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# Production and utilization of synchronized femtosecond electron and laser single pulses

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## Abstract

A subpicosecond (700 fs at FWHM) electron pulse from the S-band (2.856 GHz) linear accelerator (linac) of the NERL (Nuclear Engineering Research Laboratory) was synchronized with a femtosecond (100 fs at FWHM) laser pulse from a $T^3$ (table-top terawatts) laser with a picosecond time whose standard deviation is 3.7 ps. Then we generated a picosecond characteristic X-ray pulse by irradiating through the electron pulse a Cu target (K$\alpha$, 8.1 keV, 1.54 Å) and obstained the Bragg diffraction from a NaCl ionic monocrystal using a high sensitivity X-ray imaging plate. Further, we discuss its applications to observe lattice vibration of the monocrystal by using the synchronized laser (pump) and X-ray (probe).

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## 1. Introduction

Recently, there has been remarkable progresses in producing ultrashort pulses by lasers and particle beam accelerators. Now high-powered 100 fs laser pulses are available by table-top lasers and a 1 kA subpicosecond electron pulse by linear accelerators [1]. Ultrashort synchronized pulses lead to an ultrafast time-resolved dynamic spectroscopy, which is capable of observing new ultrafast phenomena in quantum beam-material interaction. Thus, the accurate synchronization of these pulses is of much recent interest. In the NERL of the University of Tokyo, the synchronization system is to be applied to several new experiments; a laser wakefield acceleration, femtosecond X-ray generation and its application to ultrafast dynamic microspectroscopy. It is necessary for the above applications that the subpicosecond electron beam and the femtosecond laser pulse are accurately synchronized with a time resolution of less than 1 ps.

In this paper, the synchronization system, the experimental observations and its application to ultrafast microscopy via X-ray diffraction are presented.

## 2. Synchronization system

Several trigger pulses are necessary for the generation of an ultrafast electron and laser pulses. For example, we have to generate and control trigger pulses to a grid pulser, a subharmonic bunchers (SHB), rf power fed to accelerating tubes, other pretrigger pulses for the linac components, a trigger pulse to a timing stabilizer, a YAG laser, a pulse selector and other pretrigger pulses for the $T^3$ laser. The $T^3$ laser consists of a Ti-sapphire oscillator, a stretcher, a regenerative amplifier, a pulse selector and a multipass amplifier. The schematic drawing of the synchronization system between the linac and laser is shown in Fig. 1. At first we determine 119 MHz as the main rf source. Then we generate higher harmonics (476 MHz, 2.856 GHz, etc.) and subharmonic (79.3 MHz) via frequency multipliers and dividers. Then, the trigger pulses synchronized with a

