TRAPPED ION EFFECTS WITH ELECTRON BEAMS IN THE CERN PS

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Abstract

The CERN Proton Synchrotron (CPS) as part of the LEP injector chain accelerates electrons and positrons from 0.5 to 3.5 GeV. Effects due to trapped ions have been observed with electron beams, at intensities above 1.5×10^{10} e-/bunch when the collected ions induce vertical coherent instabilities. These observations are presented and compared to theoretical expectations.

Experimental observations

Four equally spaced bunches of first positrons and then electrons are accelerated in the CPS on two consecutive and identical 1.2 s cycles. Fig. 1 shows the circulating beam current of electrons from injection to extraction. A vertical aperture limitation is introduced on the 3.5 GeV flat-top with a scraper. With such a limitation fast and regular beam losses occur when the intensity is raised from the nominal 1×10^{10} e-/bunch to about 1.5×10^{10} e-/bunch. Correlated with these losses, fast spikes can be observed on a spectrum analyser that is tuned at the vertical sideband frequency $(7-Q_y)\,f_o$ around 330 KHz, where $Q_y = 6.31$ is the vertical tune and $f_o = 477$ KHz is the revolution frequency.

Fig. 1: a) e- beam current and b) amplitude of the n=7 betatron frequency sideband versus time (100 ms/div)

A closer look at the vertical betatron line signal during the 300 ms, 3.5 GeV flat-top shows peaks with rise times much shorter than 1 ms and fall times of ~ 10 ms at intervals which are inversely proportional to intensity, of ~ 50 ms. The corresponding amplitude of the vertical oscillations is estimated to be 0.5 mm and is independent of intensity. No signs of instability were observed during acceleration and, in the horizontal plane, the beam is always stable.

No such effects have been seen with positron beams, even at still higher intensities.

Theoretical expectations and comparison with measurements

Critical mass

The observed beam behaviour can be explained by the trapping of positive ions in the e- beam potential. According to theory [1, 2] ions can be collected if their masses are larger than the critical mass A_c given by (in the vertical plane):

$$A_c = \frac{\pi\, r_p N_b R}{K_b \sigma_x \sigma_y \left(1 + \sigma_y/\sigma_x\right)} \tag{1}$$

where:

r_p is the classical proton radius (1.53×10^{-18} m)
N_b is the number of electrons/bunch
R is the machine radius (100 m)
K_b is the number of bunches
σ_x, σ_y are the rms beam width and height (m).

As the horizontal dimension of the beam is larger than the vertical one the limit comes from the vertical plane and it is the only one considered.

With the usual beam of 4 bunches, $N_b = 1.5\times10^{10}$ e-/bunch, $\sigma_x = 1.6$ mm and $\sigma_y = 0.3$ mm one obtains $A_c = 3$. Therefore ions heavier than H_2^+ can be trapped.

Ionisation time

With an average pressure of 2×10^{-8} Torr and a residual gas composed of 70% of H_2 and 25% of CO, the ionisation time, i.e. the time required for one e- to create one ion, is ~ 250 ms for H_2 and ~ 100 ms for CO.

Tune spreads

The trapped ions induce in the vertical plane an incoherent tune spread given by:

$$\Delta Q_y = \frac{r_e \langle\beta_y\rangle N_b K_b \eta}{2\pi\gamma\, \sigma_x \sigma_y \left(1 + \sigma_y/\sigma_x\right)} \tag{2}$$

where:

r_e is the classical electron radius (2.82×10^{-15} m)
$<\beta_y>$ is the average vertical betatron function.
γ is the normalised beam energy E/E_o
η is the neutralisation factor $= \frac{\text{total number of ions}}{\text{total number of electrons}}$

With a beam of transverse dimensions and intensity as before, a vertical incoherent tune spread of $\Delta Q_y \sim 0.05$ is reached when $\eta \sim 0.5$. At this value of η the ion motion becomes unstable as will be shown below. Fig. 2 shows the measured tune spread corresponding to the case $K_b = 4$, $N_b = 2\times10^{10}$ e-/bunch and $\eta \sim 0.5$. The corresponding tune spread in the horizontal plane, obtained by interchanging x and y in the above formulae, is 5 times smaller.

