OF A TRAPPED DUST PARTICLE

The properties of the electron beam lifetime disruptions that afflict the HERA electron storage ring are discussed at length in [1]. The differential equations that describe μm size dust particles trapped in electron beams such as HERA-e are discussed at length in [2, 3]. The numerical solution is merely presented in this paper for conditions typical of HERA assuming a current 20 mA, energy 27 GeV, and a dust particle of diameter $1\ \mu m$.

The transverse equation of motion and the charge development equation represent a differential equation system for the position (x, y) and charge Q of the particle: $\frac{d\mathbf{v}(t)}{dt} = f(t; \mathbf{v}(t))$ with $\mathbf{v}(t) = (x, y, \dot{x}, \dot{y}, Q)$. The system may then be integrated using standard numerical routines such as the Numerical Recipes Runge-Kutta routine RK4 controlled by adaptive time stepping RKADAP [4].

Longitudinal motion is not considered further in this paper, suffice it to mention that disrupting particles are expected to be longitudinally trapped in potential wells at horizontally defocussing quadrupoles due to tapering of the beam cross-section subject to competition with longitudinal acceleration from Møller scattering by beam electrons.

2 BEAM EXCITATION (RESONANCE) METHODS

A trapped particle in the linear region of the transverse beam force will have a well-defined oscillation frequency, thus its amplitude can easily be increased by beam kicking to the extent of the linear region $\sigma_x \approx 1\ mm$.

Hereafter, however, non-linearity dominates. At $x(t) > \sigma_x$ the frequency will be less than that in the linear region, and so the particle no longer 'sees' the excitation frequency. Formally the particle's oscillation frequency is no longer instantaneously defined, but one can define a pseudo-frequency based on the $x = 0$ crossing time of the particle.

Some insight into the difficulty of removing a trapped particle by resonance can be obtained by considering the equation of motion for a trapped particle in a cylindrical Gaussian beam, where both the linear oscillation frequency and the transverse coordinates x and $v = \dot{x}$ have been normalised:

$$\frac{d^2x(t)}{dt^2} + \frac{1 - e^{-x(t)^2}}{x(t)} = 0 \qquad (1)$$

The phase portrait Fig. 1 (left) illustrates the strong variation of frequency with amplitude in this system. At large amplitude A we have period $T(A) \approx 2\sqrt{2\pi}A$. In addition the charge reduction due to deionisation of a displaced particle will further increase its oscillation period.

In order to achieve large particle oscillation amplitudes through beam excitation one must decrease the beam excitation frequency from above the particle's linear frequency to a value many times below it, this variation being performed at a suitable sweep frequency. In Fig. 2 we see a simulation of a couple of cycles of such a sweep with $f_{\text{sweep}} = 5$ Hz and $x_{\text{kick}} = 0.06$ mm attenuated by an approximate beam-transfer function. The beam excitation was commenced 1.6 s after trapping of the disrupting particle. The right-hand plot shows the beam excitation frequencies and the particle pseudo-frequencies. The variation of the dust particle's frequency with amplitude can be

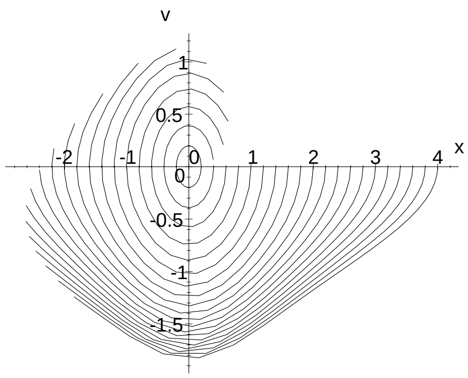

Figure 1: The phase portrait of Eq. (1) illustrates the strong variation of period with amplitude. Arcs in (x, v) correspond to $t = 0 \rightarrow 2\pi$.

seen. In order to achieve large amplitudes for a given disrupting particle one must tune the excitation sweep rate to the rate of change of frequency of that particle during excitation, whereby in HERA one expects a distribution of tens of disrupting particles [5] and so a scan of sweep rates must be performed.

