

Short pulse laser technologies for advanced accelerator applications

Katsuyuki Kobayashi

*Sumitomo Heavy Industries USA, Inc., Sumitomo Heavy Industries(USA), Inc., c/o Aculight Corp.,
11805 North Creek Parkway South, Bothell WA 98011*

Akira Endo

The Femtosecond Technology Research Association, 5-5 Tokodai Tsukuba Ibaraki 300-2635, JAPAN

Next generation short pulse laser systems for high energy accelerator physics have been developed using novel synchronization techniques. The basic techniques are the synchronization of a mode locked oscillator to an RF reference, synchronization of two mode locked oscillators, synchronization of a low-repetition amplifier to the oscillator, and multiplexing of modular laser beams. We have developed a mode locked oscillator with sub 100 femtosecond timing jitter, two synchronized oscillators with an accuracy of several tens of femtosecond, and an amplifier with 1 femtosecond timing precision to an oscillator. Assembling these techniques together with a beam combining system may enable us to generate high energy, complicated timing structure or high repetition, high power continuous laser pulses useful for future accelerators.

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I. INTRODUCTION

Femtosecond and picosecond laser pulses with precise timing accuracy are critical for advanced accelerator applications. These pulses are used for RF photo-injectors¹ as well as high energy photon (X-ray² and γ -ray) generation through inverse Compton scattering. Both for RF photo-injectors and for high energy photon, precise synchronization of laser pulses is required. The basic techniques which we have developed to synchronize laser pulse are described in section II. Further complicated timing structure will be required for the next generation accelerators. On the other hand, high repetition and high power continuous laser pulses shall be required for another type of new accelerators. New designs of laser system for the next generation accelerator, based on the basic laser techniques, are shown in section III. Section IV summarizes this paper.

II. BASIC TECHNIQUES

In this section, we describe three special techniques which will be applied to the laser system for next generation accelerators. All three techniques are for the synchronization of pulse timing. One is the synchronization of a mode locked laser oscillator to an RF reference signal. The other two, the synchronization of an amplifier to the oscillator and the synchronization of two mode locked oscillators, are derivations based on the synchronization of the oscillator.

A. Synchronization of a mode locked laser oscillator to an RF reference signal

Short pulse femtosecond or picosecond lasers are widely applied in accelerator physics such as photo-injectors or X ray and gamma ray generation. Also, short pulse lasers are used as diagnostic tools. Generally, short pulses are generated by a mode locked laser oscillator followed by an amplifier. The pulse timing of a mode locked oscillator is determined by the oscillator itself, if no special techniques are applied. However, many research works in accelerator physics require a precise timing synchronization of the laser pulses to the electron pulses. To satisfy this requirement, we have developed a precise synchronization technique of a mode locked oscillator.

The optical cavity length determines the pulse timing of a mode locked laser oscillator. The optical pulses are generated in every round-trip time. So the pulse timing can be synchronized by adjusting the cavity length. A Ti:sapphire modelocked oscillator³ was built to demonstrate the synchronization. A highly stable laser pump source is required because poor energy stability and poor pointing stability of the pumping source can cause fluctuations of the pumping distribution in the laser crystal and affects the pulse timing. The second harmonics

of a low noise all-solid-state Nd:YVO4 laser (Spectra-Physics, Millennia) was used as a pump source. Air flow and temperature changes also affect the pulse timing. So this oscillator was covered with a plastic box and the room temperature was kept within 0.1 degree centigrade. The output power was 100 mW with 3.5 W pumping. The center wavelength was 800 nm and the pulse width was 50 fs. The repetition rate was 119 MHz, 1/24 of an s-band accelerator frequency.