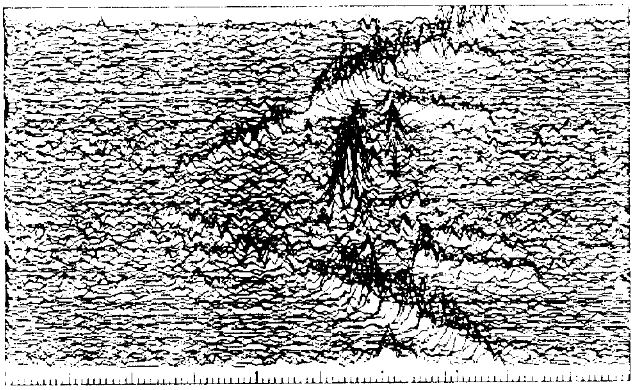

Fig. 2: Tune spread measurements during instability.
The figure shows a mountain range display of a 80 ms spectral history of the betatron sideband at frequency $(7-Q_y)f_o \sim 330$ KHz. The total width of the horizontal axis corresponds to a $\Delta Q_y = 0.1$.
To measure the tune spread, a sine wave sweeping in both directions is applied to a vertical kicker. Peaks in the middle pertain to the fast "two beam instability". Machine conditions are: $K_b=4$, $N_b=2\times10^{10}$ e-/bunch, $\eta\sim0.5$.

Vertical coherent instabilities

The observed coherent instabilities can be explained as the result of coupled transverse oscillations between ions and electrons ("dipole two-beam instability" [3,4,5]). Following ref [4] the equation of such a coupled motion can be written

$$\begin{aligned} \ddot{y}_e + Q_y^2\Omega_0^2 y_e &= Q_e^2\Omega_0^2\left(\bar{y}_i - y_e\right) \\ \ddot{y}_i &= Q_i^2\Omega_0^2\left(\bar{y}_e - y_i\right) \end{aligned} \tag{3}$$

where:

y_e, y_i are the vertical displacements of the electrons and ions respectively,

$\bar{y}_e$, $\bar{y}_i$ are the positions of the centers of mass of the electron beam and of the ion cloud,

Ω_0 is the electrons angular revolution frequency.

$$\begin{aligned} Q_e^2 &= \frac{\eta\, N_b K_b r_e R}{\pi\,\gamma\,\sigma_y\left(\sigma_x + \sigma_y\right)} \\ Q_i^2 &= \frac{N_b K_b r_p R}{\pi\, A\,\sigma_y\left(\sigma_x + \sigma_y\right)} \end{aligned} \tag{4}$$

$Q_e\Omega_0$ and $Q_i\Omega_0$ are the oscillation frequencies of one kind of particle in the potential well of the other, and A is the ion mass (28 for CO^+)

System (3) admits solutions of the form

$$\begin{aligned} y_e &= y_{eo}\exp\left[j\left(n\theta - \omega t\right)\right] \\ y_i &= y_{io}\exp\left[-j\,\omega t\right] \end{aligned} \tag{5}$$

Combination of equations (3) and (5) yields the dispersion relation

$$\left(Q_i^2 - x^2\right)\left[Q_y^2 + Q_e^2 - (n - x)^2\right] = Q_e^2 Q_i^2 \tag{6}$$

where:

θ is the azimuthal angle,

n is an integer (mode number),

$x = \omega/\Omega_0$ is the normalised frequency.

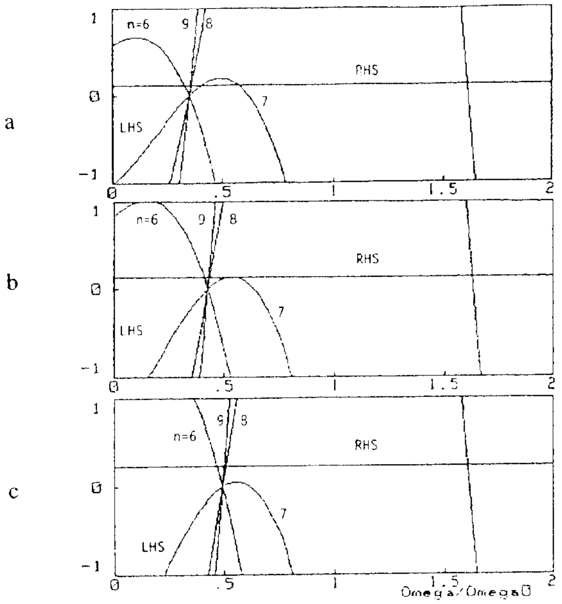

Fig. 3: Plots of lhs and rhs of equation (6) for 3 different cases:

a) $N_b = 1.0\times10^{10}$ e-/b, $\eta = 1$. All modes are stable.

b) $N_b = 1.5\times10^{10}$ e-/b, $\eta = 0.5$ mode n=7 at threshold.

c) $N_b = 2.0\times10^{10}$ e-/b, $\eta = 0.5$ mode n=7 above threshold.