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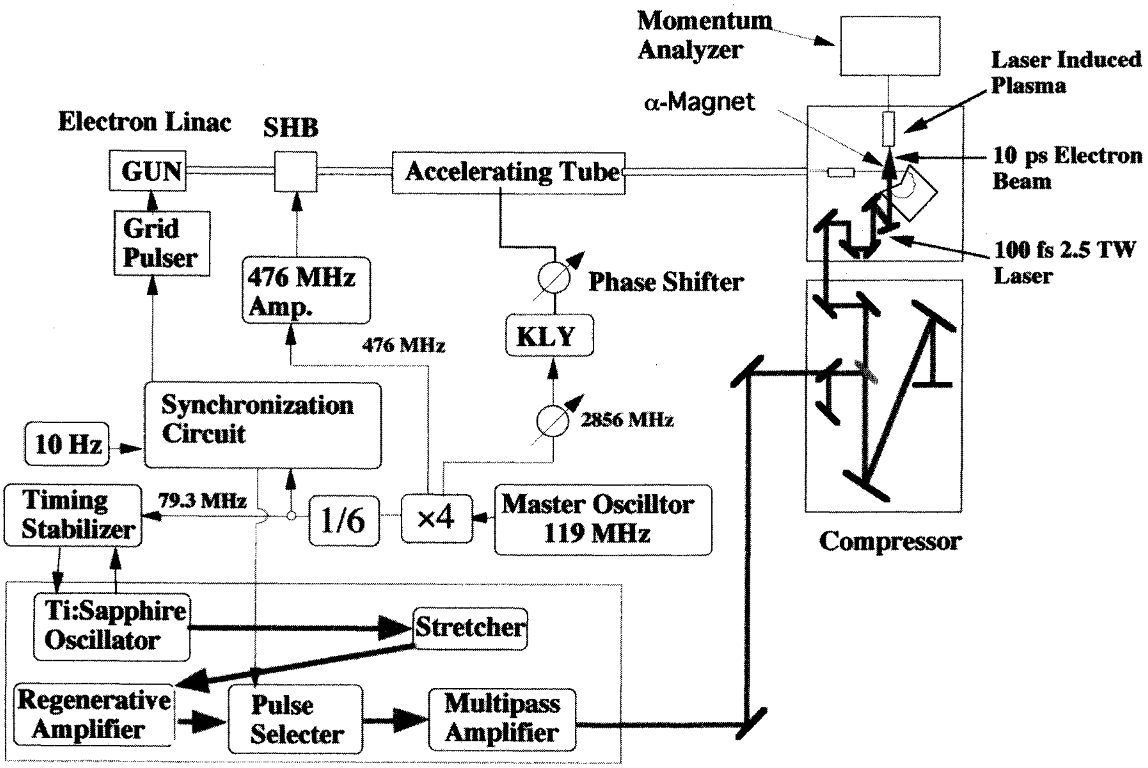

Fig. 1. Schematic diagram of the synchronization system and laser wakefield accelerator.

specified phase of 79.3 MHz is generated at 10 Hz. The laser repetition rate is precisely fixed to 79.3 MHz by the timing stabilizer (or so-called mode locker). The rf synchronized trigger pulses run the electron gun of the linac and also select the laser pulse at 10 Hz. Further, the trigger pulses are used to run several diagnosis devices including

