Ultrashort Electron Beam Pulses and Diagnosis by Advanced Linear Accelerators

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Abstract 240fs 18 MeV low emittance(6 pai mm.mrad) electron beam was generated and its pulse shape was diagnosed by the S-band laser photocathode RF gun and linac. The maximum charge per bunch was 7 nC. This electron pulse was synchronized with 100fs 0.3TW Ti:Sapphire laser with the timing jitter of 330fs(rms). Recently, the Cu cathode(QE10^-4) was replaced by Mg cathode(QE10^-3). This system is utilized for radiation chemistry analysis for supercritical water. We have adopted the four diagnostic methods(femtosecond streak camera, coherent transition radiation interferometer, far-infrared polychromator, fluctuation method) and checked their time-resolution precisely. Further, we are doing the experiment on laser plasma cathode by 12TW 50fs laser and He gas jet. Laser plasma wakefield acceleration and electron injection via wavebreaking are planned. We have developed a new theory of self-injection scheme to generate ~10fs electron pulse. We have already succeeded in observing 40 MeV low emittance electron beam of 14 nC.

TWO FEMTOSECOND LINACS AND TWO FEMTOSECOND-TERAWATT LASERS

At the linac facility of Nuclear Engineering Research Laboratory (NERL), two femtosecond linacs and two femtosecond-terawatt Ti:Sapphire lasers (0.3 TW 100 fs, 12 TW 50 fs) are operating to produce and utilize ultrashort electron beams, laser lights, X-ray and ion beams as shown in Fig. 1.

FIGURE 1. Twin linac and terawatt laser system

One of linacs, which is called the 35 MeV linac, consists of the thermionic electron injector, the sub-harmonic buncher, the two accelerating tube and the arc-type magnetic bunch compressor. The 35 MeV linac generates electron bunches with the bunch duration of 700 fs. The other is called the 18 MeV linac where the laser photocathode RF injector (BNL-GUN IV) is installed. Recently, the photocathode has been changed from Cu to Mg [1,2]. Now we are improving various stabilities. It was difficult to provide a few nC high charge with sub-picosecond bunch duration and the signal-to-noise ratio for experiments using the 18 MeV linac was not enough by using the Cu cathode. Therefore, we have introduced the new RF injector with the Mg photocathode. A quantum efficiency (QE) of the Mg, which is in the order of 10^-3, is 10 times larger than one of Cu, so that more intense electron bunch is able to be produced. The 18 MeV linac is operated in combination with the 0.3 TW 100 fs laser. The 12 TW 50 fs laser is used to generate the ultrashort electron, ion and X-ray beams via laser plasma. Details of the 12 TW laser and generation of the electron beam are described.
The 18 MeV linac consists of the photocathode RF injector as shown in Fig. 2, the accelerating tube and the chicane-type magnetic bunch compressor.

Maximum electron charge from the Mg cathode is 4 nC/bunch, corresponding to QE of $1.3 \times 10^{-4}$, so far. The electron bunch accelerated up to 22 MeV is compressed by the chicane-type compressor. Typical bunch duration is approximately 700 fs with the charge of 2 nC/bunch. This ultrashort electron bunch is usually used as a pump beam for a pulse radiolysis method of chemical reaction of water. A probe laser light and a driven laser for the RF injector are supplied from the 0.3 TW laser. The 0.3 TW laser produces a laser light with the wavelength of 795 nm, the energy of 30 mJ/pulse, the pulse duration of 300 ps and the repetition rate of 10 pps. The laser light is guided by the optics in vacuum pipe and bellows, whose length is approximately 50 m in order to avoid fluctuation by air and realize precise synchronization between the pump beam and the probe laser. One laser light is compressed into the pulse width of 100 fs, and used as the probe laser. The other is guided to the third harmonic generator, which is provided the driven laser with the wavelength of 265 nm, the energy of a few hundred J/pulse and the pulse duration of a several picosecond. Energy of the electron beam was measured using the magnetic analyzer.

The synchronization test was performed to set the Xe chamber at the end of the chicane-type bunch compressor. Cherenkov light emitted from the chamber is guided to the femtosecond streak camera with the probe laser as shown in Fig. 3.

Before we had achieved the synchronization results of 330 fs for a few minutes and 1.9 ps for an hour [1]. However, the most important subject to be overcome is to suppress the long term drift of the time difference between the electron and laser. For the purpose, we renewed the water cooler of the resolution of 0.01 °C for the RF gun and tube, and the air conditioner of the resolution of 1 °C in the linac room. Even in a much-controlled temperature environment, concrete walls and the vacuum pipe are deformed, which attribute to the drift. We filled the pipe by N₂ gas in order to avoid its deformation of the pipe, especially the bellows parts, by air pressure. Time-variation of the interval between the electron beam and laser are shown in Fig.4. Finally, the timing jitter was measured to be 1.6 ps (rms) for 2 hours and 1.4 ps (rms) for 1 hour.

