PROCEEDINGS OF SCIENCE

Online Luminosity Monitor at Belle II

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We describe a system used for online measurements of luminosity, utilizing elastic e^+e^- Bhabha scattering and two-photon annihilation processes reconstructed with the Belle II electromagnetic calorimeter. The Belle II experiment at the SuperKEKB asymmetric-energy e^+e^- collider is designed to achieve a luminosity of 6.3×10^{35} cm^{-2}s^{-1}. With the designed parameters of SuperKEKB, the statistical accuracy of the instantaneous luminosity measurement provided by the Online Luminosity Monitor is expected to be better than 1% within one second. The overall systematic uncertainty is estimated to be at the level of 1%. Comparison with a dedicated offline analysis and results on the long-term stability of the monitor's performance are also presented.

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1. Introduction

The Belle-II [1] experiment at the SuperKEKB [2] collider at KEK (Japan) has been operating since April 2018. The SuperKEKB is an asymmetric electron-positron collider with electron and positron energies of $E_{e^-} = 7$ GeV and $E_{e^+} = 4$ GeV, respectively. The experiment is running at $\sqrt{s} = 10.58$ GeV that corresponds to the peak position of the $\Upsilon(4S)$ resonance. The main goal of the experiment is to study rare decays of B and D mesons and to search for New Physics signals beyond the Standard Model in heavy flavor decays. The designed luminosity of $L = 6.3 \times 10^{35}$ cm^{-2}s^{-1} that is about 30 times the previous world record achieved at the Belle experiment.

Measurements of instantaneous and integrated luminosity in the online regime are crucial for monitoring accelerator performance and optimizing data collection efficiency by the detector. One common approach is to measure the yield of processes with known cross sections. For instance, well-studied electrodynamics processes such as Bhabha scattering ($e^+e^- \to e^+e^-$) and two-photon annihilation ($e^+e^- \to \gamma\gamma$) can be utilized for this purpose.

The Luminosity Online Monitor (LOM) was developed at the Budker Institute of Nuclear Physics (BINP) in the Russian Federation and manufactured by NOTICE in South Korea. It measures the combined rate of $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ events using only the endcap sections of the electromagnetic calorimeter (ECL), as depicted in Figure 1. The visible cross section σ_{vis} for the ECL endcaps is approximately 29.38 nb, resulting in a statistical uncertainty of 0.7% at the designed luminosity and 2.6% at the up to date achieved luminosity of 4.7×10^{34} cm^{-2} s^{-1} for a measurement rate of 1 Hz.

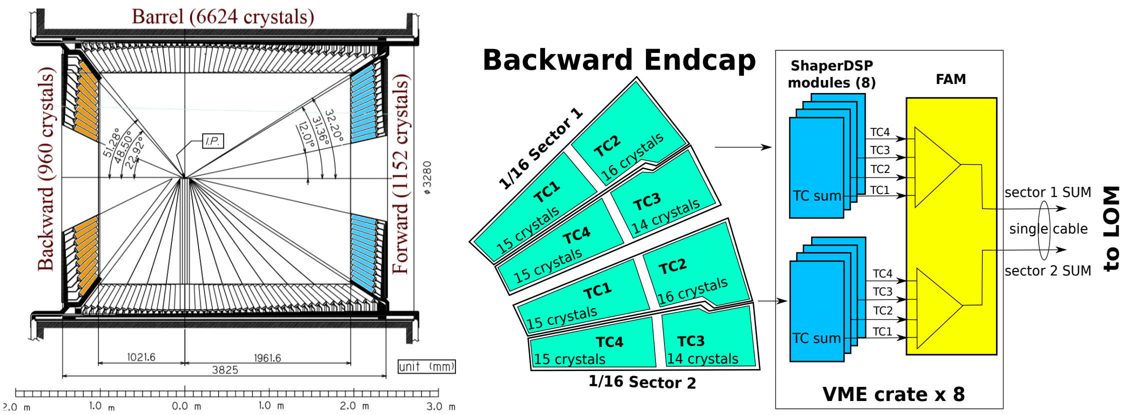

Figure 1: Left: Layout of the Belle-II electromagnetic calorimeter. Endcap sections used for the luminosity measurements are shown in color. Right: Example of trigger cell arrangement for the backward sectors.

