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BEAM LOSS MONITORS FOR ENERGY MEASUREMENTS IN DIAMOND LIGHT SOURCE

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Abstract

Resonant Spin Depolarization is a high precision technique for beam energy measurement employed in the Diamond Light Source storage ring. The relation between spin tune and beam energy can be used to determine the energy of a transversely polarized beam. Vertical oscillations excite the beam at frequencies that match the fractional part of the spin tune and the beam loss rate is used to monitor the beam depolarization. However, the standard procedure of these measurements is intrusive and not compatible with user operation of a light source. The Advanced Resonant Spin Depolarization (AdReSD) project aims to extend and improve the method with the goal of making the measurements compatible with the user operation, for instance by acting only on a small fraction of the stored beam. As a first step, we are investigating the beam loss monitors that will be used to detect beam depolarization. The material, location and optimal geometry of the detector to capture the largest fraction of the radiation footprint resulting from beam losses are studied. Results and designs are presented and future work is discussed.

INTRODUCTION AND MOTIVATION

Diamond Light Source is a 3 GeV, 561m circumference synchrotron light source in operation since 2007. The precise energy of the stored beam has been measured in 2011 [1], and at an infrequent rate thereafter.

More recently, motivation was given to an increased rate of measurements to check for correlation with photon energy fluctuations. Ultimately, this lead to the project presented here, which aims to determine the stored beam energy precisely and at the same time in a way that is not interfering with ongoing 'user operations'.

RESONANT SPIN DEPOLARIZATION

Beam Polarization

The spin of electrons in a storage ring will start to be randomly oriented after injection. The spin vector of individual electrons will develop an overall polarization due to spin flip radiation emission according to the Sokolov - Ternov effect. The spin will gradually align antiparallel with the main guide field of the bending magnets leading to a polarization build up that is given by the equation [2] :

$$P(t) = P_0(1 - e^{t/\tau_0}) \tag{1}$$

where the maximum polarization for an ideal flat storage ring without field errors is $P_0 = 8/5\sqrt{(3)} = 0.9238$ and the time constant of the exponential build-up process is:

$$\tau_0 = [\frac{5\sqrt{3}}{8}\frac{e^2\hbar\gamma^5}{m^2c^2\rho^3}]^{-1} \tag{2}$$

For Diamond Light Source, considering the depolarizing effects for a non-ideal ring, the polarization time has been calculated 27.7 minutes with a maximum polarization of 85.4 % [1]

Spin Precession

The spin precession frequency for a light source storage ring where there are no significant solenoid magnetic fields, nor transverse electric fields, is described by:

$$\Omega_z = \omega_0(1 + \alpha\gamma) \tag{3}$$

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. Since α and ω_0 are known, the beam energy can be calculated.

In order to measure the spin tune and calculate the energy of the beam, a polarized beam is needed. The beam is then excited by a horizontal magnetic field produced using a vertical stripline. The magnetic field is set to oscillate at a frequency f_{dep} which matches the fractional part of the spin tune:

$$f_{dep} = (\alpha\gamma - k) \cdot f_{rev} \tag{4}$$

where k is the integer part of the spin tune. When the horizontal excitation frequency 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 polarization. This is were the term Resonant Spin Depolarization (RSD) has its origin.

Touschek Scattering

Touschek effect is a Möller scattering collision process between two electrons of the bunch. The collision can transfer momentum from transverse to longitudinal motion, and both the electrons can exceed the longitudinal acceptance, in which case they are lost. The scattering cross section is spin dependent hence the particle loss rate depends on the beam polarization.

For a stored beam with equal current in several bunches the bunch population $N(t)$ is proportional to the current $I(t)$

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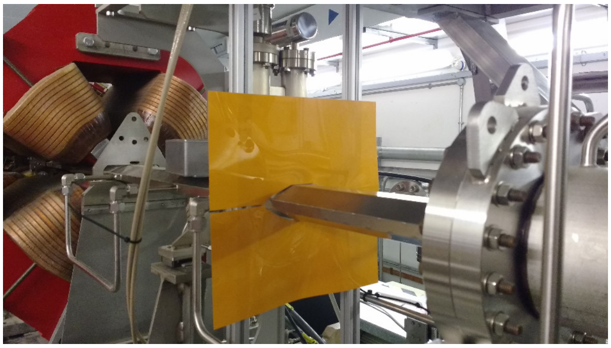

Figure 1: Radiochromic film installed in the storage ring of Diamond Light Source.

and the normalized loss rate R_{norm} can be written :

$$R_{norm} = \frac{1}{I(t)^2}\frac{dN}{dt} \propto f_1 + f_2 P(t)^2 \qquad (5)$$

where the functions f_1 and f_2 can be treated for a given measurement as constants [3]. A partial depolarization will result in a reduction of the polarization level and consequently in a rise of the normalized loss rate since the constant f_2 is a negative number [4].