The pulse train was detected by a photodiode and the timing was compared with a reference RF signal. One of the cavity mirror was mounted on a piezoelectric transducer (PZT). The PZT controlled the mirror position with a conventional phase locked loop (PLL) so that the pulse timing was synchronized to the reference signal. A motor-driven translation stage was also installed to compensate the slow but large fluctuation, while the PZT compensate the small but fast fluctuation. Figure 1 shows the power spectral density of the oscillator. The dashed line shows the power spectral density when the PLL is not operated. The timing jitter was about 5 ps. The solid line show the power spectral density with the PLL in operation. The r.m.s. timing jitter from the reference signal was about 100 fs.

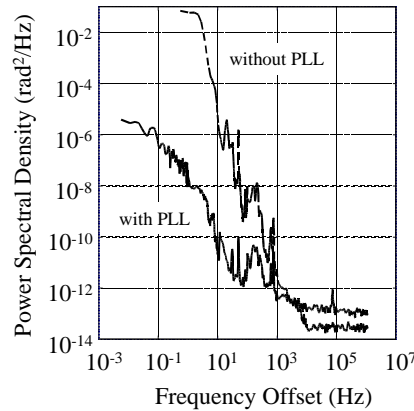


FIG. 1. Power spectral density of the mode locked oscillator. The r.m.s. timing jitter was about 100 fs.

B. Synchronization of amplified pulses to a mode locked oscillator with spectral-resolved cross-correlation technique

A conventional PLL technique can be applied for a mode locked oscillator because the repetition rate is sufficiently high, typically around 100 MHz. But the repetition rate of the amplified pulses are very low, typically 10 Hz or 1 kHz at most. A different technique is required to synchronize the amplified pulses. Furthermore, even a diagnostic technique has not been established to evaluate the low repetition rate pulse timing with femtosecond precision. High repetition pulses can be evaluated with statistical methods^{4,5}, however, another technique is required for low repetition rate pulses. We have demonstrated, for the first time, a novel technique to evaluate⁶ and synchronize⁷ the timing of low repetition pulses. This technique is based on cross-correlation of high repetition rate pulse and the low repetition pulse. As we have described above, we had made a highly stabilized mode locked laser oscillator. The optical pulse of the oscillator was used as a reference signal. The amplified pulse was stretched and linearly chirped. The amplified pulse and the reference optical pulse were cross-correlated to generate an up-converted pulse. Because the amplified pulse was linearly chirped, the wavelength of the up-converted pulse depends on the timing of two input pulses. The timing error of the two pulses can be evaluated by measuring the wavelength of the up-converted pulse. Since the pulse from the oscillator was highly stabilized, the wavelength of the up-converted pulse indicates the timing jitter of the amplified pulse. Figure 2 shows the diagnostic setup to measure the timing jitter of the amplified pulse.

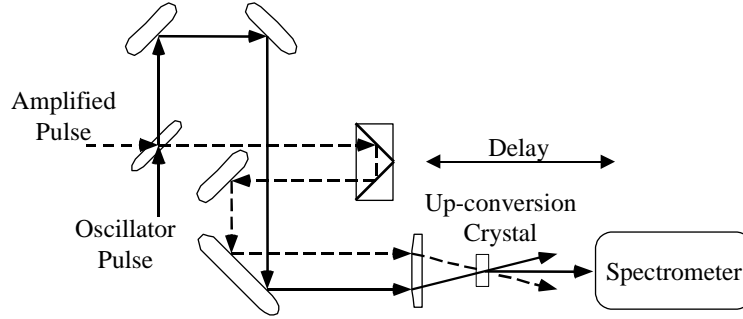


FIG. 2. The diagnostic setup to measure the timing jitter of the amplified pulse

We used a home-made Ti:sapphire regenerative amplifier as a test laser. The second harmonics of a low noise all-solid-state Nd:YLF laser (Positive Light, Evolution) was used as a pump source. For the amplifier, as well as the mode locked oscillator, a stable pump source is very important to achieve good synchronization. The timing stabilized mode locked Ti:sapphire oscillator was amplified at 1 kHz repetition rate. To achieve good energy stability, the temperature of the intracavity Pockels cell was stabilized to within 0.1 degree centigrade. To avoid fluctuations due to airflow, this regenerative amplifier was covered with a plastic box. The output energy and the energy stability were 0.6 mJ and 0.4% r.m.s., respectively with 6 mJ pumping. The amplified pulse was stretched and linearly chirped to 500 fs. This chirped pulse and nearly transform limited 50 fs pulse from the mode locked oscillator were cross-correlated and the wavelength of the up-converted pulse was measured by a spectrometer. The change in the wavelength corresponds to the relative timing error of two pulses. The relative timing error of two pulses are shown in fig. 3.

