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HIGH PRECISION SYNCHRONIZATION DEVELOPMENT FOR HIRES, THE ULTRAFAST ELECTRON DIFFRACTION BEAMLINE AT LBNL *

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Abstract

Precise synchronization between the laser and electron is critical for the pump-probe experiments in the HiRES Ultrafast Electron Diffraction facility. We are upgrading the LLRF and laser control system, which ultimately aims at a synchronization below 50 fs RMS between the pump laser pulse and electron probe at the sample plane. Such target poses tight requirements on the RF field stability both in amplitude and phase, and on the synchronization between the RF field and the laser repetition rate. We are presently developing a new LLRF system that has the potential to decrease the overall noise, reaching the required stability of tens of ppm on RF amplitude and phase. For the laser control side, we are replacing the long coaxial cables with fibers for both control signal transmission and laser signal reception. The control transmission side has been implemented, and the timing jitter has been reduced.

INTRODUCTION

Ultrafast Electron Diffraction (UED) is a powerful scientific instrument to study structural dynamics in material, chemical and biological sciences [1]. The RF photo-gun leads to larger accelerating field and higher output energies with respect to a conventional DC electron gun, generating higher brightness electron pulses for UED experiments [2]. Several experiments with GHz photoinjectors have demonstrated its advantages in terms of high space and temporal resolution [3–5]. However, the highest repetition rate of conventional photodiode GHz RF electron gun is kHz range, limiting the average current to 10 pA. The VHF gun, a room-temperature RF photo-gun [6], has been successfully developed at LBNL, which has been selected as the electron source for LCLS-II. This gun generates high brightness electron pulses with MHz repetition rate [7], leading to orders of magnitude increase in average current, opening the doors to new scientific experiments. The High Repetition-rate Electron Scattering (HiRES) beamline based on the VHF gun has been setup [8] at the Advanced Photo-injector Experiment (APEX) facility at LBNL.

Pump-probe methods are among the most useful experimental techniques in ultrafast science. First a specimen is excited by an impulsive laser pulse, and then a subsequent electron probe pulse measures its reaction. Figure 1 shows the schematic of the pump-probe experiment in the HiRES beamline. We aim at characterizing the dynamics of matter at the femtosecond and picosecond timescale. To achieve this goal, the timing jitter between the pump laser and the electron probe must be reduced to a lower timescale. Our intermediate-term goal is a precision of 50 fs or below. However, the current control system, developed in conjunction with the development of the VHF gun [9], cannot meet such requirements.

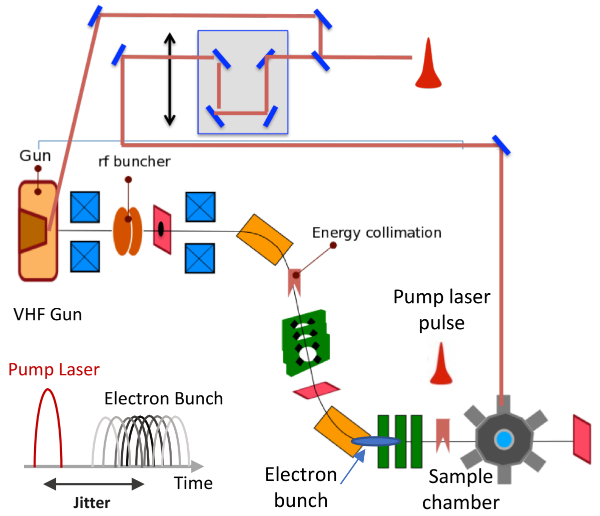

Figure 1: The pump-probe experiment setup in the HiRES beamline. The timing jitter between the pump pulse and the electron probe is critical for high temporal resolution.

A new control system is being developed for tight synchronization of the entire beamline. Here we discuss the control system upgrade plan, current status and future steps toward the final goals.

HIRES CONTROL UPGRADE PLAN

Temporal Resolution Specification

A detailed analysis on the temporal resolution of the HiRES beamline has been given in [8]. The timing jitter equation is

$$\tau(\mathrm{fs})^2_{\mathrm{eTOF}} = \left(145\frac{\tau_{\mathrm{laser}}}{100\,\mathrm{fs}}\right)^2 + \left(115\frac{\delta_{\mathrm{V}}}{10^{-4}}\right)^2 + \left(31\frac{\sigma_\phi}{0.01^{\mathrm{o}}}\right)^2. \tag{1}$$

There are three components of the jitter: the pumping laser jitter τ_{laser} with respect to the accelerating field, the gun voltage fluctuation δ_V and the RF phase jitter σ_ϕ. The laser jitter τ_{laser} and the gun voltage fluctuation δ_V are the dominating terms.