RADIATION FOOTPRINT

A beam loss monitor is going to be required for detecting the particles lost as a result of Touschek events and recording the consequential partial depolarization of the beam.

The detectors are located one meter downstream the vertical and horizontal collimator where the losses are generally high in comparison to other areas of the storage ring. The physical aperture of the beam is small, and the Touschek particles that get lost, hit the scrapers creating electromagnetic showers.

These charged shower particles are going later to be detected and counted by the beam loss monitors. Thus, the radiation around the beam pipe is studied to position the detectors under investigation in a location where the radiation is equally distributed. In addition this study will contribute to the future detector design geometry that is optimal for capturing the highest fraction of the lost particles.

A radiochromic film is used to evaluate the radiation footprint in the area of interest. Radiochromic film RTQA2 [5] is typically used for testing radiotherapy sources and commissioning therapy equipment. However, the dynamic range of the film also works in the storage ring of Diamond Light Source, with a source beam of 3 GeV electrons. The radiochromic film consists of a single or double layer of radiation-sensitive organic microcrystal monomers on a thin polyester base with a transparent coating. The darkness of the film increases with the absorbed dose, and no processing is required to develop the image.

A film of dimensions 30 cm×30 cm had been cut, formed to fit around the beam pipe and exposed for one week to the electron beam, see Fig. 1. The film darkening is shown in the Fig. 2. The exposed radiochromic film was scanned, and the dose along the film was calculated using a calibration formula that was given by the manufacturer.

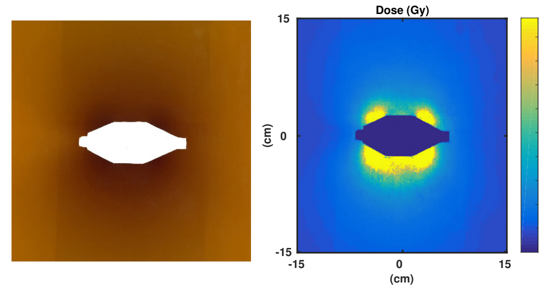

Figure 2: The darkening of radiochromic film after one week of exposure in the storage ring beam and the calculated absorbed dose by the film. The film is used as a dosimeter to measure the radiation in the tested area.

The radiation is high close to the beam pipe and starts to fade just a few cm further out. The horizontal collimator causes the dark shadow vertically in the film and set limits of an area that should sensibly be covered by a detector. The asymmetry of the results above and below the beam pipe might be related a misalignments of the vertical collimator set which was discovered independently. However, a second film is going to be installed in order to investigate further this assumption after the alignment of the collimator set.

BEAM LOSS MONITOR SETUP

Detection of light produced by scintillators or Cerenkov radiators is one of the most common method of monitoring beam losses. Three beam loss monitors using light detection were tested. The performance of polymethyl methacrylate (PMMA, commonly known as acrylic glass) that is used as the detector of the beam loss monitors in Diamond was compared with the performance of the organic plastic scintillator EJ204 [6] and fused quartz used as a Cherenkov radiator . The Scintillator EJ204 has high efficiency, high speed with decay time of 1.8 ns, attenuation length of 160 cm and wavelength that matches with the bialkali photocathode of the attached photomultiplier. The Cherenkov radiators outputs light instantaneous with continuous spectrum without interacting with background low energy x-rays making the fused silica detector a good candidate for this study.

The three materials are shaped in a rod of 15 cm length and 3 cm diameter and attached with the same model of photomultiplier (Electron Tubes ET 9126). The monitors were installed in the storage ring 1 m downstream of the horizontal collimator set. They were positioned about 2 cm above the beam pipe where the radiation distribution is in the same level according to the radiochromic film results. A sheet of lead 1.3 mm thick is used to protect the detectors from background ionizing radiation.

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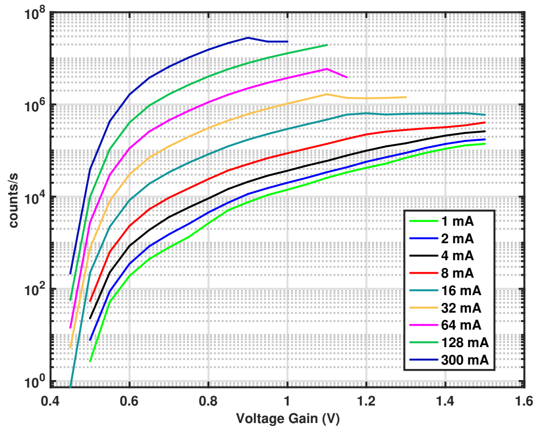

Figure 3: The count rate vs the voltage gain of the photomultiplier is presented for various beam currents. The different beam currents are illustrated by different colours. The saturation of the photomultiplier is observed for lower voltage gains as the beam current increases.

