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BEAM LOSS DIAGNOSTICS SYSTEM FOR SKIF SYNCHROTRON LIGHT SOURCE

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Abstract

The Siberian ring photon source (SKIF) is a new generation synchrotron light source designed and built by the Budker Institute of Nuclear Physics. The beam loss diagnostics system is a tool for monitoring beam loss information. It is widely used in modern large accelerators to provide a basis for diagnosing and locating machine faults, optimizing and debugging working beam parameters, and improving beam lifetime. Two types of beam loss monitor (BLM) will be applied on SKIF: fiber-based Cherenkov beam loss monitor (CBLM) and scintillator-based BLM (SBLM). Multi-mode silica fibers CBLM will be installed on linear accelerator and transfer lines. 128 SBLMs will be placed around the storage ring, dynamic ranges and sophisticated electronic equipment are employed to cover different SKIF operating modes. This article represents the details of design of beam loss diagnostics of SKIF, introduces the simulation and experimental studies of CBLM and SBLM.

INTRODUCTION

SKIF is the fourth-generation synchronous light source, with 3 GeV energy and emittance of 75 pm rad, which is planned to launch in 2023 [1]. SKIF configuration includes injector linear accelerator with maximum energy 200 MeV, linac-to-booster transfer line (LBTL), booster synchrotron with maximum energy 3 GeV and circumference of 158.7 m, booster-to-storage ring transfer line (BSTL), electron storage ring with 16-fold symmetry and 476 m circumference. The layout of SKIF is shown in Fig. 1. The beam loss monitoring system can determine the level of losses, and provide an essential basis for discovering possible faults in the accelerator and controlling residual activation [2].

The CBLM has the characteristics of wide coverage, adapting to small space and high electromagnetic field environment, fast response speed and low cost. Another common type is the SBLM. The advantages of them are good position sensitivity, fast response speed and dynamic range of 10^6. For linac, LBTL and BSTL where beam alignment is available in a single-bunch mode we proposed to use CBLMs. For the storage ring in order to control beam losses during machine tuning and operation at top-up mode, SBLMs were proposed.

CHERENKOV BEAM LOSS MONITOR

The operation principle of the CBLM is based on the registration of the Cherenkov radiation generated in the optical fiber attached to the vacuum chamber by secondary charged particles [3]. The Cherenkov light is propagated along the optical fiber to the upstream and downstream photodetector, where it is converted into electrical signals and recorded. The signal can provide the location of beam losses, and its amplitude is proportional to the beam charge losses.

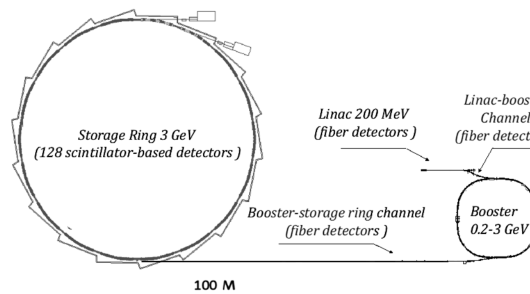

Figure 1: SKIF layout.

Simulation of CBLM Performance

The Cerenkov light generated in the optical fiber propagates to both ends of the fiber simultaneously. According to the simulation results, the sensitivity of the upstream signal is about 10 times lower than the downstream.

Approximately 5% of the generated CR will be captured in the fiber, propagate to the end of the fiber, and reach the PMT. According to the simulation, the CBLM sensitivity has a quadratic relationship with the fiber core diameter (μm): $N_{ph}=7.3\cdot 10^{-6}\cdot d^2$.

Prototype Test and Results

The CBLM prototype test was performed on the operating BINP accelerator with beam parameters similar to SKIF to confirm the reliability of the numerical simulation results (Fig. 2).

The A and B signals representing beam losses distribution along the accelerator were observed at the same time. It can be seen that the spatial resolution at upstream end is 4 times better than the downstream. Taking into account the contribution of PMT gain, the downstream signal sensitivity is 10 times higher than the upstream.

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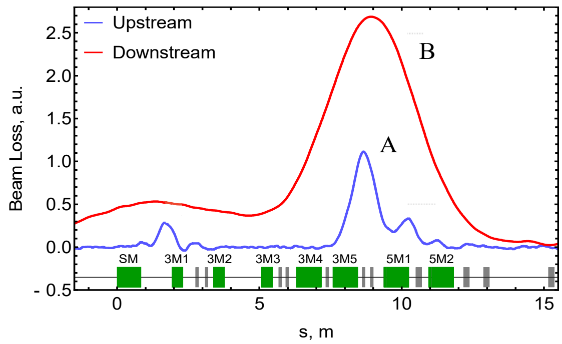

Figure 2: Upstream (blue) and downstream (red) loss distributions of the electron beam at accelerator at BINP.