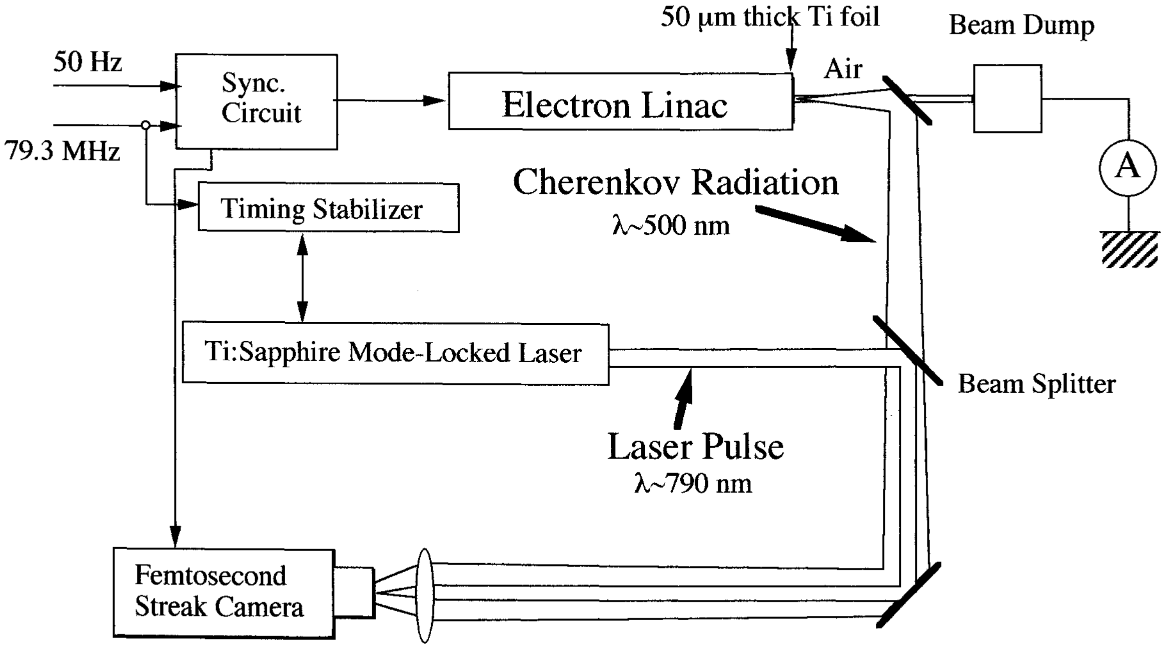

Fig. 2. Measurement setup for the synchronization.

