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CONTINUOUS BEAM ENERGY MEASUREMENTS IN DIAMOND LIGHT SOURCE

N. Vitoratou*, P. Karataev
John Adams Institute at Royal Holloway, University of London, Egham, UK
G. Rehm, Diamond Light Source, Oxfordshire, UK

Abstract

Resonant Spin Depolarization (RSD) is a high precision technique that has been employed by Diamond Light Source (DLS) for beam energy measurements. In this project, we study a new approach to make RSD compatible with user beam operation and provide a continuously updated online measurement. An array of four custom-made scintillation detectors has been installed around the beam pipe, downstream of collimators to capture the highest fraction of lost particles and maximize the count rate. The excitation is gated to half of the stored bunches and the acquisition system counts losses in both halves independently. Using the count in the un-excited part for normalisation suppresses external factors that modify the loss rate. Different parameters of the measurement, like excitation kick strength and duration have been explored to optimise depolarisation and to increase the reliability of the measurement.

INTRODUCTION AND MOTIVATION

The technique of RSD takes advantage of the natural spin polarisation due to synchrotron radiation emission and provides a high precision energy measurement with a relative uncertainty of typically 10^{-6} [1]. A continuous beam energy measurement employing this technique could reveal any correlations with the photon energy fluctuations and give information about the stability of the bending magnets power supply. Thus, in Diamond Light Source, a method is being developed to make these measurements compatible with the user operation, where the main challenges are not to disturb the stored beam and counteract external factors that could influence the measurement.

BEAM POLARISATION

The spin of the electron beam will develop a polarisation, due to the emission of the spin-flip radiation, according to Sokolov-Ternov effect, which is antiparallel with the magnetic field of the main bending magnets. In an ideal ring, in the absence of depolarizing effects, the maximum expected beam polarization is 92 % [2]. The amount of polarisation will be a combination of the polarising and depolarising effects that is given by [3] :

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

where P_{ST} and τ_{ST} are the Sokolov-Ternov values for the equilibrium polarisation level and time constant respectively, and τ_d the depolarisation time constanst. Depolarising effects can occur by horizontal magnetic fields due to closed orbit distortions or quadrupoles misalignments. However, excellent alignment, orbit correction schemes and small vertical emittance in DLS weakens these effects and allow the beam to have an equilibrium polarisation level of 82 % .

Another limit in the polarisation level is introduced by wigglers. The wigglers increase the energy spread which is related with the asymptotic polarisation level given by Sokolov-Ternov effect [4]. This effect will reduce the polarisation level to 60 % for the case of DLS, as it is shown in Fig. 1.

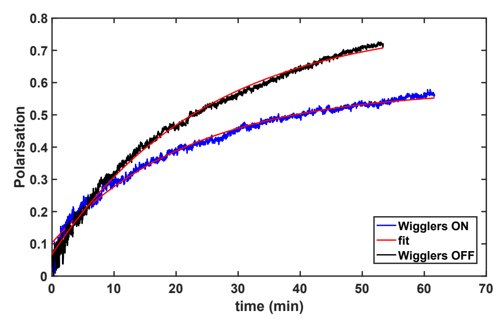

Figure 1: Polarisation build-up of stored beam with wigglers on and off, one hour after injection. The polarisation level is expressed as the relative increase of the lifetime. The lifetime is calculated by the inverse of the recorded beam losses normalised by the beam current [5]. The applied fit is based on Eq. (1).

BEAM DEPOLARISATION

The spin precession frequency of an ultra-relativistic electron in a magnetic field follows the Thomas–BMT equation which for a light source storage ring where there are no significant solenoid magnetic fields, nor transverse electric fields, can be simplified to the below form [6]:

$$\Omega_z = \omega_0(1+\alpha\gamma) \quad (2)$$

where ω_0 is the revolution frequency, α the gyromagnetic anomaly and γ the relativistic factor. The product $\alpha\gamma$ is the number of revolutions the spin vector makes about the vertical axis in one revolution of the storage ring defined as the spin tune. The equation above shows the relation between the energy of the beam and the spin precession frequency and by determining the unknown frequency, the energy can be calculated.

