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RADIATION DAMAGE TO UNDULATOR ELECTRONICS AT AN ELECTRON ACCELERATOR

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Abstract

Experience gained from commissioning and operation of three elliptical polarization undulators (EPU) at the TPS taught us that undulator driving systems can behave erratically following a beam dump or loss. In this work, we discuss possible harmful radiation sources in a storage ring and analyse the effect of lack of electronic component radiation resistance in the system. According to measurements of spatial radiation distribution at the TPS, we propose solutions and an improved design for Phase-II EPUs.

INTRODUCTION

Insertion devices (ID) play a key role to produce radiation in a light source. Photon energy tuning and polarization control typically depends on a change in the magnetic field based on movements of permanent magnets (PM) in both, hybrid and pure type devices. A reliable driving system, therefore, is required. In addition to a robust mechanical structure, electronics in a driving system also need to be stable even in a radiation environment. Radiation damage and protection on an ID becomes a worthwhile item for discussion to obtain reliable operations.

An APPLE-II is a pure PM type EPU and capable to provide full polarization control by relative motion of all four PM arrays [1]. Two EPU48 and one EPU46 have been operating in the Taiwan Photon Source (TPS) with a 3 GeV storage ring since the end of 2015 [2]. Radiation damage on PMs and induced demagnetization [3,4] has not been observed, but the driving system can become erratic. A malfunction of optical encoders, sometimes called linear scalers, is found to follow an electron beam dump or loss, as seen by the events A and B in Fig. 1. The events generate erroneous position values. The event A auto recovers but the event B is followed by a violent drive of PM arrays in a closed-loop control system. To protect the EPUs, potentiometers have been installed to retain array position values, yet at a much reduced precision compared to optical encoders.

The objective of this work is therefore to propose solutions for radiation-induced interruptions from detailed studies of optical encoders and their radiation sensitivities. We organize this paper as follows. In Section 2, we discuss radiation sources at high energy electron accelerators and show measurements of spatial radiation distribution at the TPS. In Section 3, we study the radiation sensitivity of optical encoder components, including a review of reliability reports for semiconductor devices. In Section 4, we propose several solutions and show an improved EPU design for Phase-II at the TPS. A summary is given in Section 5.

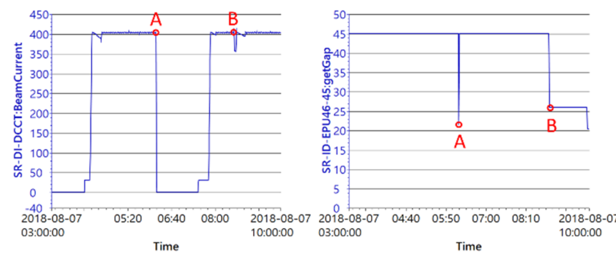

Figure 1: Archived data of beam current and gap reading values of the TPS EPU46. The erroneous gap readings are related to a beam dump or loss, indicated by A and B.

RADIATION SOURCES IN A STORAGE RING

The purpose of a storage ring is to produce synchrotron radiation (SR) for users, and hence, SR is a common radiation source in a ring. In addition, a high energy electron striking material will develop an electromagnetic cascade by bremsstrahlung and generate a shower of secondary particles and photons. The type, intensity and energy of this radiation depends on the energy of the initial electron and the irradiated material [5]. Radiation sources of concern in the TPS are mainly low energy photons (SR), gamma rays and neutrons.

To understand the radiation sources and spatial dose distribution, the radiation is monitored in a transverse plane at a short straight section where there is a Phase-II EPU installed. Opti-chromic dosimeters (OCDs) are densely distributed in the plane. The OCD (FWT-70-40M) is filled with a liquid radio chromatic dye solution in a long plastic tube, and has good linearity for photons and neutrons [6]. Figure 2 shows the dose variation with distance from the electron beam path. Positive X and Y values indicate inner and upper locations, respectively. The dose distribution is near mirror symmetric with respect to the electron beam orbital plane and is much stronger outside the ring.

To understand irradiation effects on encoders, we analyse archived data to present error rates of encoders in the existing three EPUs from March 2017 to January 2019. The error rate indicates that erratic position values occur mostly after electron beam dumps and losses. An error is defined whenever the allowable position changing speed for gap or phase is exceeded. Because the phase encoders are located behind a solid mechanical part of the EPU,

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they show lower error rates than those for the gap, as seen in Fig. 3. As to the location of the encoders in Fig. 2, the gap encoder of the EPU46 is closer to the beam and hence, generates a higher error rate.

