ENERGY MEASUREMENTS WITH RESONANT SPIN DEPOLARISATION AT DIAMOND

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Abstract

A precise knowledge of the electron beam energy is critical for the accurate determination of many light source parameters, such as momentum compaction factor, natural chromaticity, energy stability and undulator spectra. In common with other facilities, a method of energy measurement based on resonant spin depolarisation has been developed at Diamond. In this paper we report on progress towards storage ring characterisation using this method, as well as describing the diagnostics developments that have enabled these measurements to be made.

INTRODUCTION

A high-precision determination of the beam energy in an electron storage ring can be made using the technique of resonant spin depolarisation [1]. Such measurements have been made at many other facilities, notably for applications in high-energy physics, use of a light source as a primary radiation standard, or for more general applications such as in studying storage ring parameters or energy stability.

Due to the asymmetric rate of spin-flip radiation emission, electrons spins will gradually align anti-parallel to the magnetic field of the main bending magnets in a storage ring; a process known as the Sokolov-Ternov effect [2]. In an ideal storage ring, the electron spins precess about the vertical axis with a well-defined frequency, given by

$$\Omega_z = \omega_0(1 + a\gamma) \tag{1}$$

where ω_0 is the angular revolution frequency and a = 1.15965218×10^{-3} is the gyromagnetic anomaly of the electron. The quantity $a\gamma$ is known as the spin-tune (Q_{spin}) and gives the number of revolutions the spin vector makes about the vertical axis in one revolution of the storage ring. Since both ω_0 and a are known to a high precision, measurement of Ω_z gives a very precise measurement of the beam energy γ.

The polarisation build-up in an initially unpolarised electron beam is described by the equation

$$P(t) = P_{ST}\frac{\tau_d}{\tau_d + \tau_{ST}}\left[\mathbf{1} - exp\left(-t\left(\frac{\tau_d + \tau_{ST}}{\tau_{ST}\tau_d}\right)\right)\right] \tag{2}$$

where P_{ST} and τ_{ST} are the Sokolov-Ternov values for the equilibrium polarisation level and polarisation time-constant respectively. The depolarisation time-constant τ_d accounts for all naturally occurring depolarising effects in the ring. These occur whenever the electrons travel through a horizontal magnetic field (giving a vertical deflection), such as during vertical betatron motion in quadrupoles or from closed orbit distortions. However, such effects are generally weak thanks to the excellent alignment, efficient orbit correction schemes and low vertical emittance characteristic of modern light sources. For Diamond, τ_{ST} is 30.0 minutes and the effective time-constant for the polarisation build-up is measured to be 27.7 minutes. From equation 2, this gives a τ_d of 364.2 minutes and an equilibrium polarisation level of 85.4%.

In order to strongly depolarise the beam, vertical oscillations must be excited in the beam at a well defined frequency that matches the fractional part of the spin tune:

$$f_{kicker} = \left(Q_{spin} - \lfloor Q_{spin} \rfloor + n\right)f_{rev} \tag{3}$$

When the vertical excitation is in resonance with the spin tune, the spin-vector is tilted away from the vertical axis by a small amount in successive revolutions of the storage ring, gradually reducing the beam polarisation.

The most straightforward way to monitor the polarisation build-up and subsequent depolarisation is from the Touschek lifetime (τ_T), or equivalently the electron loss rate [3]. The polarisation at time t can be found from the Touschek lifetime using the relation [4]

$$P(t) \propto \sqrt{\frac{1}{\tau_T(0)} - \frac{1}{\tau_T(t)}} \tag{4}$$

For the purposes of a beam energy measurement it is not necessary to have an absolute measurement of the beam polarisation; it is sufficient to be able to detect a step-change from one polarisation state to another.

EXPERIMENTAL SETUP

First attempts of spin depolarisation were done using the lifetime calculated from the DCCT and the loss rate as recorded on PIN diode based loss monitors. However, both methods proved too noisy, the DCCT being limited by *1/f* noise and the PIN diode based loss monitors seeing too few counts (only a few 1,000 s^{-1}) for reliable statistics.

As an alternative, a PMT with a fast scintillator and counter has been installed adjacent to the scrapers, which can be driven close to the stored beam to make this the location where the majority of electrons are lost. With this setup, we were able to achieve count rates of more than 100,000 s^{-1} giving us an expected relative standard error of 0.3% on the loss rate with 1 s integration time.

For excitation we used the striplines which are normally part of the transverse multibunch feedback and drove these with a programmable oscillator instead. After some optimisation we settled for an output of 65 W from the amplifier into the pair of 50 Ω terminated striplines.

This would drive a peak current of 1.14 A which generated a peak integrated magnetic field estimated at 45 μTm resulting in a peak deflection of 4.5 μrad.

For the measurements the storage ring was filled to 225 mA in 900 bunches (0.25 mA per bunch). Due to the already high count rate from the PMT we found it was not necessary to enhance the scattering rate by reducing the coupling from the nominal value of 1% for standard user operations.