2. Luminosity On-Line Monitor

2.1 Firware and software

The Belle II ECL [3] comprises 8736 CsI(Tl) crystals along with 576 ShaperDSP modules for data readout. Each ShaperDSP module combines signals from 8 to 16 neighboring CsI(Tl) counters, forming a trigger cell (TC), and transmits it to the shaping circuit (FAM board) for fast triggering and monitoring. Both ECL endcaps are divided into 16 sectors, with six TCs in the

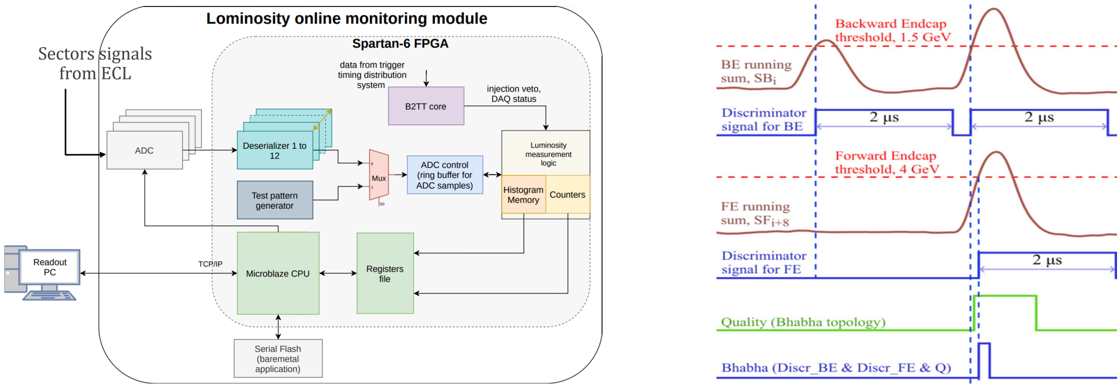

Figure 2: Left: Block diagram of the FPGA firmware implementation. Right: Timing diagram of the luminosity monitor logic.

forward endcap and four TCs in the backward endcap, as illustrated in Figure 1. For luminosity measurement, signals from TCs within the same sector are merged into a single output signal within the FAM module and then transmitted to the external dedicated luminosity online monitor (LOM) module.

The LOM module digitizes 32 analog signals from the ECL FAM and applies a luminosity calculation algorithm implemented on a Xilinx Spartan-6 FPGA chip (fig. 2). The firmware provides several basic functionalities, including the readout and analysis of a continuous stream of digitized samples from ADCs, control over peripheral devices, communication with the readout PC, and retrieval of service information from FTSW modules. Data from FTSW modules include information on injection veto, experiment and run numbers, and DAQ status signals. The LOM module operates independently of the global Belle II DAQ system [4] and is able to provide luminosity measurement even while the global DAQ is in standby mode. Consequently, it is possible to calculate both, the integrated luminosity recorded by the Belle II detector, and that delivered by the SuperKEKB. Additionally, there are secondary components that allow us to feed generated signals to the LOM ADCs, and to readout and store wavefroms.

A dedicated software (fig. 3) was developed for data readout from the module. It retrieves information from the module, calculates luminosity, exports high-level information to the EPICS network, which is accessible to all SuperKEKB and Belle II experts, and handles requests from TCP clients to the module. Additional TCP clients allow us to store low-level information, configure the module, and monitor performance in real-time.

2.2 Event selection logic

To select $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ events, we require the total energy deposition in two adjacent sectors of the forward (backward) ECL endcap to exceed a threshold value of $T_{\rm FE} = 4.5$ GeV ($T_{\rm BE} = 1.5$ GeV), while energy depositions in all other sectors should be below $T_Q = 1.0$ GeV. The fired sectors of the two endcaps are also required to form a back-to-back topology. According to Monte-Carlo simulation, the fraction of signal events with energy deposition exceeding T_Q in three or more sectors of the same endcap does not exceed 0.3% at the designed luminosity.

The timing diagram of the event selection logic is illustrated in Figure 2, where SFE (SBE)

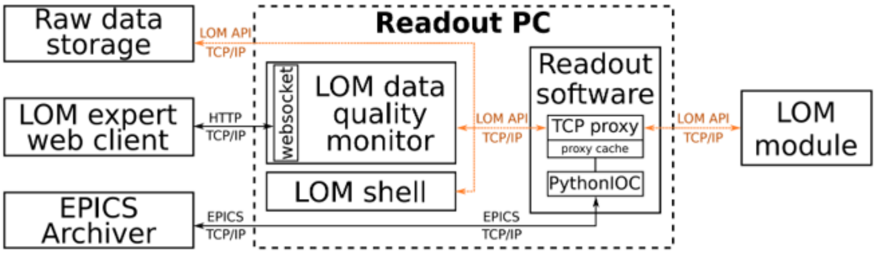

Figure 3: Block diagram of the readout software.

denotes the combined signal from the two adjacent sectors in the forward (backward) ECL. A discriminator signal, DFE (DBE), is generated if SFE (SBE) exceeds the threshold value T_{FE} (T_{BE}). A quality signal is generated if energy deposition exceeds T_Q in fewer than two adjacent sectors. If DFE and DBE signals are generated in opposite sectors (i and $i+8$) and a quality signal is generated, the trigger is activated, and the event counter is incremented.