* Niki.Vitoratou.2016@live.rhul.ac.uk

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For the determination of the spin tune, the stored polarised beam is excited by a horizontal magnetic field produced by a pair of vertical striplines. The magnetic field is set to oscillate in different frequencies that match the fractional part of the spin tune:

$$f_{dep} = (\alpha\gamma - k) \cdot f_{rev} \tag{3}$$

where k is the integer part of the spin tune. When the excitation frequency corresponds to the spin tune, the spin vector starts to tilt away from the vertical axis by a small amount in consecutive revolutions as a result of the resonance. This will lead to the depolarisation of the beam which indicates the energy of the beam.

Touschek Particles

The relation between the polarisation of the beam and the Touschek particles is used in this study to determine the level of the beam polarisation. Touschek particles are lost particles that result from a Möller scattering collision between two electrons. The electrons transfer high momentum from transverse to longitudinal motion and exceed the longitudinal acceptance limit. The scattering cross section is spin dependent hence the particle loss rate depends on the polarisation [7]:

$$-\frac{1}{N}\frac{dN}{dt} = \alpha[C(\varepsilon) + F(\varepsilon)P^2]N \tag{4}$$

where,

$$C(\varepsilon) = \varepsilon \int_{\varepsilon}^{\infty} \frac{1}{u^2}\left\{\left(\frac{u}{\varepsilon}\right) - \frac{1}{2}\ln\left(\frac{u}{\varepsilon}\right) - 1\right\} e^{-u} du \tag{5}$$

$$F(\varepsilon) = -\frac{\varepsilon}{2}\int_{\varepsilon}^{\infty} \frac{1}{u^2}\ln\frac{u}{\varepsilon} e^{-u} du \tag{6}$$

and

$$\varepsilon = \left(\frac{\delta_{acc}}{\gamma\sigma_{x'}}\right)^2 \tag{7}$$

where δ_{acc} is the momentum acceptance, γ is the Lorentz relativistic factor and σ_x' is the standard deviation of the beam distribution in horizontal angle. For a measurement, these numerical integrals, can be treated as constants. Since the $F(\varepsilon)$ integral is a negative number, a partial depolarisation will cause a rise of the loss rate.

Froissart-Stora Equation

The initially vertical polarised beam which is perturbed by a horizontal magnetic field can be depolarised when the perturbation induces a spin resonance. The Froissart-Stora formula describes the spin transport through a single resonance where the final polarisation is given by [8]:

$$P_y(\infty) = \left(2e^{\frac{\pi|\epsilon|^2}{2\alpha}} - 1\right) P_y(-\infty) \tag{8}$$

where ϵ is the resonance strength, α the rate of resonance crossing which is given as function of the frequency step Δf, the excitation time Δt and the revolution frequency f_0 by the equation $\alpha = \frac{\Delta f_{rf}}{2\pi f_0^2 \Delta t}$. $P_y(\infty)$ and $P_y(-\infty)$ refer to the initial and final polarisation, respectively. This formula shows that a large polarization loss can occur when the crossing speed is comparable to the square of the resonance strength.

BEAM ENERGY MEASUREMENT SETUP

The setup for the energy measurements by means of beam depolarisation consists of a device that generates the depolarisation field and the beam loss monitors that record the beam losses and witness the beam depolarisation.

The horizontal oscillating magnetic field is generated by the vertical striplines to depolarise the vertical oriented electron spin. Two 30 cm long kicker striplines, part of the transverse multibunch feedback system (TMBF), can produce magnetic fields up to 8 µTm. Two additional characteristics that are integrated into TMBF system assist to perform the energy measurements during user operation. Firstly, there is the possibility of using different amplifications in the strength of the kickers in order not to disturb the small vertical size of the stored beam during the excitation. Another characteristic is a numerically control oscillator that can be modulated with an internally synchronized rectangular waveform. This waveform is used to gate the sinusoidal signal and consequently the magnetic field generated in the striplines. By this way, the excitation is acting only on a part of the beam as it is illustrated in Fig. 2.