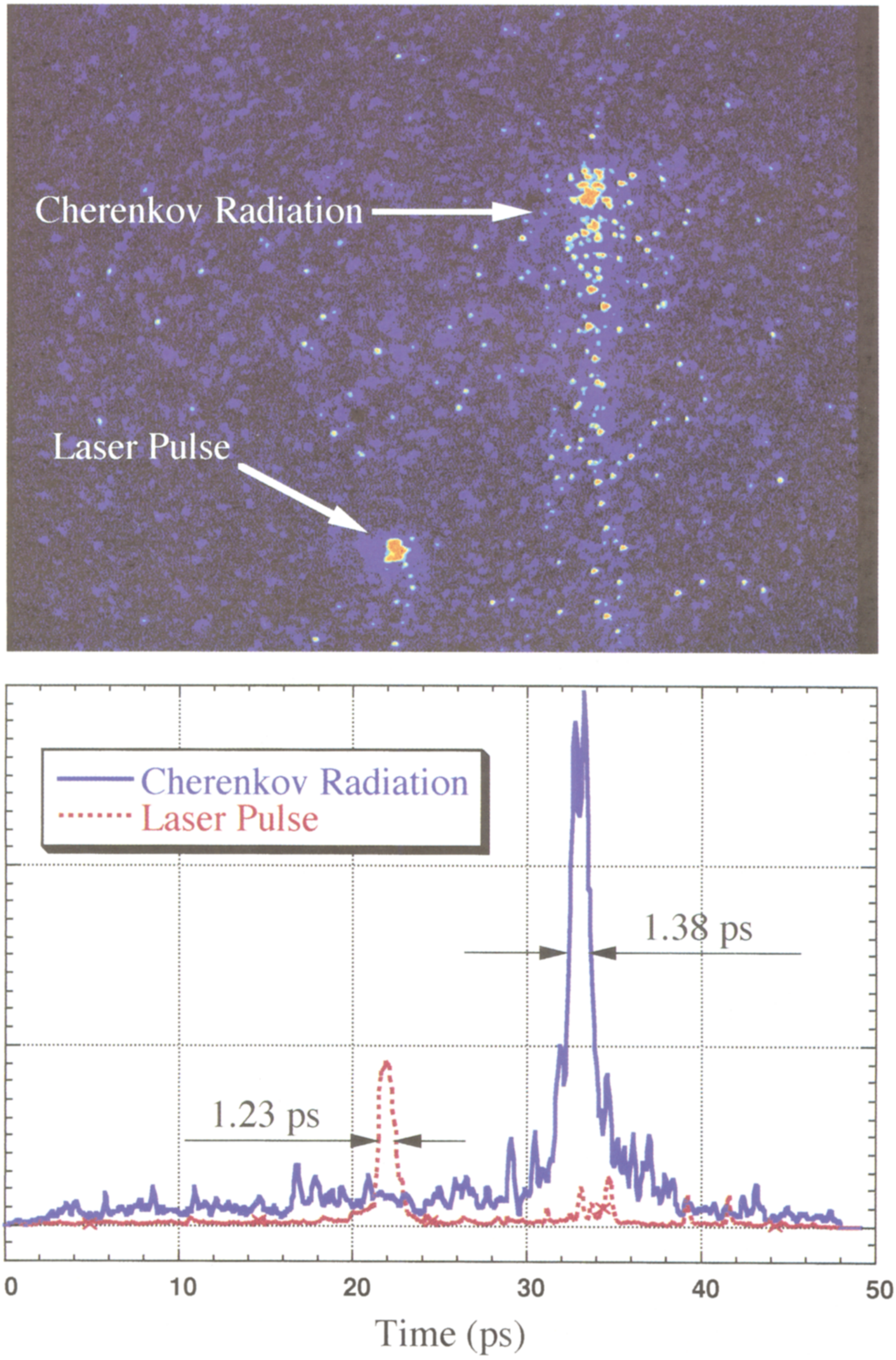

Fig. 3. Streak images and pulse shapes of subpicosecond electron pulse via Cherenkov radiation and femtosecond laser pulse.

a femtosecond streak camera. The selected laser pulse is transported to the compressor through a vacuum pipe and compressed from 300 ps to 100 fs at FWHM to be 2.5 TW as a peak power.

The measurement setup is schematically shown in Fig. 2. Cherenkov radiation pulse emitted by the electron pulse in air and the laser pulse are introduced to the streak camera. The time interval between the electron and laser pulses is adjustable by several time-delay units in the synchronization system. The synchronization was confirmed and those pulse shapes were obtained by the femtosecond streak camera whose time resolution is 200 fs (Hamamatsu Fesca-200). We can measure them on-line by a single event. We evaluated the time jitter of 3.7 ps at the standard deviation between the two pulses. The measured streak image and pulse shape are shown in Fig. 3

## 3. Applications

### *3.1. Laser wakefield acceleration*

A laser wakefield acceleration is expected to be a new acceleration method with rather high electric field gradient in the GeV/m class, which is different from conventional accelerations with solid state cavity or tube [2–4]. Laser pulses from the $T^3$ laser excite a wakefield in a plasma and the succeeding electron pulses are accelerated by the wakefield, provided it is precisely located in an accelerating phase of the wakefield. Higher field gradient gives a shorter accelerator, that is the main advantage of the laser wakefield acceleration. In order to measure the laser wakefield directly, we plan to inject the subpicosecond electron pulse with a specified delay-time from the laser pulse and to analyze its energy gain. The experiment is now under

