PRELIMINARY DESIGN OF BEAM FEEDBACK SYSTEMS FOR THE SHENZHEN SUPERCONDUCTING SOFT X-RAY FREE ELECTRON LASER*

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Abstract

The Shenzhen Superconducting Soft X-ray Free Electron Laser (S^3FEL) requires a high-quality electron beam with stable energy, bunch length, and arrival time to ensure efficient lasing. To maintain stringent beam quality, a comprehensive beam feedback system has been preliminarily designed, incorporating five dedicated feedback loops:

1. Gun Feedback: Monitors bunch charge and arrival time after the electron gun, controlling the input laser power and delay to stabilize charge and timing.
2. Laser Heater Feedback: Measures beam energy at the laser heater and adjusts the RF amplitude of small module CM00 and large module CM01 accordingly.
3. Bunch Compressor 1 (BC1) Feedback: Monitors beam energy, energy spread, and bunch length in BC1, regulating RF amplitude and phase of large modules CM02, CM03 and harmonic cavities CMH01, CMH02.
4. Bunch Compressor 2 (BC2) Feedback: Similarly monitors beam parameters in BC2 and controls RF amplitude and phase of large modules CM04–CM09.
5. Linac End Feedback: Measures final beam energy and adjusts RF amplitude and phase of large modules CM10–CM20 to ensure energy stability before transport to the undulator.

This integrated feedback design aims to suppress slow drifts, enhance beam stability, and provide the reliable beam quality required for high-performance soft X-ray FEL operation at S^3FEL.

INTRODUCTION

Free-electron lasers (FELs) have become indispensable tools in frontier research areas such as condensed matter physics, materials science, chemistry, and life sciences due to their exceptional properties, including ultra-high brightness, ultrashort pulse duration, and wide wavelength tunability [1]. The Shenzhen Superconducting Soft X-ray Free-Electron Laser (S^3FEL) requires extremely stable electron beam parameters to ensure efficient and stable laser generation [2]. In particular, beam energy stability, bunch length stability, and arrival-time stability directly affect FEL output quality.

During long-term accelerator operation, beam parameters are inevitably affected by external disturbances such as temperature fluctuations, humidity variations, RF system drift, and mechanical vibrations. These perturbations can lead to slow drifts in beam intensity, beam position, energy spread, ultimately degrading FEL performance [3]. Therefore, an effective beam feedback system is essential for maintaining accelerator stability and ensuring reliable FEL operation.

This paper presents the preliminary design of the S^3FEL beam feedback system. The system integrates five dedicated fast-feedback loops distributed across key accelerator sections. Through coordinated multi-loop control, high-speed optical-fiber communication, and FPGA-based real-time signal processing, the proposed system achieves precise closed-loop stabilization of critical beam parameters.

OVERALL ARCHITECTURE OF THE BEAM FEEDBACK SYSTEM

The electron beam in S^3FEL passes through multiple accelerator subsystems, including the electron gun, buncher, accelerating cryomodules, harmonic cavities, and bunch compressors. The primary objective of the beam feedback system is to suppress slow beam parameter drifts and improve the long-term stability of beam energy, bunch length, and arrival time.

Figure 1 illustrates the conceptual architecture of the beam feedback system. Beam diagnostics installed at critical accelerator locations continuously monitor beam parameters in real time. The measured values are compared with predefined reference values, and the resulting errors are processed by dedicated fast-feedback controllers. The controllers then adjust RF amplitudes, RF phases, laser delay, and laser power to compensate for beam fluctuations.

Benefiting from high-bandwidth optical-fiber interconnections and low-latency FPGA-based processing, the feedback system is capable of rapidly responding to external disturbances while maintaining high control precision and operational reliability.

FEEDBACK LOOP DESIGN

Gun Feedback

The topology of the electron gun feedback loop is shown in Fig. 2. The electron gun feedback loop is designed to stabilize bunch charge and bunch arrival time. An integrated current transformer (Turbo ICT) is employed to measure bunch charge, while a bunch arrival-time monitor (BAM) is used for timing diagnostics downstream of the electron gun.

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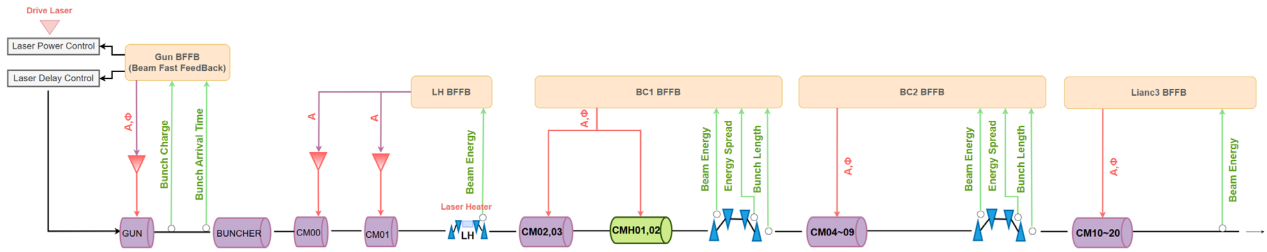

Figure 1: The conceptual architecture of the beam feedback system.