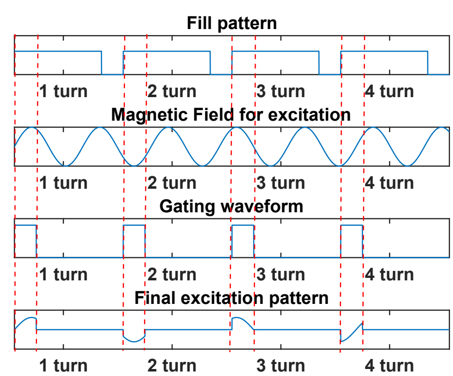

Figure 2: The sinusoidal signal is gated according to a rectangular waveform. By this way, only one selected part of the fill pattern is excited, and the rest is unaffected.

The beam loss monitor setup consists of a set of four detectors connected with a commercial acquisition instrument (Instrumentation Technologies Libera BLM [9]). Four blocks, 15 cm long, made by scintillator EJ204 [10], as it is shown in Fig. 3, were manufactured in order to fit around the octagonal shape of the beam pipe, and were installed downstream the collimators, where there is a limited physical aperture. Based on results from a radiochromic film that was installed in the same area, the highest fraction of the beam losses is captured with this custom-made blocks and the count rate is maximised [11].

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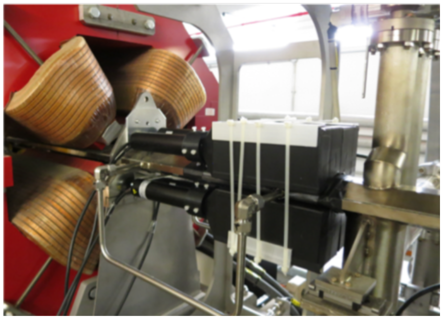

Figure 3: The four blocks of scintillator are installed downstream around the beam pipe to capture the highest fraction of the beam losses after the collimators, where the physical aperture is limited.

The four detectors are attached with a photomultiplier with a bialkali photocathode that matches with the wavelength of the scintillator light. Thin silicon pads were placed between the photocathode and the ending of the scintillator block in order to avoid any reflections when the light passes through the two different materials. The monitors are protected by a thin sheet of lead 1.3 mm thick from background ionizing radiation. The photomultipliers are connected with the acquisition instrument using two hardware interfaces. Four coaxial connectors are used for signal input and four RJ-25 connectors for power supplying and voltage gain control. The instrument is set with low impedance input of 50 Ω for short individual pulses. The input signals are sampled using an ADC with a clock which is locked to a quarter of bunch frequency, a little below 125 MHz.

The ADC data is continuously monitored and counted based on the difference between the two neighbouring samples. A dead time after a detected loss and a difference threshold are set and the counter increments the counts based on an algorithm that can detect individual pulses. The differential counting is an additional feature of the acquisition system to avoid pile-up events that were observed in pulses produced by the scintillator. The thresholds were chosen in order to avoid false triggers from electronic noise. Another characteristic of the acquisition system is the gating of the ADC samples. Two processing windows are generated synchronised to the revolution clock at 533 kHz. The processing window length is set to the number of ADC samples, which means that the beam loss events are accounted for over every four bunches. The processing delay is set to receive two independent sets of ADC samples to align with the excited/not excited parts of the fill pattern.

ENERGY MEASUREMENTS

The new approach of this project is to make the energy measurements compatible with the user operation. Diamond Light Source operates with a small vertical emittance in the range of 8 pm rad and the main challenge is not to affect this quantity when the beam is excited for depolarisation. For this reason, a low current is applied in the striplines that is enough to depolarise the beam but not to affect the size of the beam.

Another factor that disturbs these measurements is the beam losses that are created by different causes than depolarisation. To overcome these problems the idea of gating the excitation pattern and the beam losses was introduced. One part of the beam is excited and one mask of the acquisition system counts the resulting beam losses, while the second mask counts the beam losses from another, equivalent in charge, part of the beam. Thus, external factors that modifiy losses, like the changing of insertion device gaps, will be recorded by the two masks, but the losses that are created due to depolarisation will be seen only by one mask. Dividing the counts from the two masks, the ratio will be equal to one and only when the depolarisation occurs, this ratio will change and will indicate the spin precession frequency, as it is shown in Fig. 4.