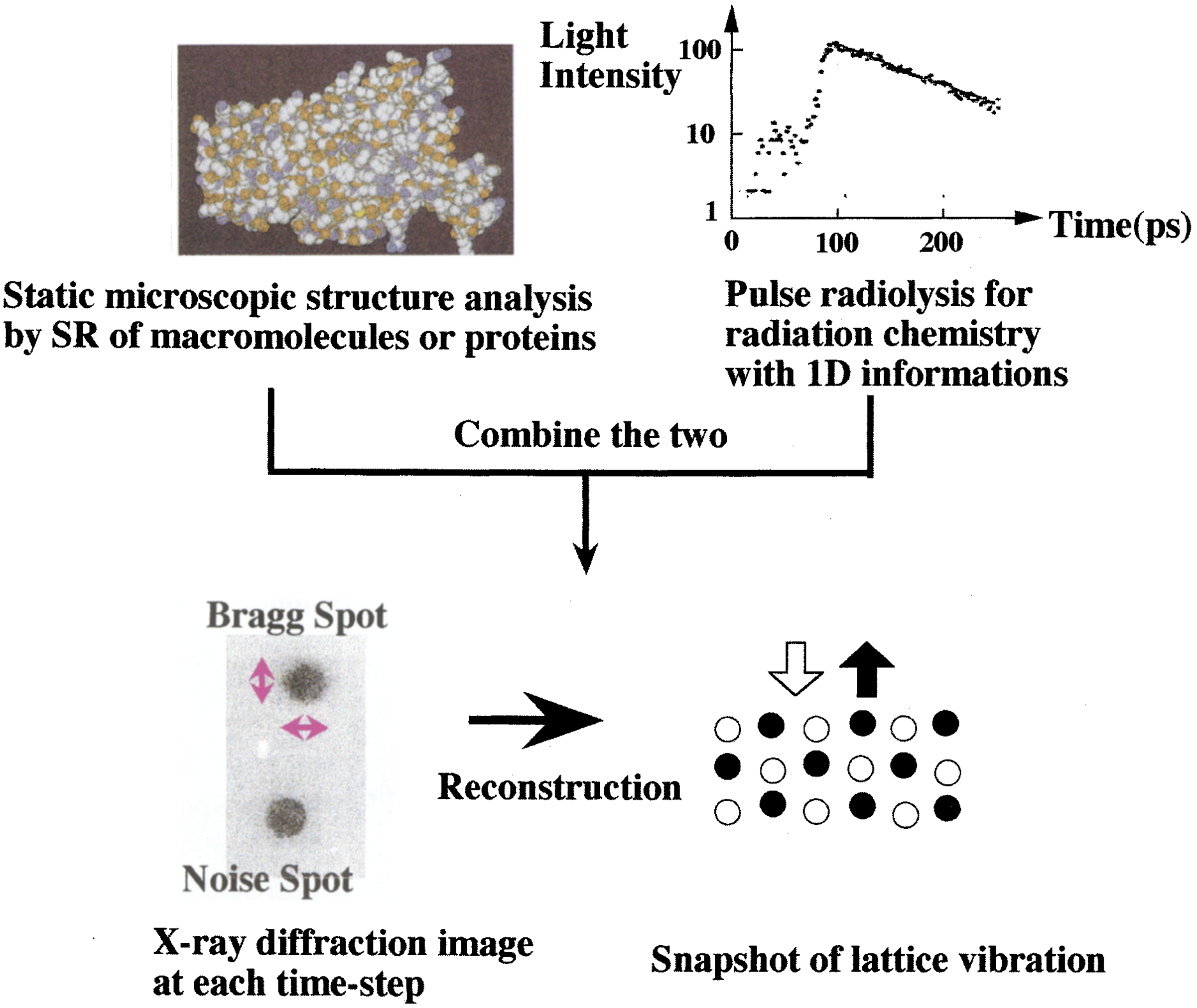

Fig. 4. Concept of the pulse-snapshot method.

way. The laser wakefield accelerator is also shown in Fig. 1.

### 3.2. Pulse-snapshot X-ray diffraction

Dantus et al. developed the technique of ultrafast electron diffraction of molecules by the synchronized femtosecond laser and picosecond electron gun [5]. Here we propose a new method of femtosecond time-resolved dynamic X-ray diffraction, which enables us to observe ultrafast quantum phenomena such as lattice vibration.

Now we can determine a structure of macropolymers or proteins via X-ray diffraction using high brightness synchrotron radiation. On the other hand, pulse radiolysis opened the window to picosecond time-resolved researches on radiation chemistry [6,7]. However, the former is basically and currently the static analysis and the latter gives us only one-dimensional data of light emission and absorption as a function of time.

The new femtosecond time-resolved dynamic microspectroscopy, named by us as 'the pulse-snapshot method', is the combination of both. We can have access to a three-dimensional (3D) snapshot of microscopic motion of atoms. Here we need to use both synchronized femtosecond laser pulse (pump) and X-ray pulse (probe) delivered from the electron accelerator. We irradiate the matter by the 100 fs laser and induces lattice vibration, and the succeeding X-ray pulse provides us an X-ray diffraction image on an X-ray imaging plate. This process is repeated until we get a clear diffraction image with sufficient signal-to-noise ratio. The lattice structure is reconstructed by introducing a certain robust inverse analysis. Next, the delay-time is varied again and the snapshots of the lattice vibration at different timesteps are obtained. Computer graphics technique enables us to get the time resolved evolution of the structure as an animation. The concept is schematically explained in Fig. 4.