MEASUREMENT RESULTS

Beam Energy

Following a series of DCCT-based beam energy measurements made in 2010, first trials using the PMT-based loss monitor were carried out in July 2011. The spin precession frequency was found by exciting the beam at a series of fixed frequencies and monitoring the loss rate as a function of excitation frequency. Optimal values for the sweep rate were found to be 7 Hz steps with a dwell time of 1 second. At the point where the vertical excitation was in resonance with the spin precession frequency, a depolarisation in the beam occurred and a step-change could be seen in the loss rate.

In order to extract the beam energy from this data, the PMT count rate was normalised to the beam current and a numerical fit was used to determine the centre of the resonance and resonance width. An example of a beam energy measurement made in this way is shown in Fig. 1, for which the energy is measured to be 3.01471 GeV and the resonance width is 56 keV.

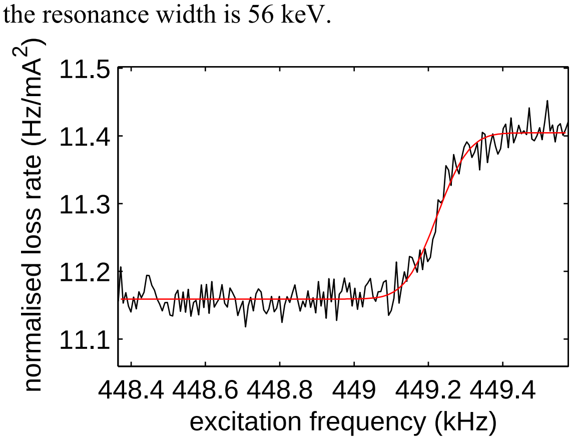

Figure 1: Normalised loss rate as a function of excitation frequency (black). The red line shows a fit to the measured data.

To confirm that the depolarisation frequency corresponds to the beam energy and not a synchrotron sideband, the scans were repeated over a larger frequency range for several different cavity voltages (see Fig. 2). The results consistently showed a depolarisation at an excitation frequency of 449.2 kHz, corresponding to a beam energy of 3.0147 GeV. Depolarisations were also observed at lower and higher excitations frequencies, separated from the main depolarisation frequency by values in close agreement with the measured synchrotron frequency.

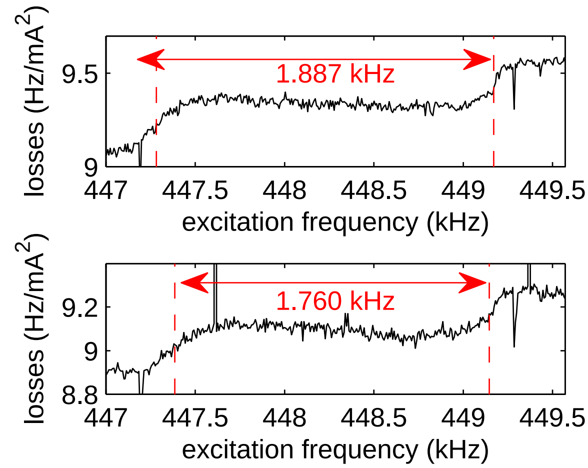

Figure 2: Normalised loss rate vs. excitation frequency for cavity voltages of 2.6 MV (top) and 2.4 MV (bottom).

A comparison has also been made to the effect of reversing the direction of the frequency sweep. It was found that the difference in measured energy was comparable to that found from repeated measurements made for fixed sweep direction, and so the systematic errors introduced by the sweep direction are judged to be negligible.

Energy Stability

The stability of the electron beam energy during top up operation was tracked by repeated resonant spin depolarisation measurements over a 5 hour period with fast orbit and RF feedbacks running. For the first 3 hours all in-vacuum IDs were left open and the super conducting wigglers (SCW) were turned off. After this, all in-vacuum IDs were closed to their typical operational gaps for 1 hour, then for the final hour both SCWs were additionally turned on to full field. The measured beam energy over this period is shown in Fig. 3, along with the RF frequency (as set by the RF feedback). The measurements have a mean value of 3.014657 GeV with 9.1 keV standard deviation.

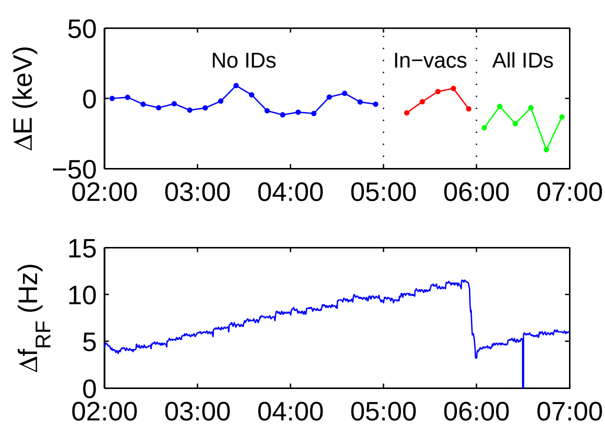

Figure 3: Measured beam energy over a 5 hour period with and without ID changes (top). RF frequency during the measurements (bottom).