It is necessary to use the step-index profile optical fiber with good radiation resistance, and there are certain requirements on the core diameter. The outer sheath is required to have a good shielding performance against visible light, but it cannot affect to electron penetration. Based on the above requirements, we have chosen Thorlabs (FG550UEC) multimode silica fiber [4]. It has a core diameter of 500 µm and a high OH-, fluorine-doped silica cladding. The measured dispersion is 0.17±0.01 ns/m.

According to test experience and simulation results, the optimal length of the optical fiber is about 40 m. Therefore, the planned CBLM system on the linear accelerator and LBTL consists of a 30 m long fiber, while a 200 m long BSTL requires 5 CBLMs. The microchannel plate-based photomultiplier (MCP-PMT) is employed in the CBLM system. Its parameters allow detecting ~1 pC beam.

SCINTILLATOR BEAM LOSS MONITOR

The SBLM consists of a plastic scintillator and a PMT, which are placed in a steel housing. The signal from PMT is recorded by ADC and transmitted to the computer [5, 6].

The scintillator is planned to be SC-205 based on polystyrene [7] and the PMT 9107B produced by ET Enterprises® was selected [8]. The reflective Tyvek® paper is wrapped around the SBLM to maximize the amount of light reaching the PMT and avoid the loss of light signal generated by the scintillator (Refl.Coeff.@440mm = 0.97) [9].

Simulation of SBLM Performance

By using the FLUKA package [10], a simulation of the electromagnetic shower caused by the beam loss was performed to determine optimal position of the BLMs and the total amount required for the SKIF storage ring.

We have simulated secondary particle showers after a lost 3 GeV electron hits vacuum tube with small incident angle relative to equilibrium orbit. According to the analysis of mechanisms that can lead to beam losses, we finally chose the locations of maximum dispersion or β-function and the centre of the magnets as the point of beam loss [11]. In a SKIF superperiod [12], the total of 62 collision points were calculated. Figure 3 shows a typical distribution of secondary particles calculated by FLUKA.

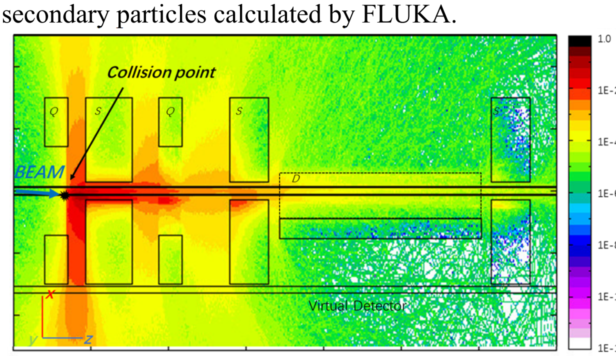

Figure 3: The typical distribution of secondary particles calculated by FLUKA. The collision on the outer radius at the maximum point of the β function.

The simulation result in one SKIF superperiod is shown in Fig. 4. Since the yoke of quadrupole weakens the particle flux, its internal collisions produce relatively more photons inside scintillator.

8 SBLMs will be installed at the locations of most significant shower peaks at each girder to achieve maximum diagnostic efficiency. Due to the 16-fold symmetry of the storage ring, a total of 128 BLM detectors are planned to be installed around the SKIF storage ring.

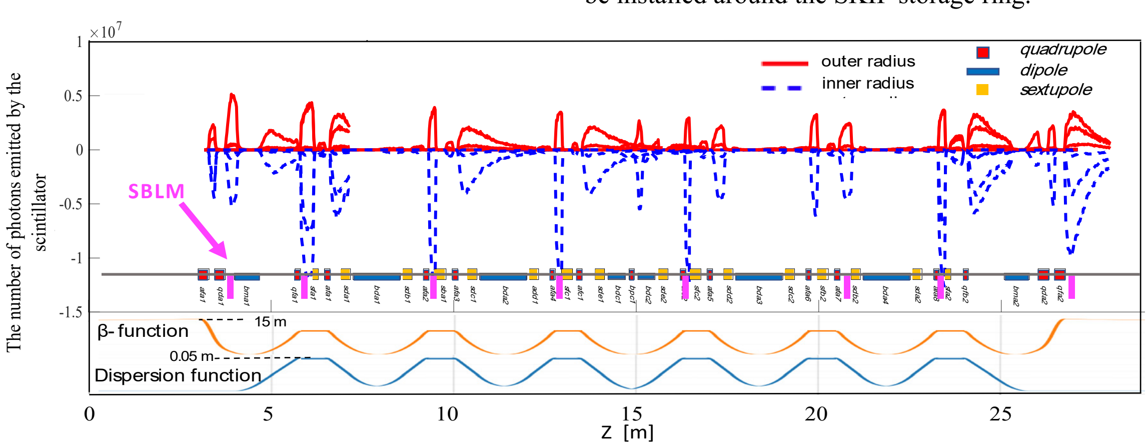

Figure 4: The simulated distribution of photon in the scintillator over SKIF superperiod. The sign of the vertical axis has only the meaning of direction.