As the first step, we generated the picosecond Kα

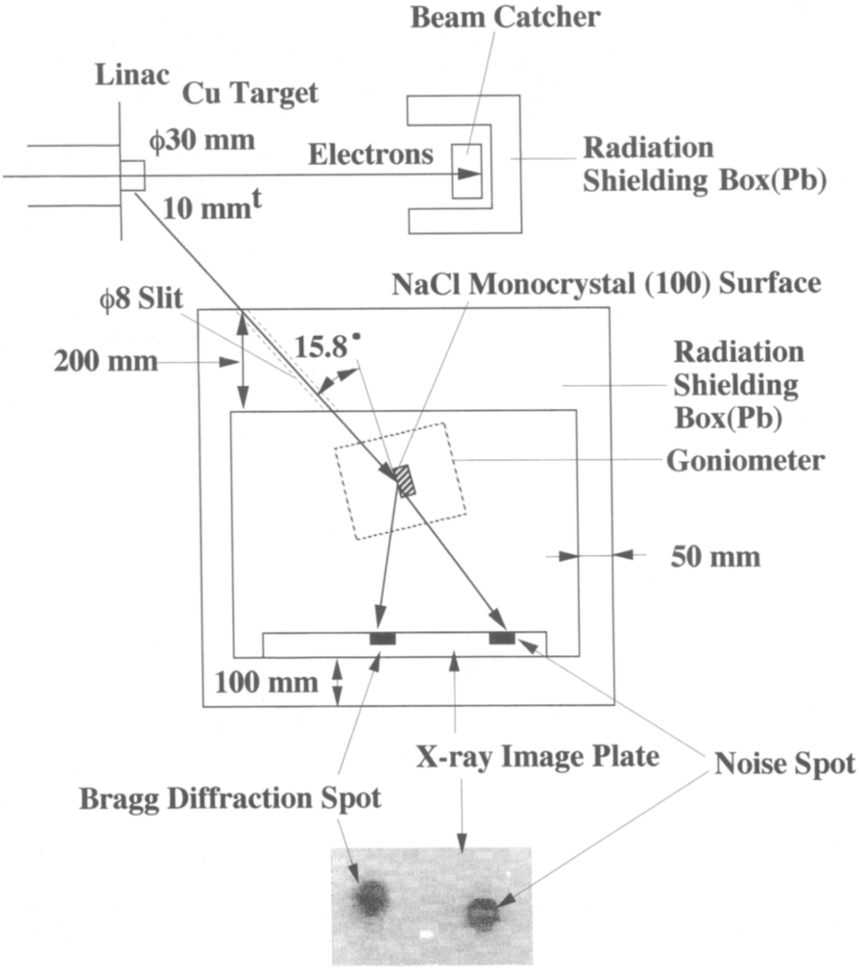

Fig. 5. Picosecond X-ray diffraction measurement system.

characteristic X-ray (8.1 keV; 1.54 Å) from a Cu target irradiated by the 10 ps electron pulse. The example of an ionic monocrystal is NaCl because it has the simplest cubic lattice structure. The static view of its lattice structure has been obtained so far by using the measurement system as shown in Fig. 5. Since we did not use any X-ray monochromator there, both the Bragg diffraction spot due to the cubic structure and the noise spot due to the X-rays with other wavelengths are obtained as shown at the bottom of Fig. 5.

We are going to improve both the synchronization system and the X-ray diffraction system to generate a subpicosecond X-ray pulse and to get a few 3D snapshots of the lattice vibration in the near future. Pulse shape measurement of the subpicosecond X-ray pulses is also planned by using a subpicosecond X-ray streak camera.

## 4. Conclusion

In this study, we constructed the synchronization system by which we could synchronize the subpicosecond electron beam with the femtosecond laser pulse with the time resolution of 3.7 ps standard deviation. Then the experiment of the laser wakefield acceleration is now proceeding by using the system. Furthermore, the experiment of the pulse-snapshot X-ray diffraction to visualize lattice vibration in matter is proceeding simultaneously. We had already got the static view of the cubic lattice structure of the NaCl ionic monocrystal using the picosecond X-rays.

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