Single Bunch Effects in the Daresbury SRS

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Abstract

Single bunch currents in the SRS have now been increased to over 100 mA injected at 600 MeV, with user beams of 50-60 mA at 2 GeV routinely obtained. Such high currents in short (500 MHz) bunches have necessitated attention to ensuring adequate lifetimes, including deliberate control of bunch volume to reduce Touschek losses. At lower energies substantial bunch lengthening has been experienced which has been compared with standard theoretical models. The associated prediction of chamber impedance has been compared with results obtained from mode shift experiments. Other aspects of single bunch behaviour in the SRS are also mentioned.

I. INTRODUCTION

During a recent shutdown to install a second superconducting wiggler magnet [1] a new injection septum and kicker magnets were installed in the SRS. This has led to greatly improved single bunch injection with over 110 mA being accumulated at 600 MeV. Much higher current per bunch is achieved than in the normal (all 160 bunches filled) multibunch mode of operation. At these high current densities the beam lifetime is limited by Touschek losses even at 2 GeV. In order to alleviate this effect the lattice is operated close to a working point with betatron tunes Qr=4.25, Qv=3.25 which has higher emittance [2]. Experiments have been carried out to increase the lifetime by varying the emittance coupling and hence the bunch volume with a view to minimising Touschek losses.

The high currents obtained have enabled a thorough investigation of bunch lengthening effects. Bunch lengthening behaviour has been assessed as a function of beam current at a range of energies up to 1.8 GeV and in particular detail at 600 MeV. A determination of the effective broadband impedance has been made from these results and also from measurements of vertical tune shift with beam current at 600 MeV.

II. MEASUREMENT SYSTEM

Beam profile and bunch length measurements are made on a dedicated optical diagnostic beam line on the SRS [3]. Profile measurements in the horizontal and vertical plane are made using photodiode arrays and captured with a Macintosh computer using the data acquisition software LabVIEW [4]. Bunch length measurements are made using a stroboscopically synchronised image dissector tube [5] and are also analysed using the LabVIEW system.

III. BEAM LIFETIME

Measurements of beam lifetime dependence on current in single and multibunch modes have been used to calculate the Touschek lifetime, which has a dominant contribution to the overall single bunch beam lifetime. Touschek lifetimes as short as 12 hours for 40 mA at 2 GeV have been measured, rising to 56 hours at 10 mA.

The bunch volume is dependent on proximity to the coupling resonance Qr-Qv=1. Small changes to the vertical tune have been made such that the horizontal/vertical tune split causes the beam to approach or avoid this resonance. Tune splits of 26 - 200 kHz which corresponds to 0.008-0.048 in non-integer tune space have been assessed. The orbit frequency is 3123 kHz. Experiments were carried out under conditions close to those during user beam i.e. with the superconducting wiggler magnet energised at 5 T and the undulator magnet at minimum gap. The variation of bunch volume as a function of tune split is shown in Figure 1.

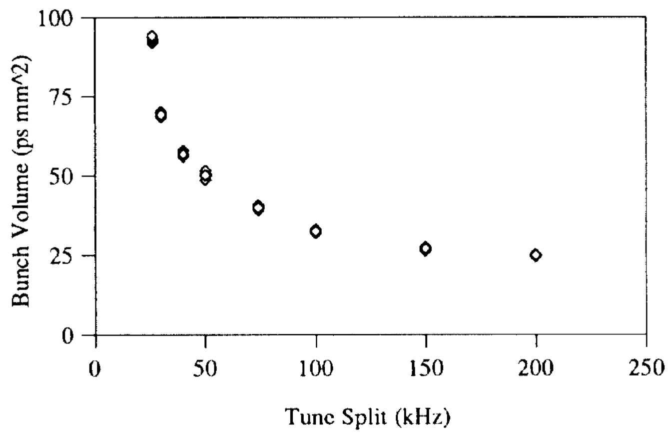

Figure 1. Bunch volume as a function of tune split for 30 mA single bunch beam.

The subsequent lifetime variation with tune split is shown in Figure 2. It is clear that a significant increase in the beam lifetime can be gained at increased coupling. Nominally a tune split of 40 kHz is used during operations.

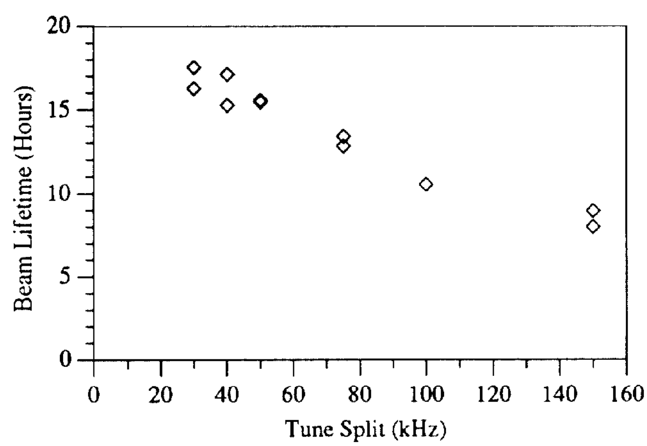

Fig 2. Total beam lifetime as a function of tune split.