The new control system includes the development of a fiber-coupled laser synchronization control, new control

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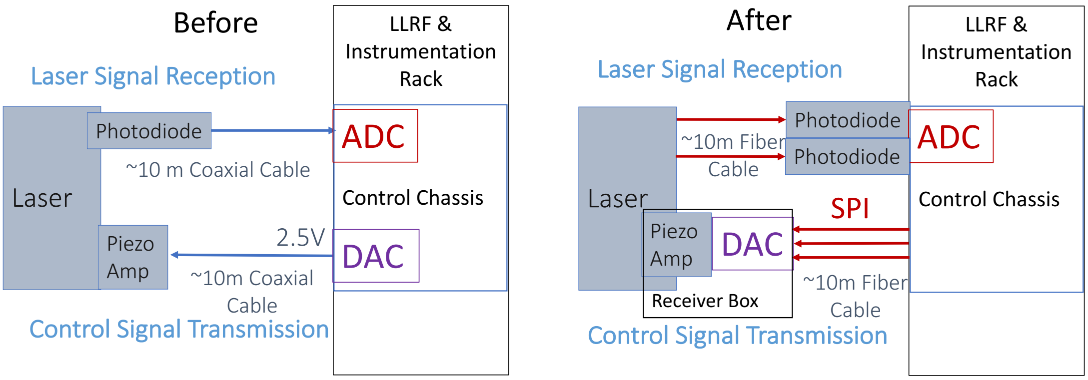

Figure 2: The laser synchronization control upgrade plan. There were long coaxial cables between laser oscillator and LLRF rack. A fiber-coupled laser control is being developed.

chassis and beam-based feedback. Our intermediate-term goal is to reduce the RMS timing jitter τ_{laser} down to 50 fs, which will be mainly achieved by the fiber-coupled laser synchronization and new control chassis development. In the long-term, we plan to explore a beam-based feedback scheme, which will use a cavity BPM to directly measure the electron beam jitter and feedback to correct the jitter.

Fiber-coupled Laser Synchronization

The laser synchronization control upgrade plan is shown in Fig. 2. In the HiRES facility, there are about 10 meters between the laser oscillator and the control chassis. There were long coaxial cables for both control signal transmission and laser signal reception paths. The analog signals in long coaxial cables had strong signal attenuation during transmission and those cables might also pick up noise due to electromagnet interference (EMI).

A fiber-coupled laser control can solve these issues. The basic idea is to reduce the analog signal attenuation and noise by replacing coaxial cables with fibers. On the transmission path, SPI digital signals are transmitted over three long fibers, thus there is no risk of signal attenuation and noise coupling. This system has been developed and implemented. More details can be found in the **CURRENT STATUS** section.

And on the reception path, we will move photodiodes into the control chassis and use two photodiodes instead of one. The optical signals on fibers instead of RF signals are transmitted. And a cross-correlation technique on the two channels has the potential to further reduce the noise reduction.

Upgrade LLRF Control Chassis

The RF ADC/DAC and related FPGA hardware are the primary components for any LLRF control chassis, which determines the system performance. The current LLRF chassis are based on the LLRF46 board [10], together with up/down converters. The RF digitizers and FPGA are on the same board. The board design is compact and cost-saving. However, the channel to channel isolation of the chassis is about 60 dB, which limits the achievable RF amplitude and phase stability.

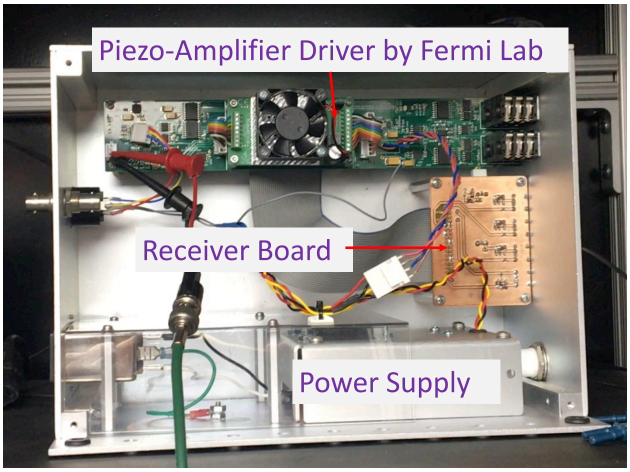

Figure 3: The receiver box we fabricated for the fiber-coupled laser control. One could see the receiver board, the power supply and the piezo-amplifier driver.