Signal Acquisition

The detectors were connected with a commercial acquisition instrument (Instrumentation Technologies Libera BLM [7]) with two hardware interfaces. Four coaxial connectors are used for signal input and four RJ-25 connectors for power suppling and voltage gain control. The instrument is set with low impedance input of 50 Ω for short individual pulses. The input signals are sampled at fixed ADC sampling clock with frequency 125 MHz. The ADC data is continuously monitored for negative peak value and when it exceeds the threshold value a counter increments by one. The threshold counter value was set to ≈1% of the 14-bit resolution ADC amplitude in order to avoid false triggers from electronic noise. The counter readout rate is set to 10 S/s.

RESULTS

Performance of Scintillator EJ204

The first results from the three beam loss monitors showed a problem of the scintillator EJ-204 for high loss rates as associated with high stored beam current, indicating that the high amount of light that is produced had damaged the attached photomultiplier tube. Using a new photomultiplier the performance of scintillator EJ204 was studied for different loss rates as produced increasing stored beam currents.

Starting with low beam current, the count rate was recorded while sweeping the voltage gain, as it is shown in Fig. 3. At 16 mA beam current, the photomultiplier started to saturate. As the beam current increases and the beam losses increase with the square of the stored beam current for a Touschek dominated beam, saturation was observed for increasingly lower voltages gains. Using this test, the maximum voltage gain for operation with the user beam of 300 mA was quantified, avoiding the saturation and any risk of damage of the photomultiplier tube.

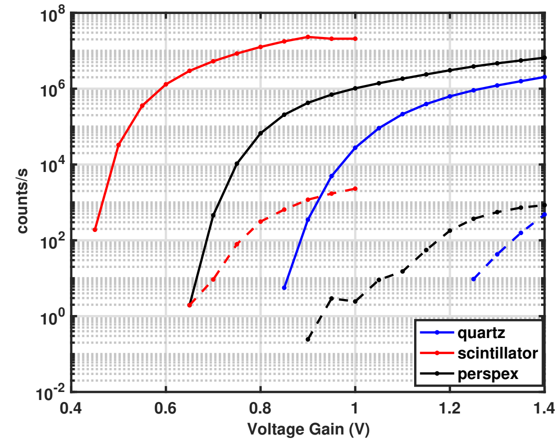

Figure 4: The comparison of the three detectors for 300 mA beam current is shown with the solid lines. The same scan was repeated to measure the background and is presented with dashed lines. The dynamic range of the detectors reduces for higher voltage gains because of the high bakcground events.

Comparison of Materials

Comparing the three detector materials the scintillator EJ204 gives the highest count rate even with lower voltage gain operation of the photomultiplier, as it is illustrated in Fig. 4. For comparison, the count rate of the detectors was also measured while there was no beam in the storage ring revealing that the scintillator and perspex count a high number of background events.

These background counts reduce the dynamic range of the detectors for higher voltage gain operation. We thus chose the voltage gain of the photomultiplier tube at an operating point where the background count rate is at a comparatively low rate of 10 counts/s, which should optimize the dynamic range. Further studies are going to be conducted to examine if a higher thickness of lead could improve the performance of the detectors eliminating the background counts.

Detector Performance in RSD

The performance of the three detectors was studied for energy measurements using resonant spin depolarization technique. A depolarization event was recorded by the three detectors as it is presented in Fig.5, and the results were analyzed. As a first step, the beam losses were normalized by the square of the beam current in order to retrieve information for the beam polarization. The rise of the normalized beam losses indicates a partial depolarization of the beam.

As it is shown in the Table 1, the count rate of scintillator is higher that the other three detectors. The expected relative error was calculated by the formula:

$$RE = \frac{\sqrt{counts}}{counts} \tag{6}$$

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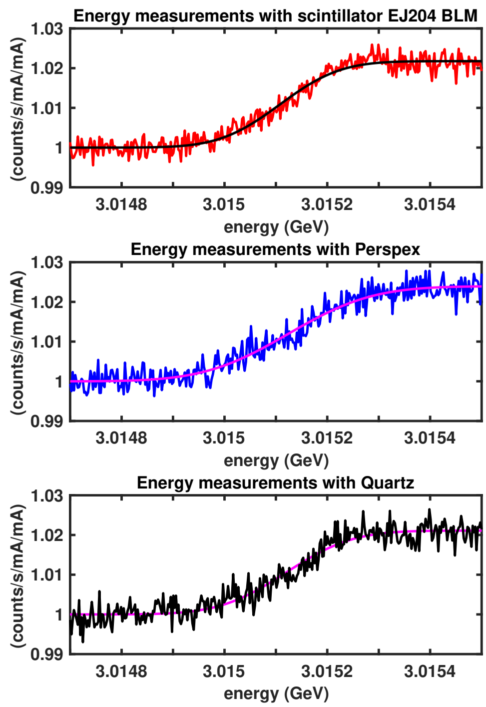

Figure 5: The performance of the three detectors recording a depolarization event. The beam losses are normalized with the square of the beam current. The count rate increases by the same amount for the three detectors. An error function fit calculates the energy of the beam and the width of the depolarization resonance.

