PROCEEDINGS OF SCIENCE

The Belle II diamond detector for radiation monitoring and beam abort

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The SuperKEKB electron-positron collider at the KEK laboratory in Japan aims to achieve a maximum luminosity 50× higher than its predecessors KEKB and PEPII, positioning the Belle II experiment at the forefront of searches for non-standard-model physics in the next decade. High collision intensity implies high beam-induced radiation, which can damage essential Belle II sub-detectors and SuperKEKB components. Twenty-eight diamond sensors, read-out by purpose-built electronics, are installed in the interaction region to measure radiation and prevent damage. This talk introduces the system features and discusses its performance in early Belle II data taking.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

1. Introduction

The SuperKEKB electron-positron collider [1] at the KEK laboratory in Japan aims to achieve an integrated luminosity 50× higher than its predecessors KEKB and PEPII, positioning the Belle II experiment at the forefront of searches for non-standard-model physics in the next decade [2]. Such a high luminosity is made possible by adopting the nano-beam scheme [3]. As a result of adopting this scheme, SuperKEKB has already achieved new world records for instantaneous luminosity in June 2020 [4].

High collision intensity also gives rise to high beam-induced radiation, which can damage essential Belle II sub-detectors and SuperKEKB components. The inner detectors of Belle II, the pixel detector (PXD) and the silicon vertex detector (SVD) are able to tolerate a maximum radiation dose of 10-20 Mrad in a decade of operation. Nevertheless, severe radiation spikes can induce localized damage, e.g., pin holes in SVD, melting heads of collimators and quenches of superconducting magnets. Thus, diamond sensors [5], which are chosen in view of their excellent radiation hardness, rapid response, and broad dynamic range, are installed in the inner region of Belle II to measure radiation dose and prevent damage.

2. Diamond system

The sensors that comprise the detector are synthetic single-crystal diamond grown by Element Six[1] using the chemical vapour deposition technique. Electrodes made of Au/Pt/Ti, are provided by CIVIDEC[2] using a proprietary process. The sensors operate as solid-state ionization chambers, providing currents ranging from pA to mA, which are proportional to radiation dose rates. These currents are measured and used to monitor instantaneous radiation, record integrated radiation, and trigger beam aborts. A more detailed description of the sensors can be found elsewhere [6].

In total, 28 diamond sensors are installed, eight on the beam pipe (four for beam abort, four for beam monitoring), 12 on the support structure of SVD, and eight near the superconducting final focusing magnets. Every four sensors are connected to one diamond control unit (DCU), which consists of front-end amplifiers, analog-to-digital converters (ADC) and an FPGA board.

The front-end amplifiers provide three dynamic ranges to cope with currents of different orders of magnitude. The output signals of the amplifiers are digitized by ADCs at a sampling rate of 50 MHz. Every 125 ADC values are summed and written in a cell of the memory buffer in the FPGA board at a rate of 400 kHz. Moving sums of the values in the memory cells are compared with thresholds; if exceeded, the DCU will make the decision to trigger aborts. In addition, the sum of every 40000 consecutive cells is calculated at a rate of 10 Hz and transmitted to a server via Ethernet. The FPGA board is also in charge of configuring dynamic ranges of the amplifiers and the high voltages applied to the diamond sensors. The software [7] to control and readout the DCUs is implemented in EPICS[3], a framework for large-scale control systems.

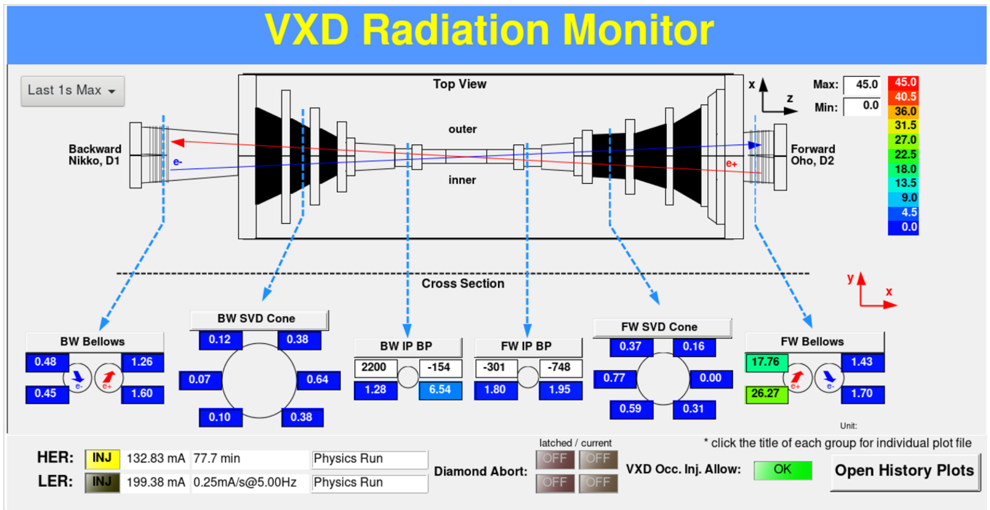
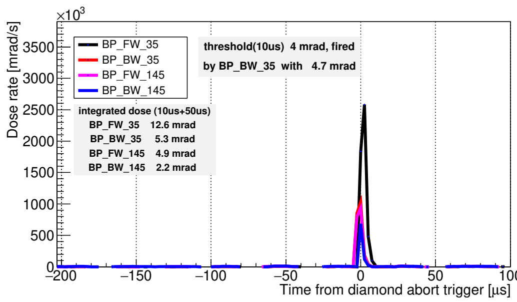
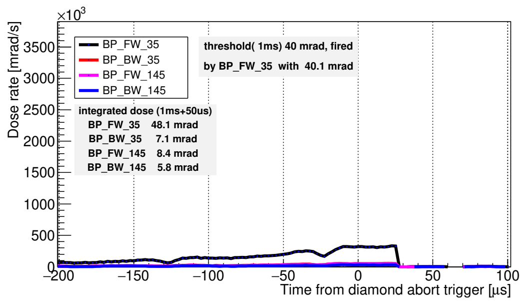