A two-board set, BMB-7 FPGA board and a Digitizer board, has been developed and applied by the LCLS-II project [11]. A over 85 dB isolation has been demonstrated and we plan to implement this new board set to the HiRES LLRF controller. The channel to channel isolation improvement makes it possible to achieve high phase and amplitude control accuracy for the HiRES pump-probe requirements.

Beam-Based Feedback

Direct measurement of the beam arrival time could give us a possible path to feedback and possibly achieve 10 fs synchronization accuracy. We plan to use a cavity BPM developed by Tsinghua University install it to the HiRES beamline and implement beam-based feedback with that.

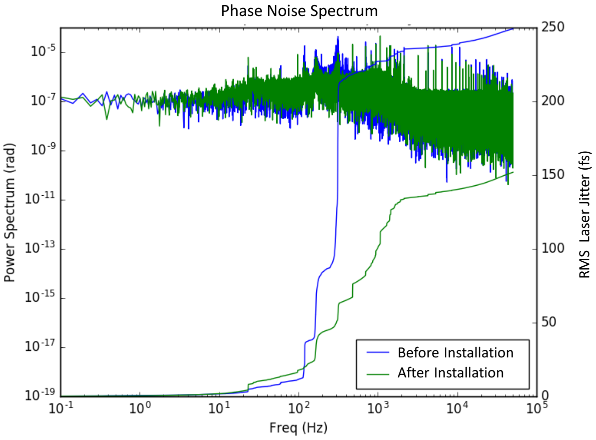

Figure 4: Laser phase noise spectrum and phase noise integral comparison before (blue curves) and after (green curves) the new fiber-coupled laser control installation.

CURRENT STATUS

A fiber-coupled laser control has been developed and installed on the transmission path to replace the long coaxial cables. To implement SPI links on fibers, two PCB boards were designed and fabricated. The transmitter board modulates SPI digital signals on the light signals, which was installed in the control chassis at the transmitter side, while the receiver board demodulates light signals back to electric signals and send to a low noise piezo-amplifier driver at the receiver side. The receiver board is enclosed in a receiver box with the piezo-amplifier driver and power supply. The piezo-amplifier board is developed by Fermilab for the LCLS-II resonance control [12], which has 90-dB SNR 10-kHz bandwidth. Figure 3 shows the fabricated receiver box.

An FPGA driver for the DAC driving the piezo-amplifier was developed and integrated with the existing HiRES firmware. Before installation, firmware bench tests were performed for verification and debugging. And evaluation tests were also setup for analyzing the safety thresholds of the piezoelectric transducer (PZT), which verified that the new piezo amplifier had an average current protection feature, which would prevent the PZT from being damaged.

This fiber-coupled laser control has been installed on March 2018. The preliminary result is shown in Fig. 4. The RMS in-loop timing jitter has been reduced after installation. But it was still far from our intermediate goal of 50 fs.

Two approaches are being explored to further improve the synchronization accuracy. Firstly, the in-loop timing jitter is limited by the resolution of the optical signal, which could be improved by upgrading the reception path. Two new photodiodes have been installed in the LLRF chassis and two fibers are going to couple the laser signals through fibers, replacing the existing long coaxial cable. More noise reduction can be made with cross-correlation technique on the two channels. Secondly, there is a 1-kHz low pass filter we applied, to protect the PZT in the laser, which limited the loop bandwidth. Based on the piezo amplifier and PZT evaluation test result, we can increase bandwidth of this filter to ~10 kHz suppress the noise from 50 Hz to 1 KHz more.

Once we have the new control chassis, we plan to develop a new synchronization loop, locking the laser at 1.3 GHz, which is the 7th harmonic of the cavity RF frequency. And higher synchronization accuracy is expected due to this change.

CONCLUSION

In summary, we are upgrading the LLRF controller for the HiRES beamline at LBNL to improve synchronization between the pump laser and the electron probe. The upgrade started with fiber-coupled laser control development, followed by the new chassis upgrade based on the LCLS-II gun LLRF controller. Beam-based feedback is also considered as a further step. A fiber-coupled laser control has been developed, characterized and installed. Preliminary test shows the in-loop laser RMS timing jitter has been reduced.

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