![FIGURE 2. Mg photocathode RF injector](image)

![FIGURE 3. Streak image of compressed bunch](image)

**PULSE SHAPE DIAGNOSIS**

Longitudinal pulse shape of the electron pulse was measured by the femtosecond streak camera, the Michelson interferometer, a 10-channel polychromator and the fluctuation method. The experimental setup is illustrated in Fig.5. Coherent transition radiation emitted from the Al foil is sent to the Michelson interferometer and the 10-channel polychromator. Incoherent Cherenkov radiation emitted in air is transported to the femtosecond streak camera. The bunch distributions were reconstructed from the interferogram taken by the Michelson interferometer and the spectrum by the polychromator. The experimental results were shown in Fig.6, where the bunch distribution taken by the femtosecond streak
camera is also shown for the comparison. As a result, good agreements within 20% were obtained among the three instruments. The good agreement can be obtained only with careful thought of error sources [3]. The misalignment of the interferometer or the polychromator yields the error of the spectrum. The transverse emittance of the electron pulse should be taken in to consideration for the estimation of the bunch form factor and the divergence factor. The current error effects the estimation of the bunch form factor as well. The spectrum contributed by a single electron is calculated under several assumptions, such that the radiator is an ideal conductor without dispersion and has a infinite dimension. One has to be careful about these factors. It is worth noticing that all the error factors do not have an effect on the measurement limit [5].

The fluctuation method was also applied to the measurement of electron pulses. The method was proposed by M. S. Zolotorev [4]. In our experiment, the time-integrated power fluctuation of Cherenkov radiation was observed as a function of the bandwidth. However, the pulse durations evaluated from the fluctuation were much longer than the actual value. The reason is that the transverse beam emittance was not considered and the formation length of Cherenkov radiation was quite short compared with the radiator length.

![FIGURE 5. Experimental setup for electron pulse measurement.](image)

![FIGURE 6. Bunch distributions by the Michelson interferometer, the polychromator and the streak camera.](image)

Measurement schemes which utilize coherent radiation observe the first-order correlation of radiation, while the schemes for incoherent radiation detect the second-order correlation function. In other words, a relation between the bunch length and the wavelength is important for coherent radiation and that between the bunch length and the bandwidth is important for incoherent radiation [4].

**PLASMA CATHODE**

We have been studying generation of relativistic electrons in a plasma wake wave-breaking scheme [6] aiming at a compact ultra-short pulse relativistic electron accelerator / injector which we called laser-plasma cathode [7]. In this experiments an ultra-intense laser pulse is focused on a gas jet, which is sufficiently strong to generate a plasma inside the jet and to excite a high-amplitude plasma wakefield. Subsequently, electrons in the plasma are trapped and accelerated in this field.

Typical experimental setup is shown in Fig.7. An axially symmetric supersonic nozzle with a pulse valve was fixed inside the vacuum chamber. The pulse valve was driven for 5 ms a shot at a repetition rate of 0.2 Hz to generate helium supersonic gas jet. The density at the exit of the nozzle ranged from $7 \times 10^{18}$ to $3 \times 10^{19}$ cm$^{-3}$. The background pressure of the vacuum chamber was kept lower than $1.0 \times 10^{-4}$ Torr during the gas jet operation.

![FIGURE 7. Experimental setup.](image)

The 12 TW Ti:Sapphire laser system based on CPA technique gives up to 600 mJ, 50 fs laser pulses at the wavelength of 790 nm at the repetition rate of 10 Hz. In this study, available laser power at the target in the vacuum chamber was up to 5 TW. The $p$-polarized laser pulse with diameter of 50 mm was delivered into the vacuum chamber and focused on the front edge of
the helium gas jet column at the height of 1.3 mm from nozzle exit with an f/3.5 off-axis parabolic mirror. The maximum laser intensity on the target was estimated to be approximately $1.0 \times 10^{19}$W/cm$^2$. In order to investigate correlation between the electron generation and laser pre-pulse, ns-order laser pre-pulse was produced before the main pulse by detuning of the pockels cell of the Ti:Sapphire laser system.

The electron emission from the gas jet was directly measured by the imaging plates (I.P.). They were laminated with an aluminum foil in 12µm thickness on the surface to avoid exposure to X-rays or laser pulses. The electron signals were accumulated for 300 shots. The energy spectra of the generated electrons were obtained by a compact magnetic electron spectrometer set on the laser axis behind the jet.

Figure 8(a)-(c) shows typical images of beam spot on the bottom plate. In case of a laser pulse with 1ns duration of the pre-pulse just before the main pulse there was no electron beam generation as shown in (a). In the second case of a 2.5ns pre-pulse, the narrow cone energetic beam was generated and an enhanced spot was observed as shown in (b). In the third case of a 5ns non-monotonic pre-pulse, the beam was exploded to pieces and smaller spots were observed as shown in (c). The experimental results clearly show that the beam generation depended strongly on the laser pre-pulse, and a proper laser pre-pulse condition is essential for generation of the narrow-cone energetic electrons. In the case of (b) the maximal energy of the beam we observed was 40MeV(detection limit).

As a future plan, we will try further acceleration of the electron bunch from the laser-plasma cathode using channel-guided laser wakefield acceleration [8]. Figure 9 shows a setup of the channel-guided laser wakefield acceleration experiment. A capillary discharge plasma will be used for optical guiding channel [9]. The electron bunch from the gas jet is accelerated to higher energy through the capillary.

![FIGURE 8. Typical images of the bottom plate of the cup-shaped I.P. detector. A laser pulse with 1ns duration of the pre-pulse just before the main pulse(a), 2.5ns (b) and 5ns (c).](image)

### REFERENCES