Table 1: Measured Count Rates for Investigated Materials

material	**counts/s**	**RE**
EJ204	18 10^5	0.7 10^{-3}
Perspex	5.9 10^5	1.3 10^{-3}
Quartz	4.1 10^5	1.6 10^{-3}

Where $\overline{counts}$ is the mean value of the measured counts. According to Poisson statistics for counting events the error is calculated by the square root of the number of counts. The expected error is calculated to be lower for the material with the highest count rate.

The data after the depolarization were normalized with the data before to compare the counting response of the detectors in the increase of the beam losses due to depolarization. An error function fit calculates the width of the resonance and the results are shown in Table 2 . The standard deviation (std) of the difference between the data and the fit is evaluated, including the confidence intervals. This is used as a criterion to estimate the agreement between the fit and the data and to assess the precision of the results by the fit. The calculated std is found to be higher than the expected error indicating that improvements in the counting system should be considered to reach higher accuracy. This

Table 2: Calculated Parameters for Investigated Materials

material	**rise**	**width**	**std**
EJ204	2.2 %	92.4 keV	(1.8± 0.2) 10^{-3}
Perspex	2.3 %	128.6 keV	(2.3± 0.24) 10^{-3}
Quartz	2.1 %	101.9 keV	(2.4± 0.26) 10^{-3}

analysis confirms that high number of counts gives better measurement accuracy.

AdReSD PROJECT AND DETECTOR DESIGN

The Advanced Resonant Spin Depolarization (AdReSD) project aims to improve the technique of energy measurements and optimize it in order to be compatible with operation of Diamond Light Source with beam line users. Different aspects of this project are studied regarding the measurements method, the parameters of the beam that can be influenced and the beam loss monitor design.

The energy measurements are based on the excitation of the beam at different frequencies. This process could cause an increase in the vertical beam size due to coupling resonances. In order to preserve the beam size and to minimize the impact on beam parameters, the AdReSD project is going to excite only a small fraction of the beam, leaving the rest of the bunches unaffected. Once the energy information has been determined from the first group of bunches, the next group will be used for excitation and depolarization. In this way, the energy measurements can be continuous without the need of waiting time for beam polarization.

This type of measurements will require a beam loss monitor that can capture the highest fraction of lost particles. The design of the detector will include four identical blocks that will be positioned around the beam pipe as it is shown in Fig. 6. Their dimensions will be decided based on the radiation footprint results and light guides will be used to connect the detectors with the photomultipliers. The four detector setup will allow us to test the depolarization detection by coincidence counting based on the principle that Touschek particles lose and gain an equal amount of momentum when they scatter [8]. In addition, the setup offers the option of summing up the counts from all the detectors. These two methods that aim to optimize the detection of the depolarization will be compared.

CONCLUSIONS AND FUTURE WORK

The AdReSD project has been introduced, and different features of the project have been discussed. The comparison of three different detectors revealed that the scintillator EJ-204 is the most efficient in terms of photon output for a given lost particle flux. However, further investigation is needed to counteract the background counts, and higher thickness of the lead sheet will be considered to resolve the problem.

The objective for a high number of counts will lead to better measurement accuracy. For this reason, different count-

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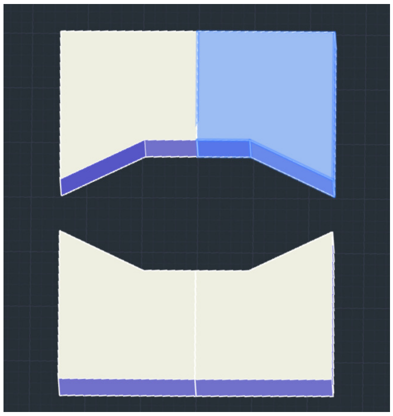

Figure 6: Future design of the beam loss monitor for the AdReSD project. Four block identical with the highlighted blue one will surround the beam pipe and capture the highest fraction of the beam losses.

ing methods for avoiding pile up problems are going to be implemented. In the end, the counts rates from the four future detectors are going to be used for testing the coincidence counting by losses due to depolarization events.

In conclusion, the design of the detector based on the radiation footprint results will be manufactured, and further details of the AdReSD project are going to be studied as soon as the detector setup is installed.

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