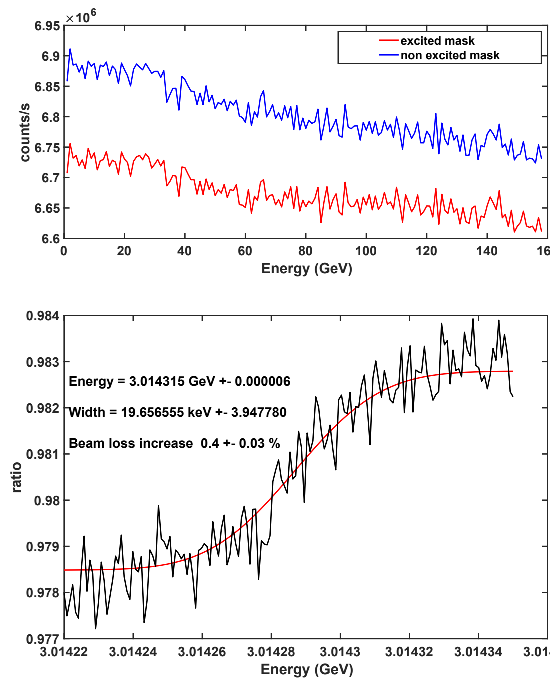

Figure 4: The red plot (mask 1) corresponds to the beam losses from the excited part of the beam while the blue plot (mask 2) to the beam losses of the unexcited part. The ratio between these two masks shows the depolarisation of the excited part and counteracts the common decreasing trend of the beam losses due to the current drop.

During the energy measurements, the beam is excited in different frequencies for a certain amount of time depending on the strength of the excitation. As it was referred, the excitation strength was chosen to be low, and this implies that for a decent amount of depolarisation the beam should be excited for a long time according to Froissart-Stora formula. Typically, scans last more than ten minutes which is the time interval for top-up at DLS. The top-up system selects to fill the bunches with the lowest charge and creates inequalities between the losses of the two masks, as the losses depend

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on the total charge in each mask. Hence, the ratio between the counts of the two masks is recorded before and after the injection, without beam excitation, and the difference is calculated and included in the analysis. Using this method, we can have long scans keeping the count ratio of the two masks unrelated with the top-up injections.

In the end, the solution to another problem that has arisen due to the high sensitivity of the beam loss detectors is explored. The geometry of the detectors is optimised to capture the highest fraction of the beam losses and maximise the counting rate. As the data follow Poisson statistics a high number of counts means high precision in the measurements and can reveal any change that happens during the excitation, as for example, some weak higher order betatron resonances that are excited and create losses that interfere with the beam loss data due to depolarisation. For this purpose, after every excitation in each frequency, the scan is suspended for one second, the beam losses due to betatron resonances fade and only the losses due to depolarisation remain. With these techniques, energy measurements were accomplished in parallel with the user operation, giving continuous readings of the energy of the stored electron beam (Fig. 5).

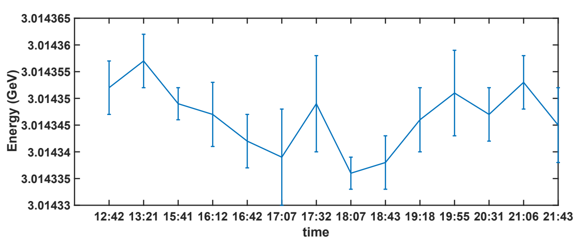

Figure 5: Continuous measurements of the energy during one day of user operation.

DISCUSSION

The optimisation of the continuous energy measurements needs a better understanding of the beam loss rise due to depolarisation, which from our recent results cannot be higher than 0.4 % with the nominal settings that are used in the control room. A higher increase in the losses would make this measurement more precise, with a smaller fit error. Using stronger magnetic fields in the striplines, the maximum rise that has been achieved is 1 %. However, this is not in agreement with the 5 % decrease that has been observed during the beam polarisation. Different steps in the frequency, as well as in the duration of the excitation did not improve the beam loss rise. More studies are carried out in this direction with the goal of increasing the beam losses step when the depolarisation occurs.

SUMMARY

The level of polarisation that can be achieved during the user operation, which includes wigglers on, has been evaluated. The characteristics of the measurements setup and the details of the technique that are used for the energy measurements have been described. A continuous reading of the energy every thirty minutes, that is the duration of each scan has been achieved and more details regarding the optimisation of the measurement are subject of the ongoing studies.

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