The left and right hand side of equation (6) are plotted in fig. 3 for n = 6 to 9. Whenever the two curves intercept, the dispersion relation has two real solutions and the motion is stable. Mode n=7 is the first mode which becomes unstable by increasing the intensity. Once the electron oscillation reaches an amplitude larger than 2 σ_y the ions are chased out of the potential well and the beam recovers its stability.

As the intensity is increased, the threshold is reached at smaller values of η thus explaining the faster instability repetition rate observed.

Effects of various actions on the beam

Change of machine optics

No major effects were found by changing tune and chromaticity. However, moving the tune on the linear coupling resonance changes substantially the vertical beam size and consequently raises the instability threshold. In this way it was possible to increase the intensity limit to 2.5×10^{10} e-/bunch.

Beam kick and excitation

A 20 mm radial oscillation of the beam produced with a fast (one turn) kicker should clear the ion cloud as the beam is only 8 mm wide. However the fast ionisation time restores the ions within a few tens of ms.

Continuous vertical beam shaking [6] has also been tried, but with limited available power (deflection of 1 % of the rms beam size). No significant effects have been observed.

Effect of missing bunches

One method to avoid ion trapping involves modulating the bunch intensity in such a way that the ion motion becomes unstable [7,8,9,10]. The periodic excitation of the ion produces a motion characterised by the transfer matrix

$$M = \left[M(\tau_0)\ M_b\right]^{k_b - k_m} M(\tau_m) \tag{7}$$

where

$$M(\tau) = \begin{vmatrix} \cosh(g\tau) & g^{-1}\sinh(g\tau) \\ g\sinh(g\tau) & \cosh(g\tau) \end{vmatrix} \tag{8}$$

is the transfer matrix of the drift space of duration τ between electron bunches, where the ion feels only the space charge force of the other ions,

$$\tau_0 = 2\,\pi\, R / K_b\, c \tag{9}$$

is the duration of the gap between each of the K_b bunches, c is the speed of light,

$$\tau_m = K_m\,\tau_0 \tag{10}$$

is the duration of the gap due to the K_m missing bunches,

$$g = Q_i\,\Omega_0\sqrt{\eta} \tag{11}$$

and where

$$M_b = \begin{vmatrix} 1 & 0 \\ -a & 1 \end{vmatrix} \tag{12}$$

is the transfer matrix of an electron bunch crossing and producing a kick

$$a = \frac{2\, N_b r_p c}{A\,\sigma_x\sigma_y\left(1 + \sigma_y/\sigma_x\right)} \tag{13}$$

The motion is stable, and consequently the ions are trapped, if the trace of M, Tr (M), satisfies

$$-2 < \mathrm{Tr}\,(M) < 2 \tag{14}$$

Fig. 4 shows the trace of M for 0, 1, 2, 3 missing bunches. With an intensity of $N_b = 1.5\times10^{10}$ e-/bunch, and $K_m = 3$, the ion motion becomes unstable.

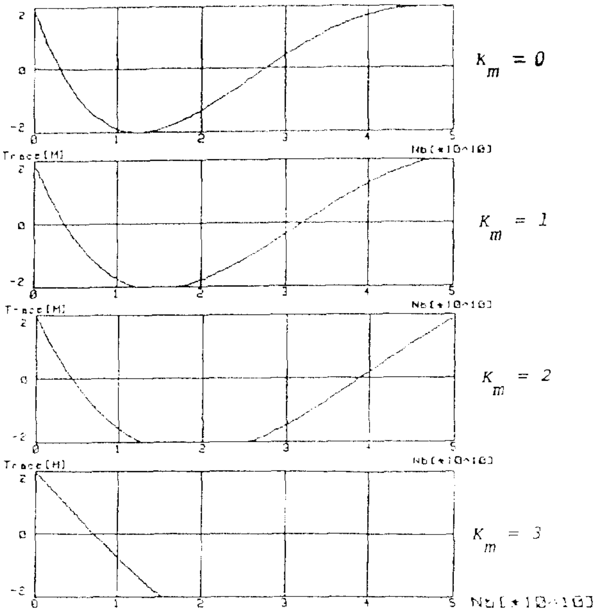

Fig. 4: Plot of Tr (M) for CO^+ ions motion versus N_b for different values of K_m (number of missing bunches) and K_b=8. When K_m=0, i.e. 8 equally spaced bunches are circulating in the machine, |Tr (M)| is always ≤ 2 and the ions are trapped. When K_m=3 and $N_b > 1.5\times10^{10}$ e-/bunch, the ions cannot be trapped.

To observe the effect of missing bunches, the PS has been set-up for the injection of 8 equidistant bunches. A change of the injection timing could provide fewer bunches. Fig. 5 shows the measured vertical beam size as a function of the number of missing bunches. The beam has a large vertical size until 3 bunches are missing, confirming the theoretical expectations.

