LIMITATIONS ON SINGLE BUNCH OPERATION IN THE SRS DUE TO BEAM INSTABILITIES

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1. Introduction

The synchrotron radiation produced by the SRS at Daresbury is frequently used for Time Resolved Spectroscopy, in which case only one of the possible 160 RF buckets is filled with electrons [1]. The number of electrons in the single filled bucket is much greater than when all buckets are filled and this poses the most stringent test of the stability of the stored electrons. Study of the limitations experienced in single bunch mode provides valuable insights of the impedance characteristics of the storage ring.

2. Limitations

Single bunches are injected into the storage ring at 605 MeV after pre-acceleration in a booster synchrotron. Injection is repeated at a rate of 10 Hz until the maximum achievable current is reached. Figure 1 shows examples of well-optimised single bunch accumulation rates.

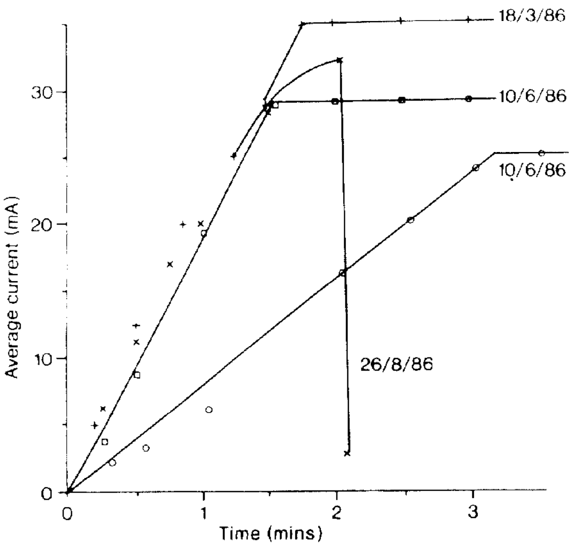

Fig.1. Examples of single bunch fill rates.

Accumulation is seen to be virtually linear with time until the onset of a limit at about 30 mA average current (equal to 6 10^{10} stored electrons). The limit has been observed to be different on different occasions and is often accompanied by an instantaneous step loss during which the bunch reduces to a few mA before accumulation continues once more. This step loss does not seem to be correlated to any of the storage ring control parameters other than perhaps closed orbit position at the cavities, but the current limit can be increased to some extent by increasing the cavity accelerating voltages. During the step loss the image of the beam produced by focusing the synchrotron light shows that the beam blows up in the horizontal transverse plane.

With a stored single bunch beam, instability may be provoked by reducing the lattice sextupoles from their normal settings for positive chromaticity. In this condition the synchrotron light image of the beam shows a pulsating type of horizontal transverse blow-up which often results in beam losses during the energy ramp, at a variable point up to 1.6 GeV. Figure 2

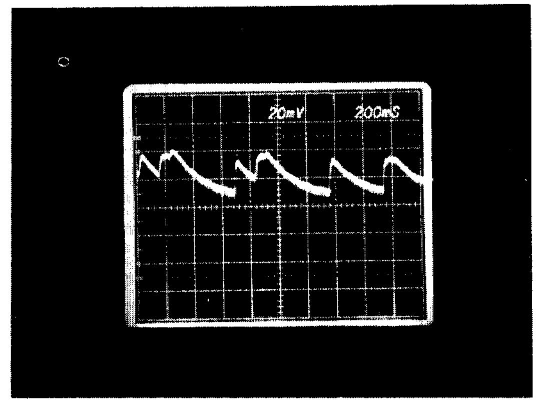

Fig. 2. Photomultiplier signal showing the transverse beam instability. Zero signal is at the top of the screen.

shows the signal from a photo-multiplier placed behind a vertical slit at the synchrotron light image. The instability causes a reduction in light transmission through the slit as the horizontal beam size increases. The beam size stabilises at some increased amplitude, possibly due to Landau damping from octupole fields, and then decreases in size by damping until the instability cycle repeats itself. During the instability the wide-band beam pick-up (1/4 wave transmission line couplers in the vacuum chamber) shows horizontal betatron sideband signals around every orbit harmonic in the range 0-1750 MHz. Longitudinal coherent motion coupled via the higher order modes of the cavities is certainly present, but does not seem to play any significant role in the single bunch limitation.

3. Bunch lengthening

The onset of the current limitations, with suitable chromaticity, shown in fig. 1, together with the absence of transverse phenomena, suggest that the reason for the limit is to be found in the longitudinal plane of the beam. Bunch length measurements have therefore been made in both single bunch and multi bunch modes using a stroboscopically synchronised image dissector tube [2] and an initial report has been made previously [3]. Further measurements and analysis have now been performed and are reported here.

Figure 3 shows the rms bunch length σ_L as a function of average current I in the single bunch at injection energy and it can be seen that there is significant lengthening. The data supports a relationship of the form

$$\sigma_L \propto I^{1/a}$$

with a = 2.87 ± 0.07 for a wide range of bunch lengths. It is thus reasonably consistent with the standard $I^{1/3}$ power law for turbulent bunch lengthening even in the short bunch length regime

$$\sigma_L < b$$

where b is the effective vacuum chamber radius.