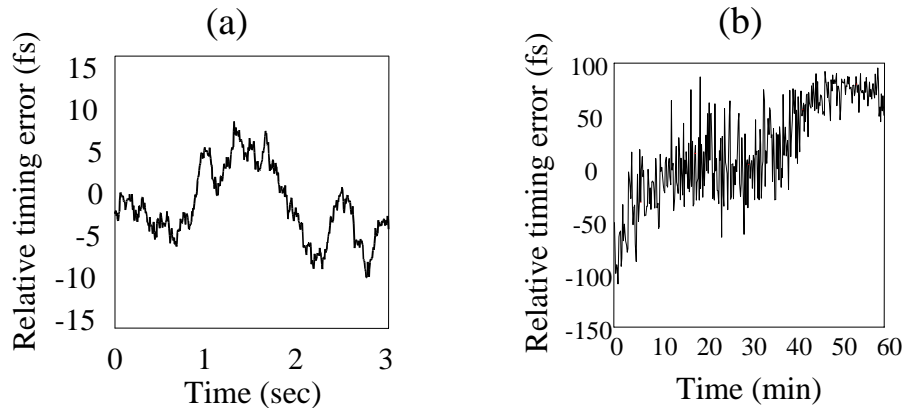


FIG. 3. The relative timing error of two pulses. (a) Short term in three seconds and (b) long term in one hour.

Two types of fluctuation can be found in fig. 3(a). One is a small but rapid fluctuation. Its time constant was about 0.1 s (10 Hz) and it might come from the mechanical vibration of the optical components, such as mirror mounts. The other is a relatively large and slow fluctuation. We assume this came from the airflow. Also two types of fluctuation can be found in fig. 3(b). One is a rapid (less than a minute) and the other is slow (10 to 20 minutes). Both fluctuations correspond to the thermal expansion. This graph shows that the fluctuation was about 200 fs. It corresponds to the change in optical length about 60 μm . The optical pulse travels in the cavity 20 round trip, so the change in the one-way cavity length is about 1.5 μm . This length change corresponds to the thermal expansion of stainless steel in a 0.1 degree temperature change.

Once the timing error was measured, the concept of synchronization is simple. One of the mirror position was controlled with a PZT so that the amplified pulses are synchronized to the reference optical pulses. Figure

4 shows the relative timing error with and without synchronization. The relative timing error was reduced to 0.7 fs r.m.s.

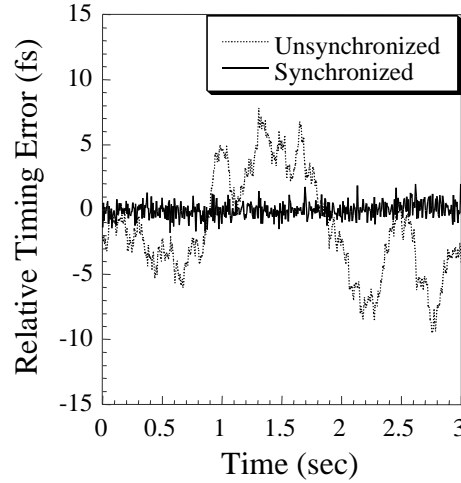


FIG. 4. The relative timing error with (solid line) and without (dashed line) synchronization. The timing error was reduced to 0.7 fs.