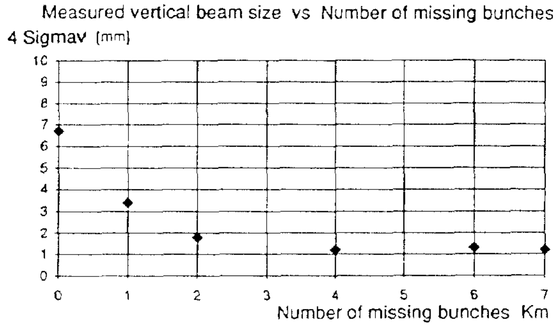

Fig. 5: Measured vertical beam dimension versus number of missing bunches. With 3 missing bunches out of 8, no collection of ions takes place.

Transverse Feedback

As the instability is of coherent nature, it has been possible to counteract its effects by means of transverse feedback. The signal from a vertical beam position monitor, filtered around the betatron frequency line, has been amplified and used to power, with the appropriate phase, a pair of vertical electrodes in the ring. With such a feedback, it was possible to damp the coherent instabilities and consequently to raise the instability threshold to 5×10^{10} e-/bunch. Fig. 6 shows the betatron frequency line with and without the transverse feedback. Note the coherent tune shift induced by the trapped ion effects.

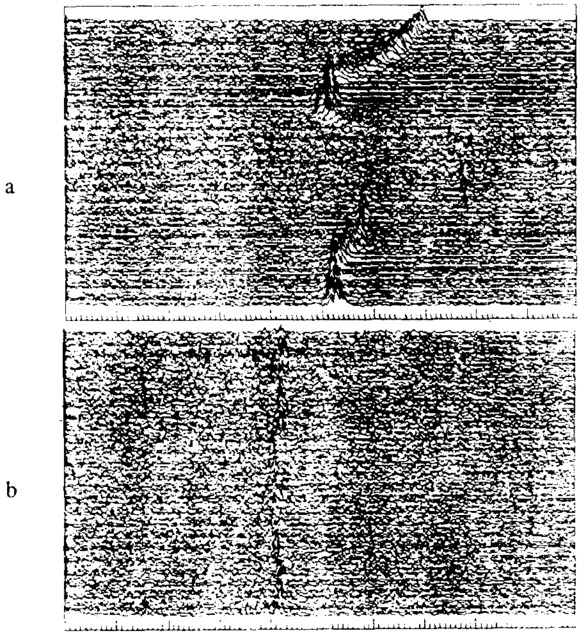

Fig. 6: Behaviour of the n=7 vertical betatron sideband, (a) without (b) with transverse feedback. Same axis as in figure 2.

Conclusions

The linear standard model explains relatively well the observed beam behaviour: trapping of CO^+ ions, vertical tune spread, missing bunch effects, coherent two-beam instability. A transverse feedback system has successfully counteracted the coherent instability and raised the threshold by a factor of 3 to 5×10^{10} e-/bunch.

Acknowledgements

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References

[1] Y. Baconnier and G. Brianti, "The stability of ions in bunched beam machines" CERN/SPS/80-2 (DI), March, 1980.

[2] Y. Baconnier, "Neutralization of accelerator beams by ionization of the residual gas", Proc. of the CERN Accelerator School, Gif-sur-Yvette, France, 1984, CERN 85-19, November 1985, pp. 267-301.

[3] D.G. Koshkarev and P.R. Zenkevich, "Resonance of coupled Transverse oscillations in two circular beams", Particle Accelerator Vol. 3 pp 1-9 (1972).

[4] E. Keil and B. Zotter, "Landau damping of coupled electron-proton oscillations", CERN-ISR-TH/71-58 (1971).

[5] L.J. Laslett, A.M. Sessler and D. Möhl, "Transverse two-beam instability in the presence of strong species-species and image forces", Nuclear Ins. and Methods 121 (1974) 517-524.

[6] J. Marriner, D. Möhl, T. Orlov, A. Poncet, S. Van der Meer, "Experiments and practice in beam shaking", Particle Accelerators 1990, Vol. 30, pp13-20.

[7] H. Schönauer, "Neutralization of bunched proton beam", IEEE Tr. on Nuclear Science NS-20,866 (1973).

[8] M. Barton, "Ion trapping with asymmetric bunch filling of the NSLS-VUV Ring", Nucl. Instr. and Methods A243 (1986) 278-280.

[9] S. Sakanaka, "The stability of ions in partially filled mode operation in the electron storage ring", KEK Preprint 86-17, June 1986.

[10] A. Poncet, "Trapping of ions in the EPA e- beam: stability conditions and diagnostics", CERN/PS 88-14, April 1988.