Energy Calibration of the Electron Beam of the ALS using Resonant Depolarization*

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Abstract

The beam energy at the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory was measured with high precision using resonant depolarization. In a storage ring where the beam lifetime is dominated by large-angle intrabeam (Touschek) scattering, the relative beam polarization can be measured by relative changes in the beam lifetime because of the dependence of the Møller scattering rate on the polarization. In the fully Touschek-dominated regime, the change in lifetime at the ALS due to a complete depolarization is larger than 10%. The energy calibration has been used at the ALS to perform high precision measurements of the machine stability, machine reproducibility and the momentum compaction factor.

1 INTRODUCTION

The energy of an electron beam can be calculated fairly accurately from a model of the integrated dipole fields around the storage ring. However, for several applications it is useful to know the beam energy to much higher accuracy. Because the precession frequency of the electron spin around the vertical dipole fields depends only on the beam energy, it is possible to accurately find the beam energy by measuring the spin precession frequency. This is done in several other accelerators, particularly high energy colliders such as the Large Electron Positron (LEP) collider, by resonantly depolarizing a polarized beam. However, this requires a measurement of the beam polarization and involves a fair amount of equipment, setup work and time.

Fortunately, for low-to-medium energy light sources like the ALS, it is possible to indirectly measure changes in the polarization and thereby determine the beam energy. The method was proposed for BESSY I in Berlin and has been frequently used there to determine the beam energy precisely for metrology applications [1, 2, 3].

As in high energy machines, the process of emission of synchrotron radiation naturally polarizes – in the absence of depolarizing resonances – any lepton beam (this is called Sokolov-Ternov effect [4]). For the ALS at a beam energy of 1.9 GeV, the calculated polarization time is about 35 minutes. The ALS beam lifetime is dominated by large-angle intrabeam (Touschek) scattering. The cross section for this scattering process is lower for electrons with parallel spins than for antiparallel spins. Therefore, a polarized beam will have fewer scattering events and a longer lifetime than an unpolarized beam. Thus we can use the beam lifetime, or equivalently a monitor of lost electrons, as a measure for changes in the polarization. The predicted relative lifetime changes depend on several machine parameters [5], especially the (dynamic) momentum acceptance. For typical ALS conditions one expects a relative change of 10-20% which has been experimentally confirmed.

Table 1: Nominal ALS parameters.

Parameter	Description	
E	Beam energy	1.5–1.9 GeV
C	Circumference	196.8 m
f_{rf}	RF frequency	499.654 MHz
h	Harmonic number	328
α	momentum compaction	$1.61 \cdot 10^{-3}$
I	beam current	200-400 mA

2 SPIN DYNAMICS AND DEPOLARIZATION

In a flat ring only the vertical component of the polarization is preserved. Every spin vector precesses around this direction according to the Thomas-BMT equation (electrical fields are neglected here):

$$\frac{d\vec{S}}{ds} = \frac{e}{m_e\, c\, \gamma} \left((1+a)\vec{B}_{\parallel} + (1+\gamma a)\vec{B}_{\perp} \right) \times \vec{S}, \quad (1)$$

where γ is the relativistic Lorentz factor, a is the gyromagnetic anomaly ($a = 1.159652 \cdot 10^{-3}$ for electrons and 1.792846 for protons), m_e is the electron mass, c the speed of light and $B_{\parallel}, B_{\perp}$ are the magnetic fields parallel and perpendicular to the motion of the electron, respectively. Therefore the precession frequency in storage rings to first approximation only depends on the particle energy: $Q_{sp} = \gamma a$, where Q_{sp} is the spin tune.

Due to an asymmetry in the spin-flip probabilities for the emission of a synchrotron radiation photon in a magnetic dipole field, lepton beams tend to become polarized if depolarizing effects [6] are sufficiently weak

$$P = A \left(1 - e^{-\frac{t}{\tau_{\mathrm{pol}}}} \right), \quad (2)$$

P is the polarization, A its equilibrium value and τ_{pol} is given by

$$\frac{1}{\tau_{\mathrm{pol}}} = \frac{5\sqrt{3}}{8} \frac{c \lambda_c r_e}{2\pi} \frac{\gamma^5}{\rho^3}, \quad (3)$$

where λ_c is the Compton wavelength, r_e the classical electron radius and ρ the magnetic bending radius.

Depolarizing resonances arise from resonant coupling of the spin precession to periodic horizontal magnetic fields. They can be divided into two main categories: intrinsic resonances due to the vertical betatron oscillations in

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quadrupoles and imperfection resonances due to vertical closed orbit distortions caused by magnet and alignment errors.