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IV. IMPEDANCE EFFECTS AT 600 MeV

Bunch Lengthening Effects

The longitudinal microwave instability threshold in the SRS has been calculated to be ≈1.5 mA using the program ZAP [6]. All of the bunch length data collected has been in excess of that current, and hence it is assumed that bunch lengthening is predominantly due to this effect. Provided the bunch length is greater than the beam pipe radius, the dependence of bunch length σ_l on beam current I_b is given by [7]

$$\sigma_l = \left[\frac{I_b \alpha e}{\sqrt{2\pi} E \nu_s^2} \left| \frac{Z_{//}}{n} \right|_0^{BB} \right]^{1/3} R \qquad (1)$$

where α is the momentum compaction, e the electronic charge, E the beam energy, ν_s the synchrotron tune, R the ring average radius and the longitudinal broadband impedance denoted by

$$\left| \frac{Z_{//}}{n} \right|_0^{BB}.$$

Several experiments have been carried out to measure bunch length as a function of beam current at 600 MeV. Previously two state bunch lengths have been reported [8] but this phenomena has recently been uncommon. For the few points where two state bunch length was observed, the shorter bunch length has been used. The results were fitted to equation 1 which yielded a value for the longitudinal effective broadband impedance of 8.6 Ω ±0.6 Ω.

Above the microwave instability threshold, both bunch length and momentum spread are increased. Bunch lengthening behaviour at 600 MeV has been modelled using the lattice simulation program ZAP, and a comparison made with the experimental results. From the results presented above, an impedance of 8.6 Ω was assumed for the modelling. The experimental data along with the theoretical model is shown in Figure 3.

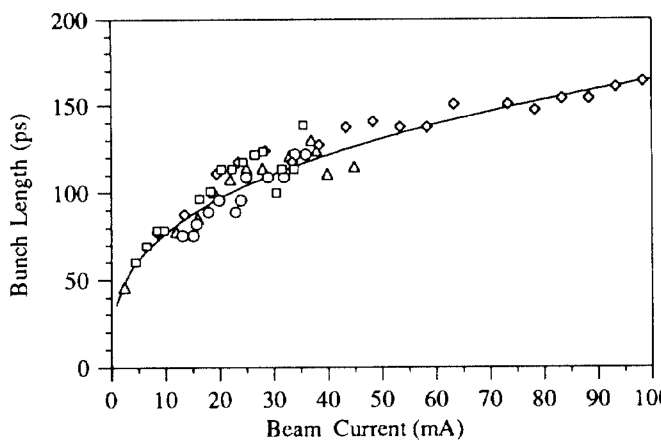

Figure 3. Measured and theoretical bunch length as a function of current.

Previous results from bunch lengthening and independetly from direct vessel impedance measurements have indicated that the impedance is of the order 10-15 Ω [8]. These earlier measurements were made with different septum and kicker magnets which would be expected to have slightly higher impedance. At high currents the bunch-length may be increased by potential well distortion, however the effects of this are small over the current range normally seen in the SRS.

Radial Beam Size

The increase in momentum spread in the beam causes an increase in the beam size at points of finite dispersion in the ring. The SRS is of a FODO design, and has finite dispersion all around the lattice.

In conjunction with bunch length, measurements have been made of beam sizes. Horizontal beam size as a function of beam current has been measured between 10 and 50 mA. The program ORBIT [9] has been used to calculate radial beam size as a function of beam current. The results are inconsistent with an assumed impedance of 8.6 Ω. The modelled beam size behaviour for an impedance of 6.4 Ω together with experimental data is shown in Figure 4.

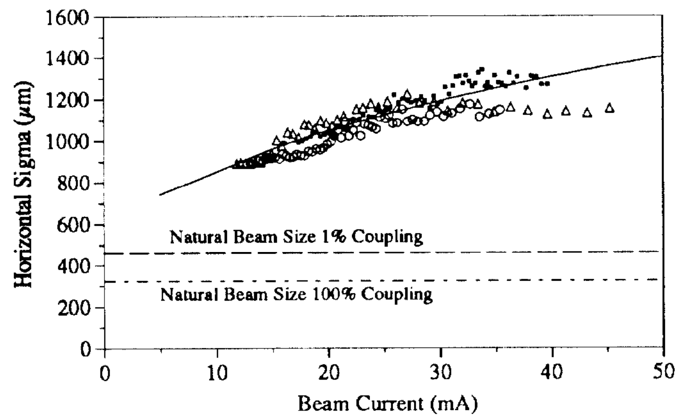

Figure 4. Horizontal beam size as a function of current showing modelled and measured beam sizes.