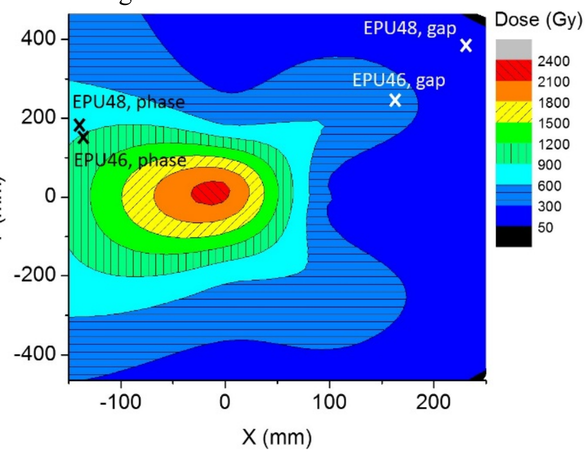

Figure 2: Dose distribution in the transverse plane at a short straight section in the TPS. Encoder positions for three existing EPUs are also indicated.

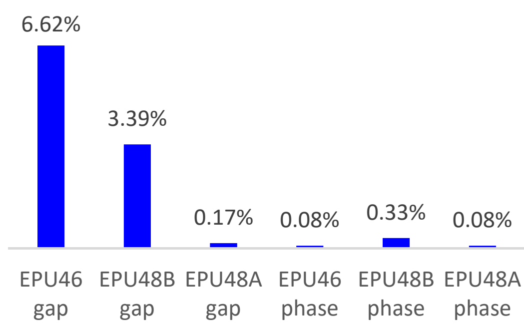

Figure 3: Error rates of encoders for phase and gap values of three EPUs at TPS.

IRRADIATION EFFECTS ON OPTICAL ENCODERS

An optical encoder mirrors a precise position value and is widely used to monitor mechanical motion of PM arrays in an ID. Several manufacturers have uniquely proprietary technologies. It's therefore difficult to study the irradiation sensitivities of components in every commercial product, but a typical system consists of a scale, sensor head and processing electronics. The first two are mounted on an ID in a storage ring exposed to irradiation. The sensor head, an active device, is most suspicious to exhibit a malfunctioning behaviour. A typical sensor head consists of three element groups: optical detectors, emitters and electronic circuit, as seen in two examples in Fig. 4, for the HEIDENHAIN LC series and for the Mitutoyo AT2 series. To reduce size and enhance spatial resolution, designs of these elements rely heavily on semiconductor technologies. Irradiation effects on semiconductor devices therefore become an issue for reliable operation. According to a review of semiconductor physics and irradiation effects on semiconductor devices, we discuss the effect on typical elements in an optical encoder.

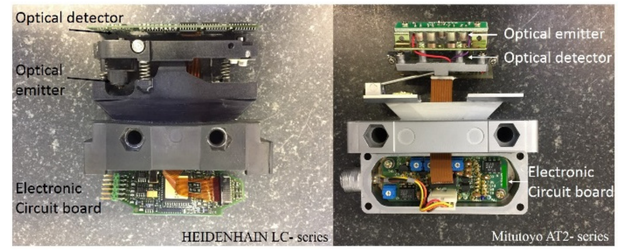

Figure 4: Typical structures of a sensor head in optical encoders.

The fundamental working principle of a semiconductor device happens in a so-called depletion region. When positive (P) and negative (N) charge doped semiconductors are joined, electrons and holes diffuse into regions with lower concentrations of them. In a dynamic equilibrium, a recombination between diffused electrons and holes results and majority charges get eliminated in the depletion region around the junction interface. The region can be operated as a capacitor or a current switch by an external bias [7].

In an optical encoder, the optical detector is usually a P-I-N type photodiode, where an intrinsic (I) semiconductor layer is sandwiched between a P-type and N-type layer. When a photon of sufficient energy enters the depletion region of the diode, it creates an electron-hole pair. The reverse bias field sweeps the carriers out of the region creating a current. When a gamma ray or a neutron irradiate the depletion region, the dark current increases and responsivity decreases [8,9]. A degradation of the performance does not happen immediately but gradually with increasing dose.