C. Synchronization of two independent mode locked laser oscillators

Two types of lasers are applied to the γ -ray or X-ray generation system. One is a high energy IR femtosecond laser for collision with an electron pulse, and the other is a UV picosecond laser for photo cathode irradiation. The electron pulse and the IR femtosecond laser pulse should be synchronized to generate γ -ray or X-ray pulses. Accurate synchronization of IR and UV pulses is essential because the timing of the electron pulse is determined by the timing of UV pulse irradiated onto the photo cathode. UV pulses are also generated by a Ti:sapphire CPA system, followed by a wavelength conversion to the third harmonics.

We applied a phase locked loop technique to synchronize two mode locked laser oscillators⁸. The first oscillator was synchronized to an RF reference signal with a conventional PLL technique described above. Then two pulses from the first and the second oscillators were cross-correlated to generate an up-converted pulse. The intensity of the up-converted pulse corresponds to the overlap ratio of two pulses. The intensity was used as a feedback signal, and one of the cavity mirrors of the second oscillator was controlled by a PZT. Figure 5 shows the setup for the synchronization of two oscillators.

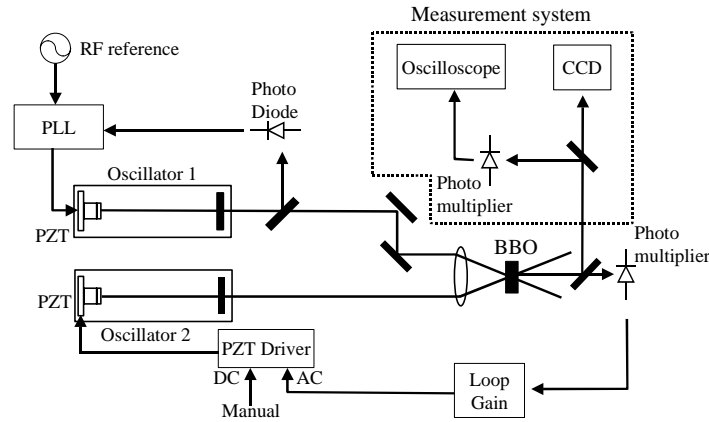


FIG. 5. Experimental set up for the synchronization of two mode locked oscillators.

The first oscillator is the same as described above. The center wavelength and the pulse width of the second oscillator were 855 nm and 109 fs, respectively. Another cross-correlator, with an optical delay line, was applied to measure the cross-correlation trace. Figure 6 shows the cross-correlation trace of two oscillators. We assume that the cross-correlation width is the superposition of two pulse widths and the relative timing error, as shown in equation. 1.

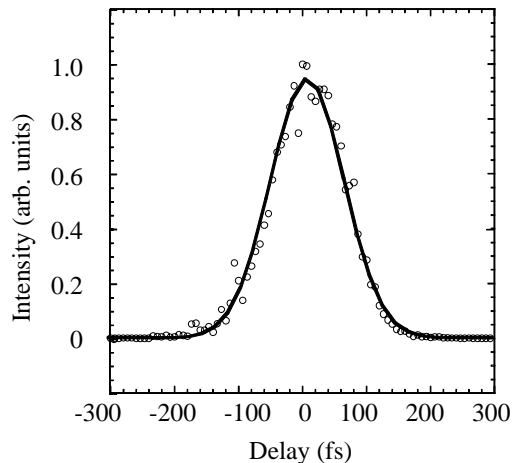


FIG. 6. Measured (circle) and the least square (solid line) of the cross-correlation trace of two synchronized mode locked oscillators. Relative timing error of two oscillators was 28 fs (rms).

$$\tau_c = \sqrt{\tau_1^2 + \tau_2^2 + \tau_j^2} \quad (1)$$

where τ_c is the cross-correlation width, τ_1 and τ_2 are the pulse width of the first and the second oscillators, respectively, and τ_j is the relative timing error. The cross-correlated width was 137 fs. Substituting into eq. (1), the relative timing error was calculated to be 66 fs (FWHM) and 28 fs (rms).