Clearly the revised estimate of 6.4 Ω gives a good fit to the experimental points. It should be noted however that the coupling is assumed to be 100% in the modelled case in order to give an upper estimate of Z/n. It is difficult to assess the real emittance coupling at 600 MeV as the vertical beam size is blown up to a greater extent than would be found with 100% coupling of the natural horizontal emittance.

Betatron Tune Shift

Vertical tune shift as a function of beam current has also been measured. The results are illustrated in Figure. 5. The data has been fitted to the lowest head-tail mode in the following form [7];

$$\Delta\nu_v = -\frac{e\hat{\beta}_v R}{4\sqrt{\pi} E \sigma_l} Z_v I_b \qquad (2)$$

where $\hat{\beta}_v$ is the average vertical beta function, equal to 5.8 m and Z_v the effective vertical impedance. The transverse impedance is related to the longitudinal broadband impedance by

$$\left|\frac{Z_{//}}{n}\right| = \frac{b^2}{2R} Z_t \qquad (3)$$

for a round beam pipe of radius b.

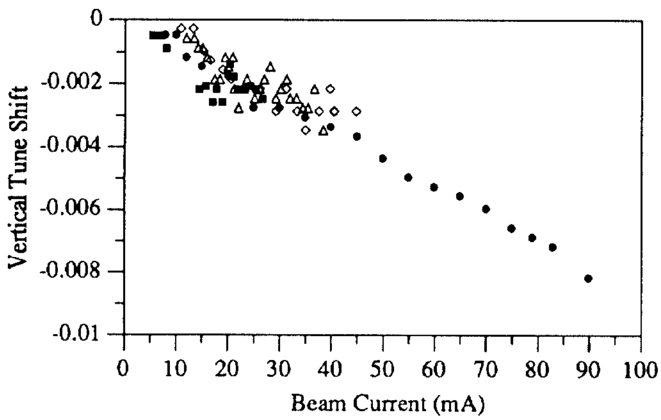

Figure 5. Tune shift as a function of beam current.

If the assumption is made that $Z_t = Z_v$ and the average geometrical beam pipe radius is ≈30 mm, the measured data gives a value for the broadband impedance of 6.8 Ω - similar to that predicted by the horizontal beam size increase.

V. BUNCH LENGTH VARIATION WITH ENERGY

Bunch length has also been measured as a function of beam current at 1.0, 1.5 and 1.8 GeV. At injection energy measurements have been made with currents up to 100mA, however rather lower currents were measured at higher energies due to current losses during the energy ramp. The experimental data is shown in Figure 6.

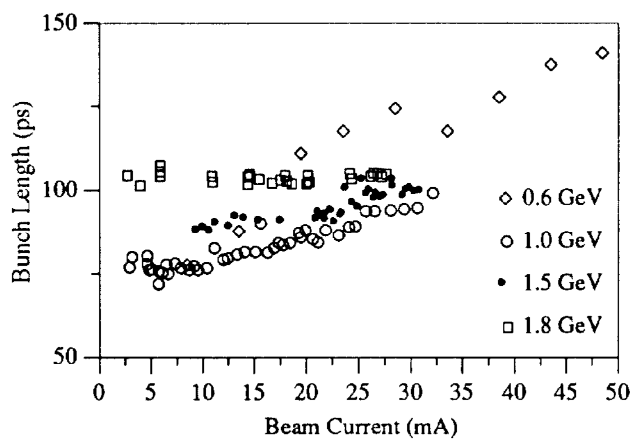

Figure 6. Bunch length variation at different energies.

A fit to the experimental data using equation 1 gave results largely in agreement with previous experiments. An impedance of 8.9 Ω was calculated from the 1.0 GeV data. At 1.5 GeV however, the calculated 14.1 Ω is more questionable, but this contains a large error since only a few points were obtained above threshold. No bunch lengthening was observed at 1.8 GeV as the beam current was well below threshold.

VI. CONCLUSIONS

Experiments to vary the emittance coupling have shown that beam lifetime can be significantly increased at lower tune splits due to the reduction of Touschek effects. It is possible that in future operations this result could be used to improve lifetime such that current losses during the energy ramp from 0.6 to 2.0 GeV are minimised, and operational lifetimes are improved.

The behaviour of bunch length as a function of current has been studied at 600 MeV and at higher energies up to 1.8 GeV. An estimate of the longitudinal broadband impedance was made from the bunch lengthening work of 8.6 Ω. A fit to the radial beam size experimental data required coupling to be set to 100%. Because of uncertainties in the true coupling at 600 MeV it is not clear whether this is a realistic simulation. This data predicted an impedance of 6.4 Ω. Calculation of impedance from mode shift measurements at 600 MeV implies that the impedance is 6.8 Ω.

Bunch length as a function of current at different energies has given a number of different results for broadband impedance. However the best fits to the experimental data gave results of 8.9 Ω and 14.1 Ω, which are not too far removed from previous experiments.

VII. REFERENCES

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