3 SIMPLE KICK METHODS

The kicking of disrupting particles of various sizes with kickers of various strengths was simulated. Particles initially at $x = 0, y = 0$ and with stable ionisation were subjected to a beam oscillation $0.026\ mm\ \exp(-t/\tau) sin(2\pi f_\beta) B_{\rm kick} l$, with the kicker strength $B_{\rm kick} l$ measured in $gauss\ m$. The HERA betatron frequencies were taken to be $f_{\beta,x} = 10\ kHz$ and $f_{\beta,y} = 15\ kHz$ respectively. The maximum dust particle oscillation amplitudes obtained are shown in Fig. 3. The HERA-e vacuum chamber horizontal and vertical half-diameters are 40 mm and 20 mm.

Particles with oscillation frequencies below the respective betatron frequencies can be removed from the beam with large single kicks. For example, particles of size $0.3\ \mu m$ were displaced to amplitudes comparable to the vacuum chamber dimensions with kicks of strength $15\ gauss\ m$. Very small particles, whose oscillation frequencies lie above the betatron frequencies, can't be removed by this method in HERA at the current tune operating point; the resonance is then constrained to $amplitude \propto Bl$.

The time for a highly ionised but greatly displaced disrupting particle to return to and be stably trapped in the linear region of the beam (the recovery time) is according to simulation of the order of 1 s, so an improvement in the maximum displacement may be achieved by repeated kicking at repetition rate > 1 Hz.

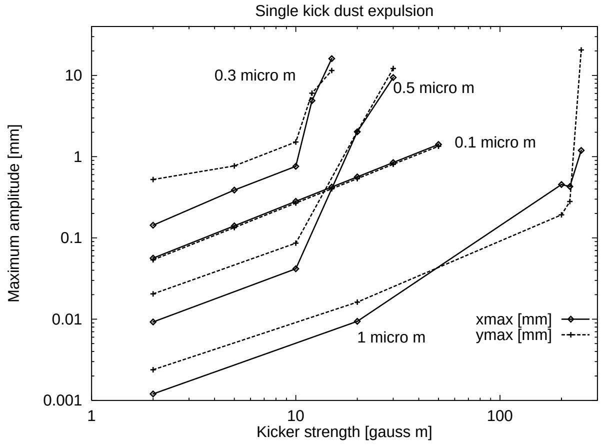

Figure 3: Simulation of particle removal by large single kicks. Small particles (with frequencies well above the betatron frequency) can't be removed by this method.

4 EXPERIMENTAL RESULTS AND DISCUSSION

Disrupting particles were apparently removed from the PETRA electron beam in Nov 1995 (betatron frequencies $f_x = 30$ kHz, $f_y = 40$ kHz) with an injection kicker at a repetition rate of 12.5 Hz (Balewski, Ehrlichmann, Kouptsidis, *Pers.Comm*). In Dec 1995 a horizontal injection kicker at 10 Hz repetition rate was successfully used to improve the disrupted HERA-e beam lifetime from ≈ 2 h to ≈ 9 h at 27 GeV and > 30 mA current. The *gradual step-wise* improvement of lifetime corresponded to the gradual removal of individual particles (tens being apparently trapped at high current), as evidenced by abrupt rate reductions in individual loss monitors. Step-like reductions in rates at various experiment detectors at ZEUS and H1 could also be seen. Lifetime improvement was **not** achieved at kick repetition rates < 5 Hz, suggesting that the recovery time of a displaced trapped disrupting particle is less than 1 s.

Improvement of the lifetime was also achieved by employing a feedback kicker (with the feedback system on) sweeping from frequencies near or above the beam tunes $f_x \approx 10$ kHz, $f_y \approx 15$ kHz to low frequencies ≈ 100 Hz at a sweep period of ≈ 200 ms, whereby much fine-tuning and scanning of these values was required – perhaps due to the need to match the excitation sweep rate to a distribution of particle sizes. Excitation in the vertical and horizontal planes was fixed at a frequency ratio 2:1 corresponding approximately to the respective dust particle transverse frequency ratio $\sqrt{\sigma_x/\sigma_y}$. The lifetime was thus improved from 3 h to 7.5 h.

The HERA-e lifetime worsened in both cases gradually and discretely within one hour of ceasing excitation – dust particles apparently making their way back into the beam readily after expulsion.

