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UPGRADE OF LLRF CONTROL SYSTEM FOR INFRARED FREE-ELECTRON LASER*

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Abstract

Hefei Infrared Free-Electron Laser device (IR-FEL) is a user experimental device dedicated to energy chemistry research that can generate high brightness mid/far infrared lasers. It is driven by an S-band linear accelerator with a maximum electron energy of 60 MeV. The stability of the final output laser is determined by the energy stability and spread of the electron beam, and the Low-Level RF control system (LLRF) is opitimized to improve the energy stability of the electron beam. There are two klystrons in the linear accelerator of IR-FEL, and the periodic oscillation of out power output of the klytrons is existed (approximately ± 0.2%~2% for amplitude). The oscillation period of two klystrons are exchanged in the case of exchanging the filament power supplies of two klystrons. The pulse-to-pulse feedforward and in-pulse feedback algorithm are developed to compensate the periodic fluctuations of the output power of the klystrons, and the IQ demodulation is changed to the Non-IQ demodulation (13/3) to separate and suppress the odd harmonic. After the optimization, the stability of klystron output signal has been improved from 0.12%/0.07° (rms) to 0.04%/0.09° (rms).

INTRODUCTION

The IR-FEL is a tunable infrared free electron laser source developed by the National Synchrotron Radiation Laboratory of the University of Science and Technology of China [1].

The main parameters of the linear accelerator section are shown in Table 1.

The microwave acceleration system of IR-FEL's linear accelerator consists of a subharmonic pre-buncher, a buncher, and two accelerating tubes. The combination of buncher and the first accelerating tube, and the second accelerating tube are driven by two 30 MW klystrons, respectively.

The block diagram of the IR-FEL linear microwave acceleration system is shown in Fig. 1. The digital LLRF system based on MTCA.4 board is manufactured by the STRUCK company.

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Table 1: IR-FEL LINAC Parameters

Parameter	Value
Electron beam energy /MeV	Max:60
Energy spread(root mean square) /MeV	<0.24
Normalized emittance /(mm·mrad)	<30
Peak current /A	100
Charge /nC	1
Macrobunch repetition rate /Hz	1-10
Macrobunch width /μs	Max:10
Microbunch repetition rate /MHz	238/119/59.5/29.75

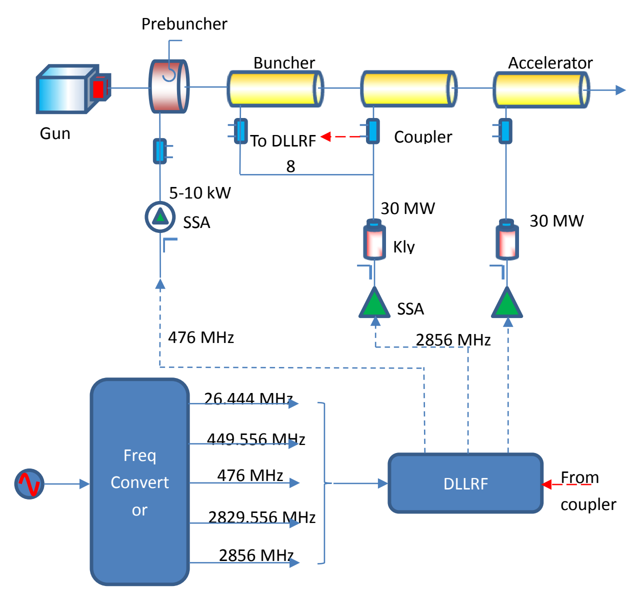

Figure 1: Block diagram of microwave acceleration system.

During the operation of the IR-FEL, we observed periodic oscillations in the output power of the two klystrons (approximately ±0.2~2% for amplitude, depending on the output phase of the klystron), with oscillation periods of approximately 100 s and 9 s respectively. This fluctuation of

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input power to the accelerating tube, impacting the energy fluctuation of the final output electron beam from the linear accelerator [2–4]. In the case of exchanging power supply of filament of two klystrons, the oscillation periods are exchanged at the same time. The test results of output signal of the klystron before upgrading is shown in Fig. 2.