Fortunately for third generation synchrotron light sources, like the ALS, both resonance types are very weak, because of small alignment errors, excellent orbit correction and a very small vertical emittance. Calculations show that for the parameters of the ALS the equilibrium polarization resulting from the polarization build-up and depolarizing effects is close to the possible maximum value of 92.4%, unless the beam energy is chosen to be extremely close to an integer or first order intrinsic resonance.

To depolarize the beam for the energy measurement one excites a parametric depolarization resonance using a horizontal rf magnetic field with a frequency equal to the fractional spin tune. Using this technique the beam in the ALS can be depolarized completely within a few seconds.

3 EXPERIMENTAL TECHNIQUE

To generate the time-varying horizontal magnetic field we use a vertical stripline kicker normally used to excite vertical betatron oscillations for tune measurements or bunch purification in single bunch operation. We drive the kicker using a continuously swept excitation from the tracking generator of a spectrum analyzer (via a 150 W amplifier). We measure the beam lifetime from the rate of change of a DCCT (direct current current transformer) or we use a beam loss monitor to measure relative changes in loss rate. The beam loss monitor consists of a scintillating material connected to a photomultiplier and is located outside the vacuum chamber just downstream of a small-gap insertion device. The counts are integrated over one second. The small-gap chamber is the minimum vertical aperture in the ring and primary location where electrons are lost.

An example of the variation of lifetime with polarization is shown in Figure 1. Over the course of a 25 minute period the beam was excited at the spin frequency. The time of two partial depolarizations is evident in both the lifetime and the count rate. As the lifetime decreases slightly, the count rate increases. The slow lifetime increase during the complete measurement results from the slowly decaying current. Because of the higher sensitivity of the beam loss monitor and the faster time response, we used it as the primary monitor for changes in the lifetime.

In Figure 2 the normalized count rate from the beam loss monitors is shown as the excitation is swept through the spin resonance at upper and lower sideband frequencies. In the limit of the Touschek-dominated lifetime, the normalized loss rate should be a constant, barring polarization effects. As one can see the measurement agrees well with this expectation. The normalized loss rate is constant during most of the frequency sweep and only rises once, exactly when the excitation frequency coincides with the spin precession frequency and the beam gets depolarized. The measurement was carried out on both, the upper and the lower sideband in order to quantify the systematic error arising from the fixed sweep direction of the excitation. Systematic errors would shift the measured energy in both cases into different directions. Our result was that the difference is very small, of the order of $1 \cdot 10^{-5}$ which is about the same size as other errors of our measurement.

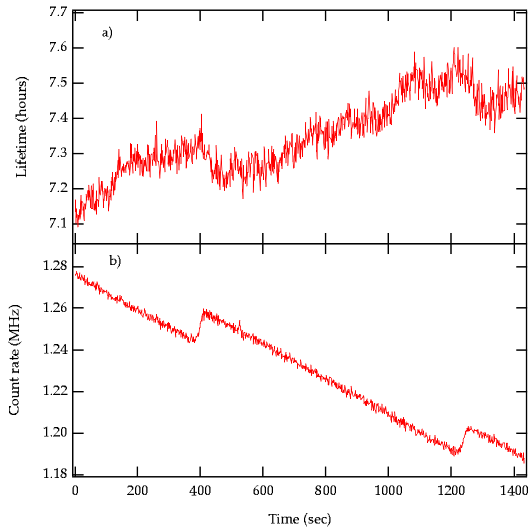

Figure 1: Beam lifetime derived from current monitor and count rate from beam loss detector showing two partial spin depolarizations over a 25 minute period.

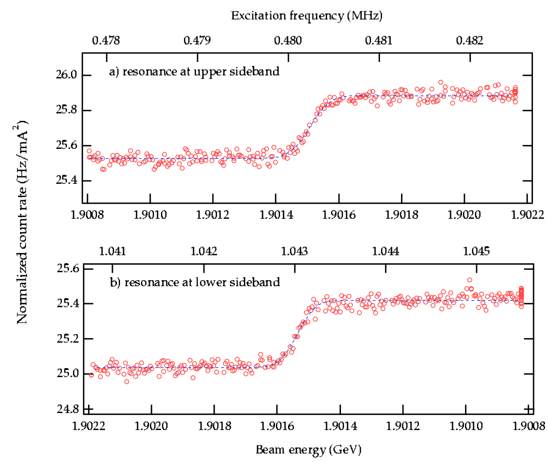

Figure 2: Normalized loss detector rate during excitation sweep of spin resonances. a) Sweep through upper sideband and b) lower sideband.