III. LASER SOURCES FOR NEXT GENERATION ACCELERATORS

Rapid and steady progress both in accelerators and in laser technologies brings us to new stages of research. In this section, we propose two laser systems based on the laser techniques described above. One is high energy multi-pulse generation and the other is high power continuous pulse generation. The requirements for these laser systems are very difficult, and they are impossible to satisfy with a single state of the art laser. A common concept for both systems is to make multiple lasers and combine into one. Since the optical pulses come from plural amplifiers and then combined, synchronization of the laser pulses is most critical.

A. High energy multi-pulse generation

One of the current trends in accelerator physics is the high energy photon collider ($\gamma\gamma$ collider). The Joint Linear Collider(JLC) in Asia, Next Linear Collider (NLC) in America and TESLA in Europe are under design as next generation high energy facilities, and $\gamma\gamma$ collider is one of the main applications of these facilities. The common significant feature is the complicated timing structure, such as a bunch of many micro pulses.

Let us consider the laser system for JLC as an example. A bunch, consist of 95 pulses with 2.8 ns interval, repeats at 150 Hz. The energy and the pulse width of each pulse are 1 J and 1 ps, respectively. The timing structure is shown in fig. 7.

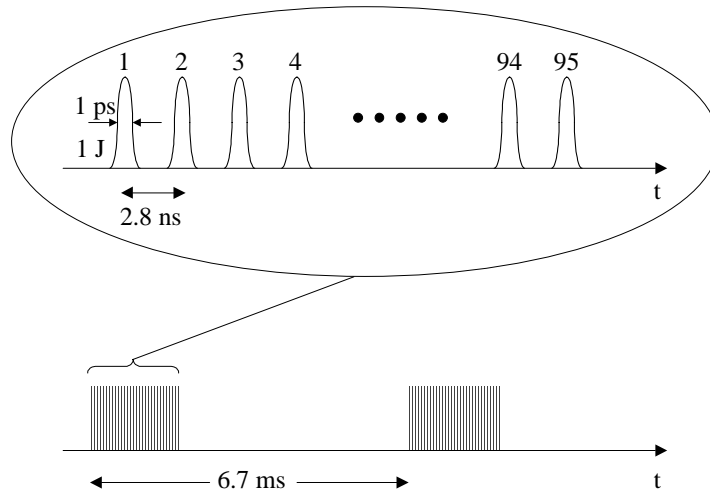
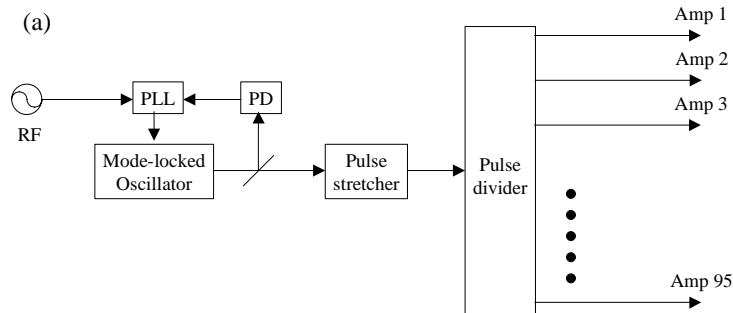


FIG. 7. Timing structures of pulses for JLC $\gamma\gamma$ collider.

It is almost impossible to generate such high energy and complicated time structure pulses with a single laser. One of the promising solutions is to build 95 amplifiers and combine the pulses. In this case, each amplifier is assigned to 1 J/pulse at 150 Hz. A single mode locked oscillator generates continuous pulses at 357 MHz (2.8 ns interval). This oscillator is synchronized to an RF reference signal by a PLL technique. After being stretched, the pulses are divided into 95 sets of 150 Hz pulses by a series of Pockels cells. 95 parallel amplifiers enlarges the pulse energy up to 1 J. Each amplifier is synchronized to the mode locked oscillator with a spectral-resolved cross-correlation technique. Deformable mirrors might be required to compensate the wavefront distortion. Thermal inhomogeneity in the amplifier crystals causes a wavefront distortion making it difficult to focus the beam into a tiny spot. Also, active mirrors might be required for a good pointing stability. Finally, each pulses are compressed to 1 ps and delivered to the interaction region. Figure 8 shows the diagram of the proposed laser system.