The data does not however allow a precise determination of the ring impedance because of an unknown contribution from coherent bunch motion which

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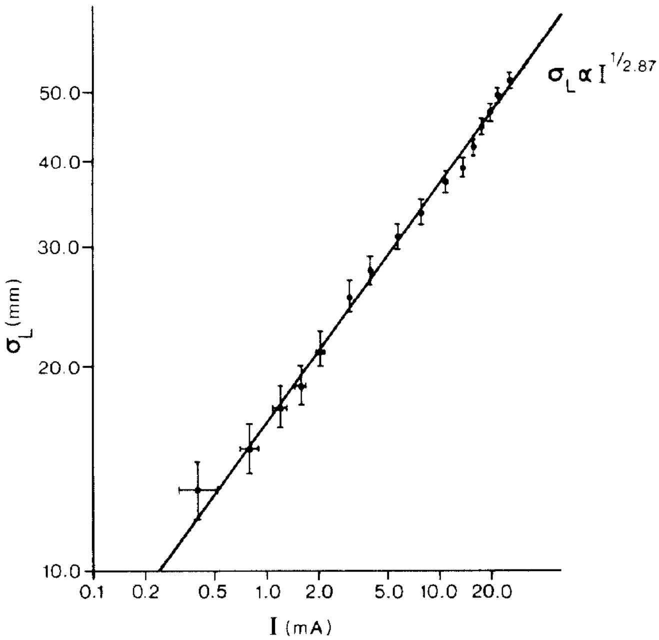

Fig. 3. Measured bunch length as a function of current at injection energy. Log-log scales.

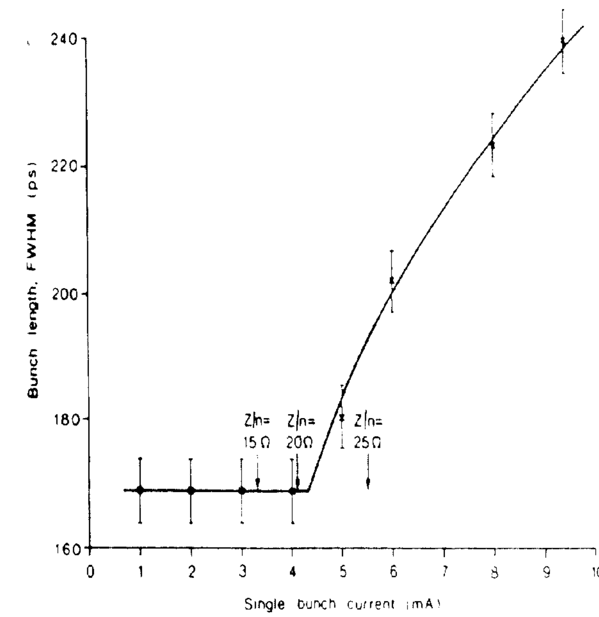

Fig. 5. The variation of bunch length with current at an energy of 1.25 GeV, showing the threshold.

cannot be resolved with the detector. A more reliable estimate has therefore been made by observing the threshold at higher energies, figs. 4 and 5. When the turbulent bunch lengthening formula [4]

$$\sigma_L^3 = \frac{I}{\sqrt{2\pi}} \frac{Z}{n} \frac{\alpha}{E} \frac{R^3}{Q_S}$$

where Z/n is the broadband chamber impedance
- α is the momentum compaction factor (0.137)
- E is the beam energy
- R is the average machine radius (15.3 m)
- Q is the synchrotron oscillation tune (0.05)

is fitted to this data, good agreement is obtained with a value of Z/n of 20 ohms. This would be a relatively high value for a colliding beam electron storage ring but is not inconsistent with the complex vacuum chamber of a synchrotron radiation source.

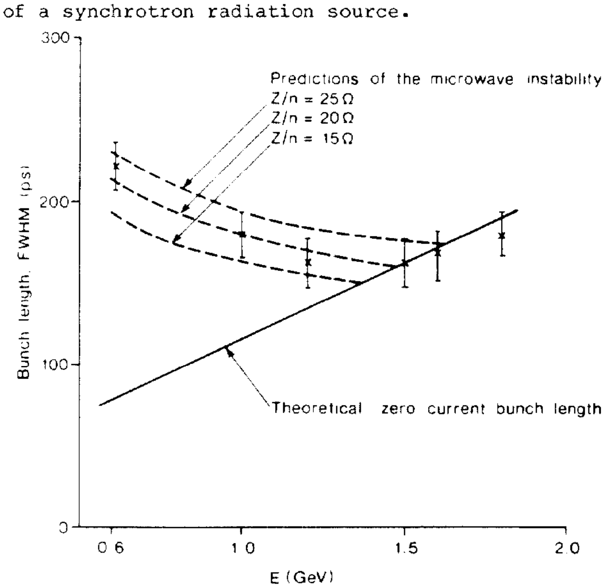

Fig. 4. Measurement of bunch length for a constant current as a function of energy.