2.3 Monte Carlo simulation

The instantaneous luminosity is calculated based on the event rate measured by the LOM module using the formula:

$$L = \frac{\text{Count rate}}{\sigma_{\text{vis}}},$$

where σ_{vis} represents the visible cross section for the combination of $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ processes. To determine σ_{vis}, a GEANT-based [5] Monte-Carlo simulation is performed. Within the Belle II Analysis Software framework [6], BhabhaYaga@NLO [7] generates parameters of the final-state particles (e^+e^- or $\gamma\gamma$), while the GEANT-based software simulates the detector response, which is then processed with the analysis script with implemented monitor logic. The visible cross section is determined as:

$$\sigma_{\text{vis}} = \frac{N_{\text{det}}}{N_{\text{gen}}}\sigma,$$

where N_{gen} is the number of generated events, σ is the total cross section for a particular process, and N_{det} is the number of events passed through the monitor logic and counted as signal event. The calculated visible cross sections are $\sigma^{ee}_{\text{vis}} = 28.46 \pm 0.02$ nb for the $e^+e^- \to e^+e^-$ process and $\sigma^{\gamma\gamma}_{\text{vis}} = 0.92 \pm 0.01$ nb for the $e^+e^- \to \gamma\gamma$ process. The combined visible cross section is found to be $\sigma^{\text{tot}}_{\text{vis}} = 29.38 \pm 0.04 \pm 0.28$ nb, where the first uncertainty is statistical and the second is systematic. Since the Belle II experiment is capable of taking data at various center-of-mass energies in the $\Upsilon(4S) - \Upsilon(6S)$ region, a correction factor for the cross section is applied:

$$\sigma_{\text{vis}}(s) = \sigma_{\text{vis}}(s_0)\frac{s_0}{s}\left(1 + 1.4\% \times \frac{\sqrt{s} - \sqrt{s_0}}{1\ \text{GeV}}\right),$$

where $\sqrt{s_0} = 10.58$ GeV, and $\sqrt{s}$ is the current center-of-mass energy.

The dominant systematic uncertainty in luminosity measurements is determined by the accuracy of the ECL endcaps relative to the interaction point (IP) and the event generator uncertainty.

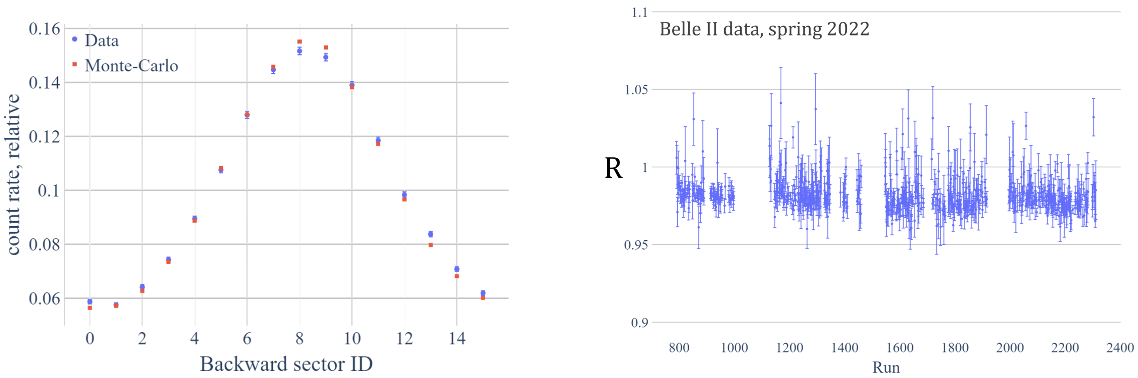

Figure 4: Left: Relative event rate in dependence from sector ID, which is equal to ϕ angle distribution. Right: run-by-run ratio R of online to offline measurements.

Varying the IP position by 5 mm, we find the corresponding uncertainty to be 0.8%. The BhabhaYaga@NLO generator uncertainty is 0.4% [7]. The total uncertainty is estimated to be 1.0%. We also test consistency of selection efficiency in data and in MC simulation: the monitor shows 0.01% discrepancy when the same simulated signals are processed.

2.4 Results

We observe good agreement in amplitudes distribution and up to 5% difference for angular (ϕ) distribution (fig. 4, left), that could be accounted for background influence. A run-by-run comparison of online measurements to an independent offline measurement of the integrated luminosity, based on full event reconstruction [8], shows an average difference of 2% (fig. 4, right). This difference varies from 1% to 5% depending on injection background conditions. The source of such dependency is found to be timing misalignment between the luminosity monitor and the delivered injection veto signal. After proper timing adjustment, the difference between online and offline results is expected to be reduced down to 1% level, that falls within the target systematic uncertainty.

3. Conclusion

In conclusion, the developed for the Belle-II experiment luminosity online monitor demonstrates stable performance and provides reliable operational information on instantaneous and integrated luminosity in real time. It is also successfully utilized by the SuperKEKB collider team to tune beam parameters and provide official SuperKEKB/BelleII luminosity data. A statistical accuracy of 2.6% is achieved at a luminosity of approximately 4.7×10^{34} with a measurement rate of about 1 Hz, while the overall systematic uncertainty is estimated to be at the level of 1%. The results of the online measurements agree with the offline analysis within the systematic uncertainty.

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