During the first 4 hours of the measurement the RF frequency was shifted upwards by a total of 7.8 Hz, which should correspond to a drop in beam energy of 275 keV. However, no such drift in beam energy was observed, suggesting the RF feedback is correctly compensating for real changes in the ring circumference.

In the final hour, a small step down in the beam energy of ~10 keV was observed at the point when the SCWs were turned on. At this point, the RF feedback adjusted the RF frequency downwards by 7.4 Hz. The expected theoretical increase in path length due to an ID of length L_u and undulator parameter K_u is $\Delta\ell = (K_u/\gamma)^2 L_u/4$, equivalent to a combined change in RF frequency 6.3 Hz. Again, the RF feedback responds correctly to a change in path length and maintains constant beam energy.

Momentum Compaction Factor

The momentum compaction factor was measured by stepping the RF frequency between ±100 Hz and recording the beam energy each time. Between each measurement, the beam current was topped up and orbit feedbacks run to minimise the effects of thermal and environmental drift. The results are shown in Fig. 4. Using a polynominal fit, the momentum compaction factor was measured to be $\alpha_1 = 1.72\times10^{-4} \pm 0.02\times10^{-4}$ compared with $\alpha_1 = 1.66\times10^{-4}$ from the machine model. The reason for the slight discrepancy remains to be determined, but is thought to be related to the different ID configuration between the time of the measurement and the previous storage ring linear optics correction.

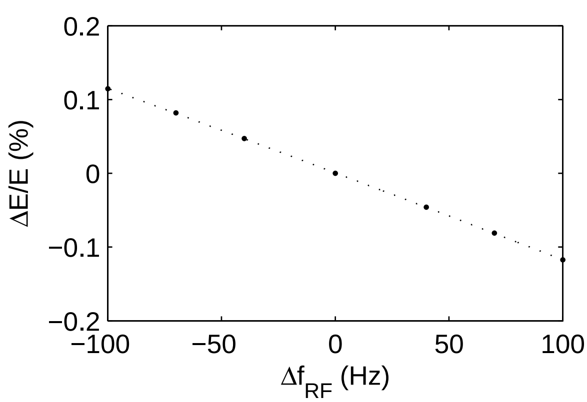

Figure 4: Measured change in beam energy with change in RF frequency. The slope of the curve can be used to calculate the momentum compaction factor.

Natural Chromaticity

The natural chromaticity was measured by changing the field strength of the main dipole bending magnets and measuring the resulting change in betatron tunes. The dipole current was varied in 6 steps between 1354.4A and 1354.9A, corresponding to a change in beam energy of +406 keV / -330 keV. The results are shown in Fig. 5. From the slope of this data, the measured horizontal and vertical natural chromaticities are -81.4±0.5 and -31.6±0.5 respectively. This experiment can be simulated in AT [5] using a model for the bending magnets based on the exact Hamiltonian with a symplectic second order fringe field that varies with the main dipole field [6]. This calculation gives values of -81.9 and -31.6 for the horizontal and vertical natural chromaticities, in good agreement with the measured values.

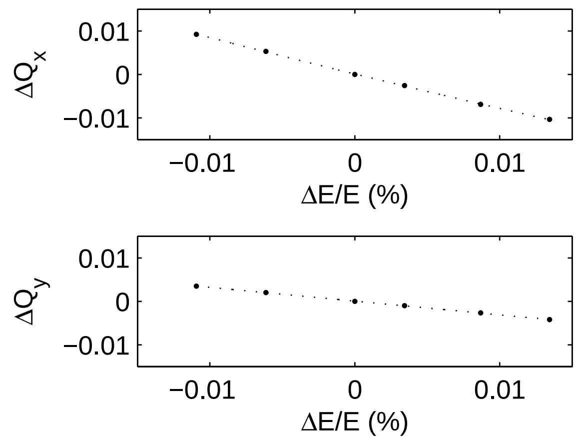

Figure 5: Horizontal (top) and vertical (bottom) tune shift as a function of relative change in beam energy. The slope of the data gives the measured natural chromaticity.

Quadrupole Strengths

The quadrupole gradients are regularly corrected using the LOCO algorithm [7]. This process increases the mean gradient by 0.40% above the theoretical values, previously attributed to imprecise knowledge of the calibration factors and magnetic lengths. However, these studies have shown the discrepancy can in large part be accounted for by the machine energy offset of 0.49%.

CONCLUSIONS

Measurements of the beam energy can be carried out routinely in a matter of minutes. Thanks to the operation of top-up, orbit and RF feedbacks, the beam energy has been demonstrated to be very stable over timescales from a few hours to several weeks. Further trials are planned to establish whether such measurements can be carried out during user time for long-term tracking purposes.

ACKNOWLEDGEMENTS

The authors would like to thank R.P. Walker and J.H. Rowland for suggestions and contributions to this work, particularly regarding the simulation of the natural chromaticity measurement.

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