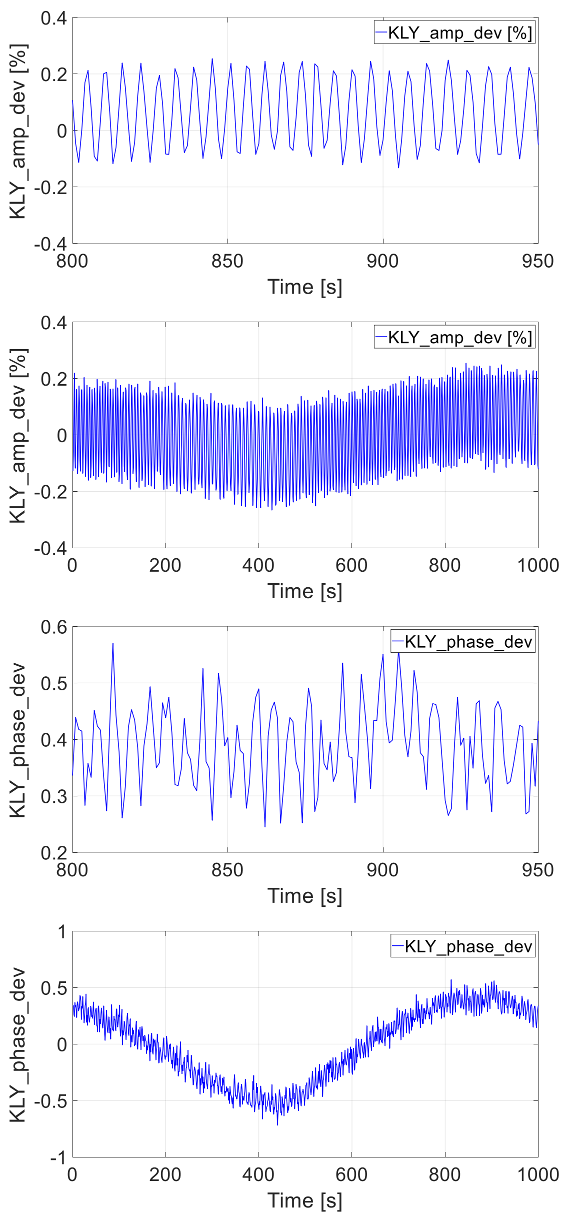

Figure 2: Test results of output signal of the klystron before upgrading.

Now, the optimization of the LLRF system has been completed and the oscillation has been suppressed. We employed a pulse-to-pulse feedforward and in-pulse feedback algorithm to compensate for the periodic oscillation in microwave signals, and replaced the IQ demodulation with a Non-IQ demodulation.

LLRF SYSTEM DESIGN

The microwave control system is employed to stabilize the amplitude and phase of the microwave field within the accelerating tube, comprising a reference signal source, frequency synthesizer, and low-level system. The signal source generates the 2856 MHz signal to the frequency synthesizer, which in turn generates REF (reference), CLK (clock), and LO (local oscillator) signals for the LLRF system. In the LLRF system, the signals' amplitude and phase are calculated by employing IQ or Non-IQ demodulation, and a 2856 MHz signal is generated, which is controlled to objective amplitude and phase. This excitation signal drives a 1 kW solid-state amplifier and a 30 MW klystron step by step, which in turn feeds power into the accelerating tube to generate a microwave field for accelerating electrons [5,6].

IQ and Non-IQ Demodulation

The microwave signals are mixed with the LO signal in the LLRF to produce an IF (intermediate frequency) signal for sampling by the ADCs. Compared with the IQ demodulation, the Non-IQ demodulation can separate the odd-order higher harmonics from the fundamental mode and suppress it by digital filter [7].

In our scheme, we selected $F_{if} = (3/13) \cdot F_{clk}$.With the clock frequency remaining of 105.778 MHz (2856/27), F_{if} has shifted from its original 26.444 MHz (IQ) to 24.41 MHz (Non-IQ), and the LO signal is chosen of 2831.59 MHz.

The spectrums of IQ and Non-IQ sampling are shown in Fig. 3, the odd-order is obviously separated.The design of a digital LLRF system using Non-IQ demodulation algorithm is shown in Fig. 4.