Figure 1: On-line interface: a real-time monitor of radiation for accelerator operators. On this interface, several options for dose rates are provided: the original 10 Hz values, the average of 1 s, the maximum in 1 s, the average of 100 s, and the average of 1000 s.



(a) Radiation burst



(b) Continuously increasing radiation

Figure 2: Examples of the two types of aborts. The first type (a) is configured to cope with radiation bursts which have spikes-like shape. While the second type (b) is responsible for continuously increasing radiation in the shape of growing tails. Doses integrated within the corresponding time window of each sensor are calculated and the sensor whose dose exceeds the threshold is highlighted.

3. Radiation monitor

To facilitate the operation of the collider, an online interface (see Fig. 1) is provided, which serves as a real-time monitor of radiation dose rates. The position of a diamond sensor with a large rate indicates which beam is in need of tuning. The diamond dose rates are also archived and frequently used for beam background studies [8]. In the case of beams being aborted, the online software immediately reads the memory of DCUs and generates plots of dose rates (see

[1] http://www.e6.com/
[2] https://cividec.at/
[3] https://epics-controls.org/resources-and-support/base/series-3-14/

Fig. 2), which offers prompt feedback for post-abort analysis. The interplay between machine and the beam-abort system contributes significantly to achieving new world records for the highest instantaneous luminosity [4].

4. Beam Aborts

As aforementioned, sums of ADC outputs are written in a 4 Gbit revolving buffer memory in the FPGA board at a frequency of 400 kHz. Furthermore, the FPGA is comparing moving sums of values in these memory cells, adding the value in the latest cell and discarding the value in the oldest cell every 2.5 μs, with two thresholds: one designed for radiation burst (see Fig. 2a) and one for continuously increasing radiation (see Fig. 2b). Due to SuperKEKB's revolution time of 10 μs, the first threshold is set to 4 mrad of dose in a moving sum of four memory cells, which corresponds to 10 μs. The second threshold is set to 40 mrad of dose in a moving sum of 400 cells, which corresponds to 1 ms. The thresholds are chosen to prevent both radiation damage of the inner detectors of Belle II (SVD and PXD) and quenches of superconducting final focusing magnets during the operation. More details can be found in Ref. [9].

In order to guarantee a successful delivery of diamond aborts, a hand-shaking procedure with SuperKEKB has been implemented. Once an abort is triggered, the diamond system keeps firing the abort until a reception confirmation from SuperKEKB arrives. After reception of the acknowledgement, the diamond system starts to dump the memory file and clears its abort signal. In the 2020 runs up to July 1st, SuperKEKB in total has received ~1500 aborts from all beam loss monitors [10]. Among them, the diamond system has fired 655 times (see Fig. 3), most of which are triggered by radiation bursts. In the cases where several beam loss monitors simultaneously trigger an abort, the signal from the diamond system usually is the first that arrives at SuperKEKB's central control room.

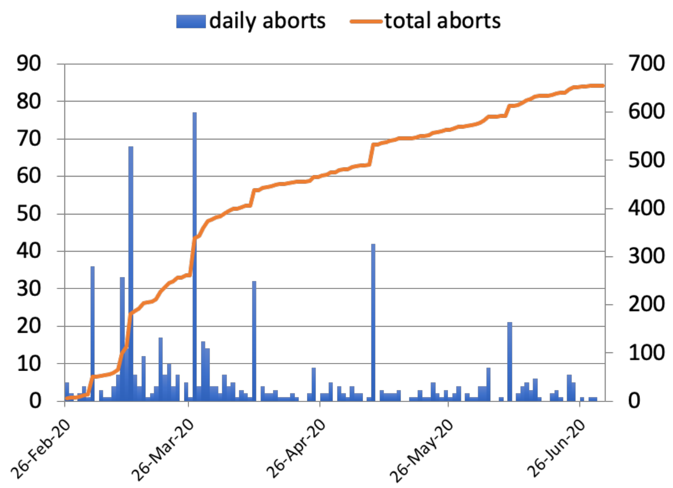


Figure 3: Statistics of diamond aborts during the 2020 running until July 1st. During machine studies, the frequency of aborts triggered by the diamond system is ~10 /hour, while the frequency decreases to ~1 to 2 /day during physics data taking.

5. Conclusion

The diamond system is doing an excellent job in protecting the Belle II detector from radiation damage. As a beam loss monitor, the diamond-based system offers prompt feedback for beam tuning and background study. As a beam abort system, it is sensitive to both radiation bursts and continuously increasing radiation; the aborts that it delivers precede all other abort sources.

6. Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreements No 644294 and 822070. This work is supported by MEXT, WPI, and JSPS (Japan); ARC (Australia); BMWFW (Austria); MSMT (Czechia); CNRS/IN2P3 (France); AIDA-2020 (Germany); DAE and DST (India); INFN (Italy); NRF-2016K1A3A7A09005605 and RSRI (Korea); and MNiSW (Poland).

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