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ELECTRONICS

Measuring Module for CBLM

Measuring modules based on switch capacitor array (SCA) technology are developed to fix the signal from the photodetector. Capacitive storage arrays (such as PSI's DRS4 [13]) are the key elements in such systems. They provide data logging at a sampling rate of several GHz. The following main elements can be distinguished (Fig. 5) in the developed measurement module for CBLM:

- Programmable gain input amplifiers (PGA).
- DRS4 chip in the configuration with two lines of capacitive storage arrays up to 4096 elementary cells for everyone.
- A unit that generates signals for carrying out amplitude and time calibration for DRS4 chip.
- ADC of the megahertz range.
- Node of synchronization and timing, linking DRS4 data recording cycles to external events.
- Digital node based on Intel Cyclone V SoC FPGA.

It is possible to organize both unilateral and bilateral signal registration modes in the loss measurement system containing several CBLMs.

Signals are provided to their inputs from the final and initial ends of neighboring sensors (Fig. 6).

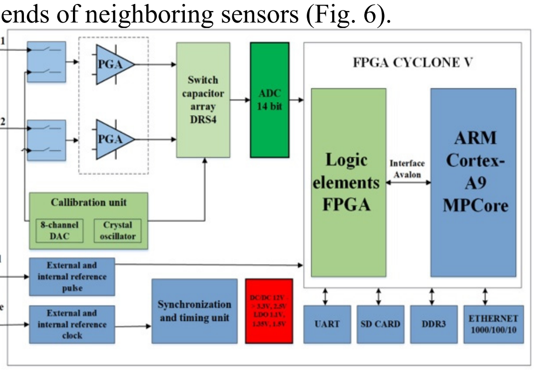

Figure 5: Simplified diagram of the measurement module for CBLM.

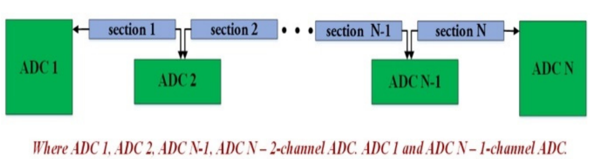

Figure 6: System for loss level measuring in successive segments of the magnetic structure.

Measuring Module for SBLM

Four-channel measuring modules built on the data recording oscillographic method are proposed to be used for SBLMs. The measurement module has characteristics similar to LIBERA BLM [14]. Each channel of the measuring module will provide data recording with sampling rate of 250 MHz and amplitude resolution of 14 bits. The resources of the Intel Cyclone V FPGA installed on the board of each module will be used for implementing various operation modes of the measuring modules, as well as for receiving, preprocessing and transmitting data via the Ethernet channel. The developed measuring module (Fig. 7) has four identical measuring tracts, each of them includes:

- Wideband input amplifier (0-100 MHz) with programmable gain.
- 14-bit ADC with sampling rate up to 250 MHz.
- Synchronization and timing node, built on the basis of PLL (generator with a phase-locked loop) and FPGA elements.
- The generator of the test signal for amplitude calibration of SBLMs.
- The PMT supply voltage controller for gain adjusting when changing the operating mode of the measuring tracts (from oscillographic to counting and vice versa).

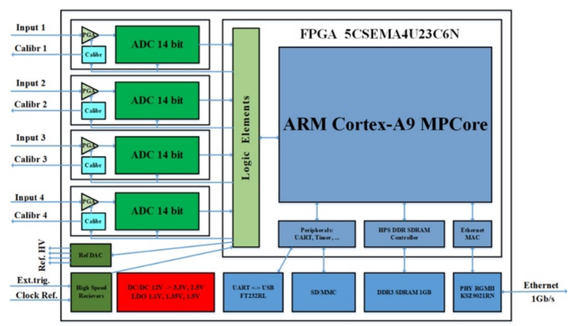

Figure 7: Measuring module of SBLM.

The developed measuring module for SBLM will have two operating modes:

1st mode: Oscilloscope mode allowing to record the shape of the detector signals in a sequence of time windows with a duration set by the operator;

2nd mode: Counting mode allowing to fix signals in a sequence of successive time windows, the duration of which is set in software.

Measuring modules of the CBLMs and SBLMs are combined into the general data acquisition system by the cable synchronization lines that ensure the binding of data acquisition cycles to external events. They interface with a PC-based operator console using a standard switch over Ethernet-1000 communication channels.

CONCLUSION

The design of the beam loss diagnostics system of the synchrotron radiation source SKIF is basically completed. The experience of using a CBLM at the injection complex allows us to select BLM elements with optimal parameters that meet the requirements for beam loss diagnostics at SKIF. Through Monte Carlo simulation of the electron beam shower, the best SBLM installation position on the SKIF storage ring was obtained. It is expected that the use of PMT will achieve the expected dynamic range at least 10^6. The electronics of CBLM and SBLM have been developed, both of them could be combined into a general data acquisition system and could interact. Further experiments with a prototype of SBLM are expected.

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