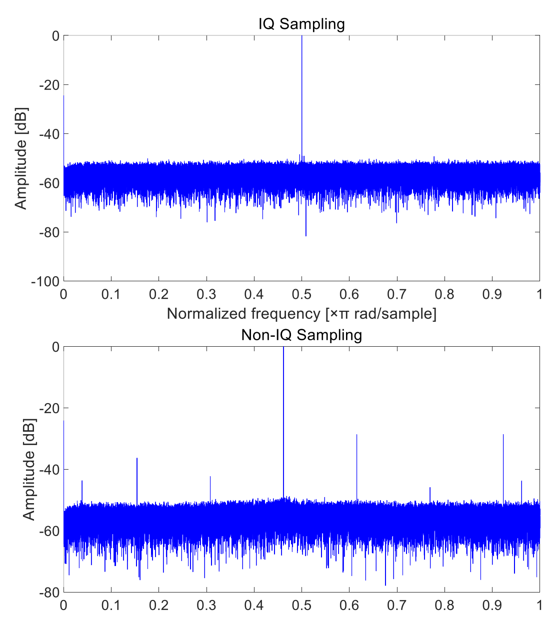

Figure 3: Spectrums of IQ and Non-IQ sampling.

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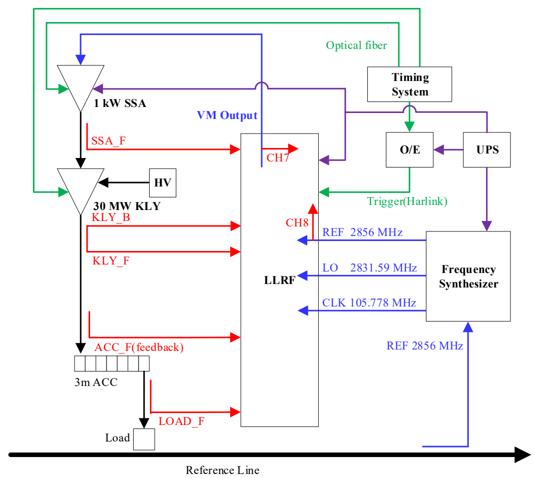


Figure 4: Block diagram of LLRF system using Non-IQ demodulation.

Pulse-to-pulse Feedforward and In-pulse Feedback

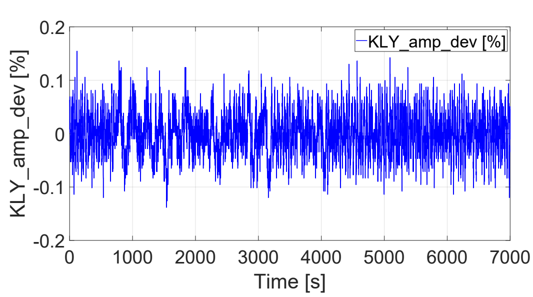
Pulse-to-pulse feedforward is the adjustment of the overall amplitude and phase of the next pulse based on the amplitude and phase error of the previous pulse. The oscillation period and amplitude of klystron can be measured in advance, then the adjusted value of amplitude can be predicted and set in the LLRF [5].

Considering the oscillation period and amplitude of klystron being variable during the long term operation, the in-pulse feedback algorithm is adopted to increase the stability and decrease the loop delay of the system. The observed point of feedback system is the front part of pulse, then the amplitude and phase are controlled in this pulse after the loop delay which contains the calculated time of the FPGA and response time of amplifier and klystron. The total loop delay is estimated of being less than 2 µs by the IQ-based in-pulse feedback.

PERFORMANCE TESTING

After the upgrade, a two-hours test was conducted on the microwave system. The amplitude and phase results of the klystron forward (KLY) signal are presented in Fig. 5.

During the two hours of closed-loop testing, KLY exhibited an amplitude stability of 0.04% (rms) and phase stability of 0.09° (rms).



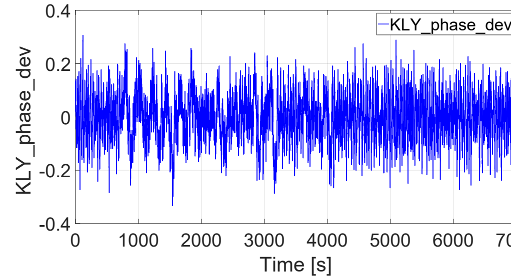


Figure 5: Two-hours test results of the output signal of klystron.

CONCLUSION

In this optimization, the oscillation reason of klystron is figured by swapping the filament power supplies of two klystrons. The pulse-to-pulse feedforward and in-pulse feedback algorithms are used to decrease the amplitude oscillation of klystrons, and the original IQ demodulation has been replaced with Non-IQ demodulation to suppress odd-order harmonics. After optimization, the 3rd harmonic noise of the klystron is reduced to -50 dBc. The amplitude and phase stability of output signal of klystrons are increased from 0.12%/0.07° (rms) to 0.04%/0.09° (rms).

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