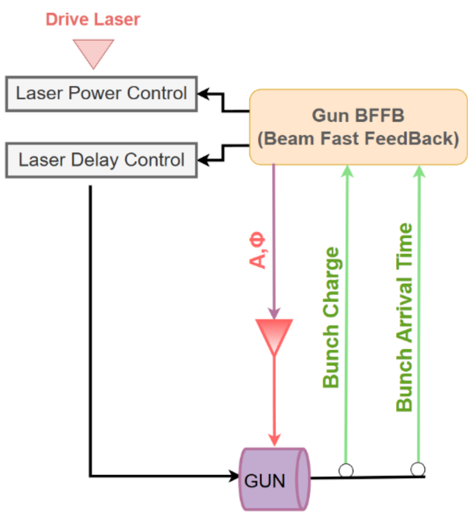

Figure 2: The topology of the electron gun feedback loop.

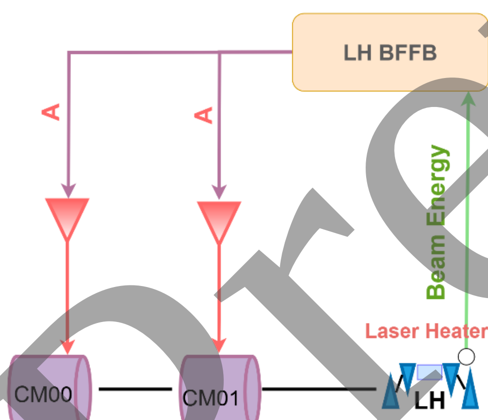

Figure 3: The topology of the laser heater feedback loop.

Based on real-time diagnostic data, the fast-feedback controller dynamically regulates the drive laser power and timing delay applied to the gun. Within the operating range, increasing the laser power generates more photoelectrons, thereby increasing the bunch charge. Meanwhile, adjusting the laser timing delay changes the electron emission timing and consequently controls the bunch arrival time.

When deviations from the target operating point are detected, the controller compensates by modifying the laser power and timing delay, thereby maintaining stable beam generation.

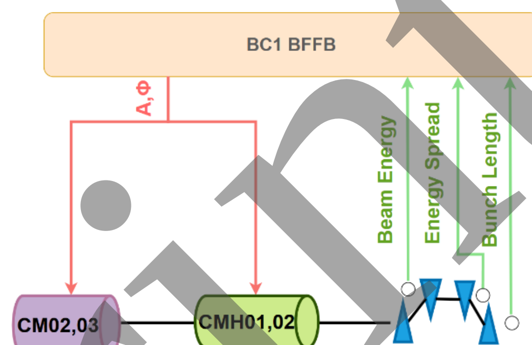

Figure 4: The topology of the bunch compressor 1 feedback loop.

Laser Heater Feedback

The topology of the laser heater feedback loop is shown in Fig. 3. The laser heater feedback loop is mainly responsible for beam energy stabilization. Beam position monitors (BPMs) located in a dispersive section are utilized to infer beam energy based on the local dispersion function.

Using the measured beam energy as feedback input, the controller regulates the RF amplitudes of the CM00 and CM01 accelerating modules. Since the RF amplitude is approximately linearly related to the beam energy gain, precise amplitude regulation enables effective beam energy stabilization.

Whenever the measured beam energy deviates from the target value, the controller adjusts the RF amplitudes accordingly to suppress energy fluctuations.

Bunch Compressor 1 Feedback

The topology of the bunch compressor 1 feedback loop is shown in Fig. 4. The Bunch Compressor 1 (BC1) feedback loop controls beam energy, and bunch length. The diagnostic system consists of BPMs, a synchrotron radiation monitor (SRM), and a bunch length monitor (BCM).

Based on the measured beam parameters, the feedback controller regulates the RF amplitudes and phases of the CM02 and CM03 accelerating modules as well as the CMH01 and CMH02 harmonic cavities.

The RF phase plays a crucial role in longitudinal phase space manipulation. In an accelerating field, different RF phases introduce different energy chirps along the bunch. If the bunch head gains more energy than the tail, after passing through a magnetic compressor the temporal distribution of the bunch will be broadened, resulting in an increase in bunch length. Conversely, if the bunch tail gains more energy than the head, bunch compression can be achieved.

Therefore, by appropriately adjusting RF amplitude and phase, the system can effectively regulate bunch length. When deviations are detected by the BCM, the controller updates the RF phase settings to restore the desired beam conditions.