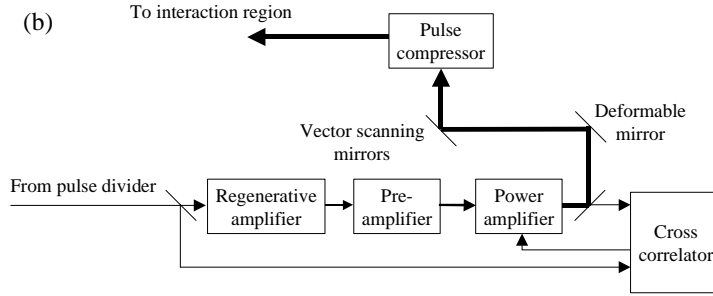


FIG. 8. The diagram of multi-pulse laser system. (a) oscillator stage and (b) amplifier stage.

B. High power continuous pulse generation

Another trend in accelerator physics is to apply high repetition, high charge, continuous electron pulses. The electron pulses are generated on a photo-cathode, irradiated by optical pulses. Let us consider the laser system for the Photo-injected Energy Recovering Linac (PERL) as an example. The next generation PERL requires UV continuous pulses of several tens of Watts at 1.3 GHz. Let us assume that IR pulses of 200 W is required to generate sufficient UV pulses. It is impossible to achieve such a high power by a single existing laser. We propose to build parallel lasers and combine. For instance, 10 parallel lasers each 20 W, 130 MHz will meet this requirement. Such a high power UV laser source is within the current state of the art. Because of geometrical restrictions, all of the beams from the multiple lasers must be exactly overlapped onto one axis. One promising way is that the beams are combined by a grating, shown in fig. 9

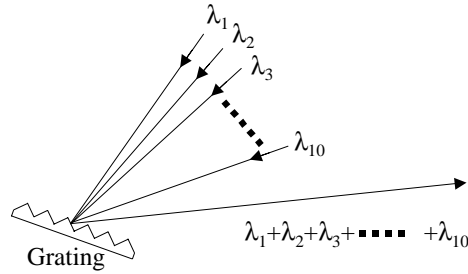


FIG. 9. Combination of multiple laser beams into one axis

This type of combination is widely used for wavelength-division-multiplexed (WDM) systems. In this case, the wavelengths of the 10 beams should be different. The 10 beams come to the grating from different angles, and all of the reflected beams exactly overlap into one axis. The 10, 130 MHz lasers must be synchronized so that the combination of these lasers results in a time of 1.3 GHz continuous pulses. We plan to use one 1.3 GHz mode locked oscillator for a reference signal. Since up to 3 GHz repetition rate has been demonstrated, it is not difficult to obtain 1.3 GHz. This oscillator is synchronized to an RF reference signal by the PLL technique. The pulses are split into 10 beams. Each of the 10 lasers, each operating at a different wavelength, is synchronized to the 1.3 GHz pulses by the OPLL technique. The OPLL technique can be applied because it does not depend on the wavelength.

IV. SUMMARY

We have developed laser systems with precise timing accuracy. We demonstrated the synchronization of a mode locked laser oscillator to an RF reference signal with an accuracy less than 100fs, the synchronization of two mode locked laser oscillators with an accuracy of 28 fs, and the synchronization of amplified pulses with

an accuracy of 0.7 fs. Based on these techniques, we proposed advanced laser systems for new generation accelerator physics. One laser system is for the generation of high energy pulses with complicated timing structure for next generation linear colliders, and the other is a system for generating high power continuous pulses for PERL photo-injector.

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