4 APPLICATIONS

One of the useful applications of the energy measurement is the precise determination of the lattice momentum compaction factor α, defined by $\frac{\Delta E}{E} = -\frac{1}{\alpha}\frac{\Delta f_{rf}}{f_{rf}}$, where f_{rf} is the RF frequency. The momentum compaction factor is notoriously difficult to measure other than with a direct beam energy measurement. Shown in Figure 3 is a measurement of the beam energy for several RF frequencies. The momentum compaction factor can be determined from the slope. We were able to measure the momentum compaction

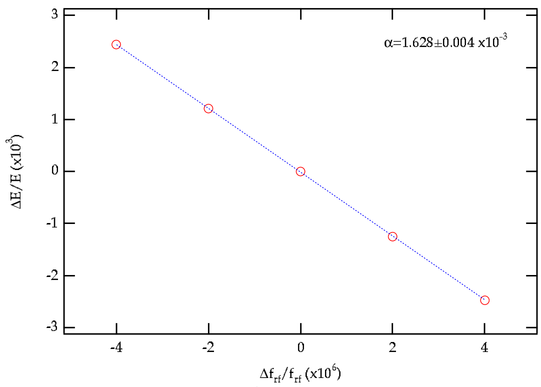

Figure 3: Measurement of the beam energy variation with RF frequency. The slope is the inverse of the momentum compaction factor.

factor to $(1.628 \pm 0.004) \cdot 10^{-3}$ with a relative accuracy of about 0.2%. The measured value is in good agreement with calculations based on the calibrated machine model of the ALS [7] which yield $(1.616 \pm 0.008) \cdot 10^{-3}$. Currently we are working to expand the measurement to determine the nonlinear momentum compaction factor α_2.

Another application of interest is to measure the stability of the energy over time. Shown in Figure 4 is the relative beam energy variation measured every half hour over an 8 hour period during user operation. Because this process was automated, some measurements were invalid because they were made during either the injection process, energy ramping, or during insertion device movement and have been taken out of the plot. During this particular measurement, two injections and energy ramps occurred. The measurements show an energy variation of less than $1 \cdot 10^{-4}$ over an eight hour period. Repeated measurements over a week have confirmed, that the typical energy variations over that time period are of the same size. This is remarkable, since no feedback is used to correct the rf-frequency. Reason for variations of this order are mostly thermal (air and water temperatures at the ALS are constant to a few tenths of a degree) and tidal effects.

In another measurement series we tested our magnet calibration by measuring the absolute beam energy for different energy setpoints. Next year the dipole magnets in the ALS will become decoupled with the replacement of three normal conducting bending magnets with so called Superbends (C-shaped, superconducting, 5 T dipoles) in order to expand the capabilities of the ALS in the hard x-ray region [8]. This will require a better knowledge of the relative magnetic field of both bend magnet types. In addition the reproducibility of the dipole magnets will be a more important factor, since mismatches between the bend families would generate large horizontal orbit distortions. Our measurements showed that the calibration of the main bending magnets is known with sufficient accuracy and that the reproducibility is good enough for the requirements of Superbend operation.

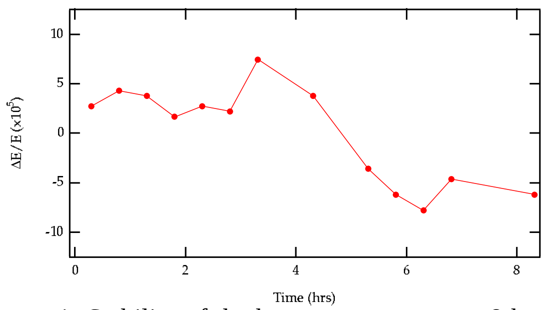

Figure 4: Stability of the beam energy over an 8 hour period. Two beam injections and energy ramps occurred during this time.

5 CONCLUSIONS

We have measured the ALS beam energy with a relative precision of $1 \cdot 10^{-5}$ using resonant spin depolarization. The spin depolarization was indirectly observed by the change in Touschek lifetime because of the spin-dependent scattering rate of the electrons. Because the beam lifetime at most lower energy synchrotron light sources is dominated by Touschek scattering, this should be a relatively simple technique to measure integral machine quantities like the momentum compaction factor and monitor machine stability, as long as the polarization time is smaller than the beam lifetime.

6 ACKNOWLEDGEMENTS

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