A laser diode and a light emitting diode (LED) are commonly used as the optical emitter in an optical encoder, as seen in Fig. 4. In a review paper on the subject, it is stated that particle radiation is substantially more damaging for emitters than gamma radiation [10]. When a high energy particle, e.g. a neutron, impinges the LED output power decreases and the threshold current to turn on the laser diode increases. Device damage happens gradually with increased dose, instead of a sudden event.

The main purpose of the electronics circuit is to calculate the spatial phase from the interference fringe pattern to derive the position value. For commercial products, the electronics design is strategic and abundant to perform analog and digital signal processing. For example, a microprocessor can be recognized in the HEIDENHAIN LC and TR-electronic LT series, but not in the Mitutoyo AT2 series. The TR-electronics LT series also integrates a Flash and Random-Access Memory (RAM) into the circuit board to process data [11]. It is therefore difficult to define a general integral circuit (IC) on electronic circuit boards for encoders, but ICs can be considered to be an integration of Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET),

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which is composed of two P-N junctions connected by a depletion region under a metal-oxide layer. When a high energy particle, e.g. an alpha particle or neutron, passes through the junctions, the kinetic energy of the particle generates electron-hole pairs followed by a charge collection to form a very short-duration current pulse [12]. In memory elements, these current pulses can cause bit flips, which are known as soft errors in semiconductor test standards [13].

The malfunction of an optical encoder happens abruptly after a beam dump or loss at the TPS. The damage is "soft" and recovers by a power cycle. According to these characterizations, the encoder errors are attributed to soft errors in memory elements.

STRATEGIES TO PROTECT ENCODERS IN AN ID

According to semiconductor test standards: JESD89a, ICs in commercial products are tested using soft error sources: alpha particle or cosmic rays for general use environments. This is not sufficient for radiation environment applications, e.g. in aerospace and nuclear power plants. A radiation-hardened encoder is also required for accelerators. Few products have been announced to having been operated successfully in space [14-15], but more tests and studies are required to verify their efficacy to the TPS control system.

To minimize erratic position values, we have some strategies for the Phase-II EPU designs at the TPS. Encoders are enclosed in more than 12mm lead material, which is a tenth and a half value layer required for gamma rays with an energy of 412 or 1332 keV [16]. The distance between encoder and nominal electron beam position is increased, as seen in Fig. 5. Compared to the least distance of an encoder in Phase-I, the distance with Phase-II EPUs is more than twice as great. The radiation dose of neutrons therefore is supposed to be reduced by 50 to 75% [17]. In addition, we reserve an installation space for a second encoder in the Phase-II EPUs. In addition to TR-electronics encoders, Renishaw's encoders will be installed and tested.

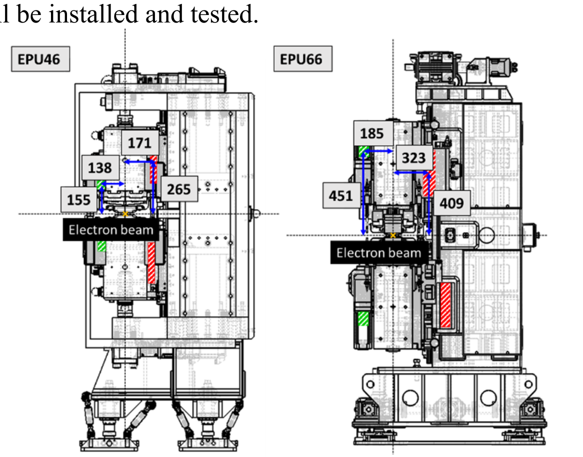

Figure 5: Gap (red) and phase (green) encoder positions and EPU layout for Phase-I EPU46 (left) and Phase-II EPU66 (right) at the TPS.

DISCUSSIONS

Radiation effects on electronics are a complex but important subject for reliable operation. Because electronics rely heavily on semiconductor technologies, significant efforts and pioneering developments are contributed by the semiconductor field. According to a review, our work discusses the effects on components in an optical encoder. The radiation-induced interruption of EPUs in a control system at the TPS is attributed to soft errors in encoder memory elements. We evaluated historical error rates for existing EPUs and measured the dose distribution at the TPS to devise an improved design for Phase-II EPUs. Radiation doses on encoders for radiation of much concern are minimized. An improved reliability of operation for Phase-II EPUs is expected, but a truly radiation-hardened encoder requires more developments.

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