With such clear indications of turbulent bunch lengthening it is proposed that the injected beam current limit is reached when the length and energy spread of the beam has increased to the point where the quantum lifetime losses equal the beam accumulation rate. The quantum lifetime shortens dramatically as the energy spread of the bunch, which increases with the lengthening, becomes an appreciable fraction of the potential well defined by the RF. If the injection rate is ΔI mA per shot and the quantum lifetime of the turbulent bunch is τ seconds, then the limiting current I_{max} is given for 10 Hz injection by

$$\Delta I = I_{max}\left(1 - e^{-\frac{1}{10\,\tau}}\right)$$

since it can be assumed that the quantum lifetime remains constant over the small change of current between injection shots (approximately 1/30 mA). This relationship may be restated as

$$\tau = I_{max}/10\,\Delta I$$

In fig. 6 the calculated quantum lifetime of the turbulently lengthened bunch is plotted as a function of current, assuming a broadband chamber impedance of 20 ohms. This is shown for three typical values of the RF accelerating voltage which give the synchrotron tune values shown. The limiting current is reached at the intercept of these curves with the injection rate relationship and it can be seen that the current limit is relatively insensitive to injection rate. There is good agreement between the generally observed single bunch current limits of 25-30 mA and the predictions of fig. 6.

4. Chromaticity-dependent instability

A very clear transverse instability is induced in single bunch mode when the chromaticity is changed by adjusting the lattice sextupoles. The beam pulsates repetitively as depicted in fig. 2 with a damping coefficient consistent with the horizontal radiation damping time of 315 ms. However, once induced, the amplitude and the exact periodicity of this instability is controlled by the lattice octupoles, which suggest that it is partially stabilised by Landau damping.

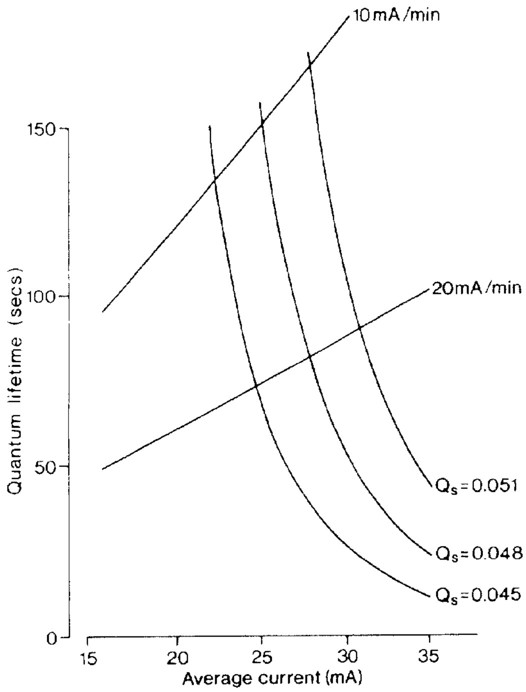

Fig. 6. Predicted quantum lifetimes as a function of single bunch current.

The threshold for this instability in sextupole settings is very sharply defined and reproducible, and is not a function of beam current, at least in the range 1-25 mA. When the sextupole settings are translated into radial chromaticity, the threshold as a function of energy is as shown in fig. 7. It appears that this is not the zero-order head-tail effect since a comparatively large positive chromaticity is needed for stability at low energies. At higher energies additional damping seems to swamp the instability and even negative chromaticity allows stability.

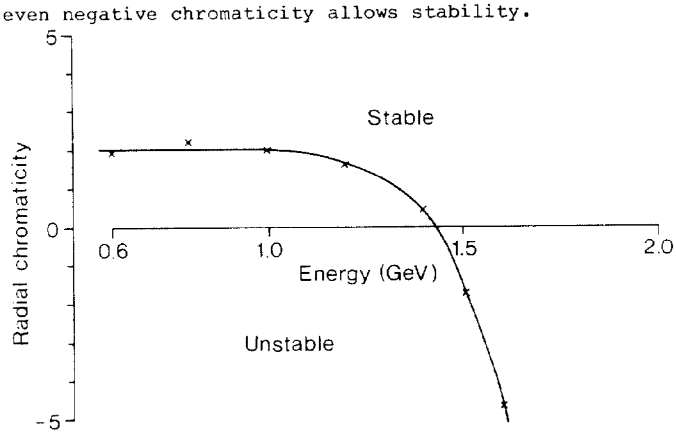

Fig. 7. Chromaticity threshold of the single bunch transverse instability as a function of energy.

Finally, it has been demonstrated that the instability can be stabilised completely by a horizontal transverse feedback system working at the betatron sidebands of the orbit frequency (3.123 + 0.500 MHz).

5. Conclusions

The complex vacuum chamber of the SRS has a relatively high broadband impedance of 20 ohms. This fits well the observed bunch lengthening in single bunch mode and the consequential increased energy spread provides a good explanation for the observed single bunch injection current limit.

The chromaticity-dependent transverse instability in singlebunch mode does not appear to be the zero-order head-tail effect, and its exact nature remains unexplained.

6. References

[1] E.A. Hughes et al., "Single bunch system for the Daresbury SRS", IEEE Trans. Nucl. Sci. NS-30 No.4, pp.2633-2635, Aug.1983.

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