Bunch Compressor 2 Feedback

The topology of the bunch compressor 2 feedback loop is shown in Fig. 5. The bunch compressor 2 (BC2) feedback loop adopts a diagnostic configuration identical to that of BC1 to ensure measurement consistency and reliability. The corresponding feedback controller regulates the RF amplitudes and phases of the CM04–CM09 accelerating modules.

The control principle is similar to that used in BC1. Through real-time compensation of longitudinal beam dynamics variations, the BC2 loop further improves beam quality before the beam enters the downstream accelerator section.

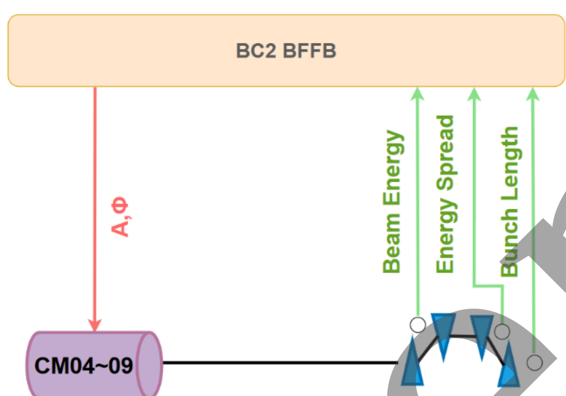

Figure 5: The topology of the bunch compressor 2 feedback loop.

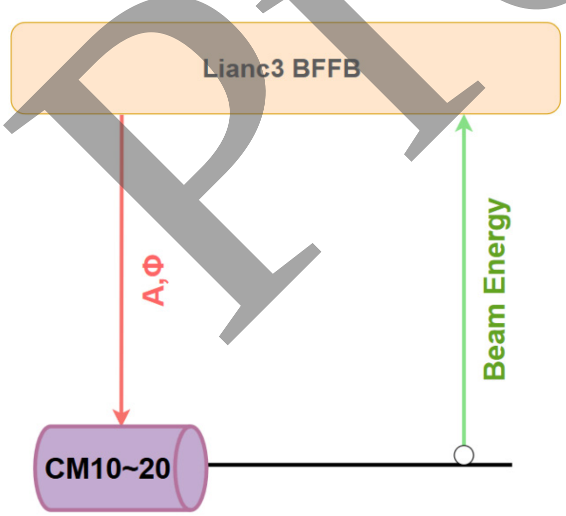

Figure 6: The topology of the linac end feedback loop.

Linac End Feedback

The topology of the linac end feedback loop is shown in Fig. 6. The linac end section represents the final beam stabilization stage before injection into the undulator line. Beam energy stability at this location directly affects FEL lasing efficiency and output stability.

The linac end feedback controller uses beam energy measurements to regulate the RF amplitudes of the CM10–CM20 accelerating modules. Similar to the upstream energy feedback loops, real-time RF amplitude correction is applied to suppress residual beam energy fluctuations and ensure stable FEL operation.

KEY TECHNOLOGIES

Several key technologies are adopted to ensure stable and efficient operation of the beam feedback system.

High-Precision Beam Diagnostics

High-precision diagnostics are deployed throughout the accelerator to provide accurate measurements of bunch charge, beam energy, bunch length, and arrival time. These diagnostics form the foundation of the feedback control system.

High-Speed Optical-Fiber Communication

Optical fibers are employed as the primary communication medium due to their high bandwidth, low latency, and excellent immunity to electromagnetic interference. This architecture enables rapid transmission of diagnostic data and feedback control signals across the accelerator.

FPGA-Based Fast-Feedback Hardware

Dedicated fast-feedback hardware equipped with high-performance FPGAs and multiple optical transceivers is developed for real-time signal processing and control implementation. The FPGA architecture enables parallel processing with deterministic latency, ensuring efficient execution of feedback algorithms.

Modular and Reliable System Architecture

A modular multi-loop architecture is adopted to improve system reliability and maintainability. Each feedback loop operates independently, allowing localized failures without affecting the overall accelerator operation. The modular hardware design also facilitates future system upgrades and scalability [4].

CONCLUSION

This paper presents the preliminary design of a beam feedback system for the Shenzhen Superconducting Soft X-ray Free-Electron Laser. The proposed system integrates five dedicated fast-feedback loops to achieve precise closed-loop stabilization of critical beam parameters across the accelerator.

By combining high-precision diagnostics, optical-fiber communication, and FPGA-based real-time feedback hardware, the system effectively suppresses slow beam drifts and significantly improves long-term beam stability. The proposed architecture provides a solid foundation for stable and efficient operation of S^3FEL.

Future work will focus on physics simulations, open-loop and closed-loop experimental verification, optimization of feedback control algorithms, and mitigation of coupling effects between different feedback loops. These efforts are expected to further enhance system performance and operational reliability.

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