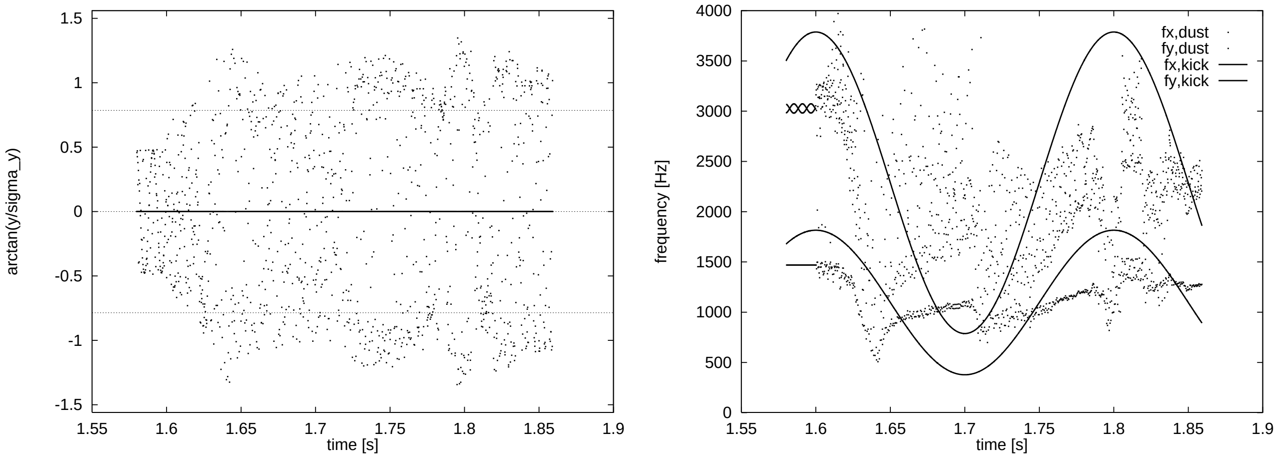

Figure 2: Trapped particles can be excited to large amplitude by sweeping the beam excitation frequencies from above the linear frequencies to well below them. The particle's y position (left) and the dust oscillation frequencies and beam excitation frequencies are shown (right). The beam excitation was commenced at $t = 1.6s$.

The amplitude and frequency of abrupt rate changes usually observed during electron operation in 214 electron loss monitors and in a range of detectors at the ZEUS, H1 and HERMES experiments was greatly reduced during both excitation procedures, suggesting that disrupting particle trappings are substantially prevented during beam excitation.

Lifetime values typical of positron operation in 1995 (> 10 h at 30 mA current under similar vacuum conditions) were however not quite obtained. To judge by small persistent fluctuations in the lifetime curve after these kicking methods were employed, many smaller particles may remain in the beam - consistent with the notion that their oscillation frequencies lie above the betatron frequency in HERA. Particle removal from PETRA, with its higher operation point, is more straightforward.

5 CONCLUSION

Both repeated simple kicks and kHz frequency swept beam excitation were shown, in agreement with simulation, to improve the HERA electron beam lifetime, i.e. to apparently temporarily remove trapped dust particles. The method does not seem viable for pre-luminosity 'cleaning' of the beam, as the lifetime worsens after excitation ceases. The method is nevertheless a useful diagnostic of the HERA lifetime problem, and the results add support to the trapped-dust particle hypothesis. The kick repetition rates (simple kicking) and sweep frequencies (resonant beam excitation) required for successful lifetime improvement were in agreement with predictions for disrupting particles of size $< \mu$ m.

More extensive results of numerical simulation, theoretical analysis and experimental observations and results are available in [6].

6 REFERENCES

[1] Kelly, D. R. C. (1995), *Characterisation of Lepton Beam Lifetime Behaviour in HERA*, Technical Report DESY HERA 95-01, Deutsches Elektronen Synchrotron

[2] Bochetta, C. J. and Wrulich, A. (1988), Effects of ions in the Sincrotrone Trieste, in *European Particle Accelerator Conference*, EPAC

[3] Zimmerman, F. (1994), *Trapped Dust in HERA and Prospects for PEP-II*, Technical Report PEP-II AP Note No.: 8-94, Stanford Linear Accelerator Center

[4] Press, Flannery, Teukolsky, and Vetterling (1987), *Numerical Recipes: The Art of Scientific Computing*, Cambridge University Press

[5] Kelly, D. R. C. (1995), *Many-event lifetime disruption in HERA and DORIS*, Technical Report DESY HERA 95-02, Deutsches Elektronen Synchrotron

[6] Kelly, D. R. C. (1996), *Removing trapped dust from the HERA electron beam by transverse beam excitation and kicking*, To be submitted to Particle Accelerators.