FEMTOSECOND PHOTOCATHODE ELECTRON SOURCE*

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Abstract

A photocathode-based low-emittance femtosecond-bunch electron source is developed in Osaka University to reveal the hidden dynamics of intricate molecular and atomic processes in materials through experimentation such as time-resolved pulse radiolysis or time-resolved electron diffraction. The transverse and longitudinal dynamics of femtosecond electron beam in the photo-cathode rf gun were studied by particle simulation. The growths of the emittance, bunch length and energy spread due to the rf effect and the space charge effect were investigated by changing the laser injection phase, the laser parameters and the bunch charge. The beam simulation indicates that a sub-100-fs MeV electron source with the normalized transverse emittance of 0.1 mm-mrad and the relative energy spread of 10^{-3}~10^{-4} at bunch charge of 0.1-1 pC is achievable in the rf gun driven by a femtosecond laser light.

INTRODUCTION

High-brightness electron sources, producing short, intense, low-emittance electron bunches, are key elements not only for new developments in accelerator physics, i.e. future electron-positron colliders, laser or plasma wake-field acceleration, and x-ray free electron lasers (FELs), but also for structure and dynamics research in material science, biology, physics and chemistry. Femtosecond electron bunches of the order of 100 fs are essential to reveal the hidden dynamics of intricate molecular and atomic processes in materials through experimentation such as time-resolved pulse radiolysis, ultrafast electron diffraction (UED) or ultrafast electron microscopy (UEM). In the pulse radiolysis [1], a short electron bunch is used as a pump source. The electron-induced ultrafast reactions are analyzed generally with an ultrashort probe light such as femtosecond lasers. A femtosecond single electron bunch with beam energy from a few to a few tens MeV is very important to be utilized in this technique for observing information of the most basic reaction mechanisms on femtosecond time scale, e.g. excitation, ionization, and relaxation of atoms and molecules.

The UED or UEM provides a unique opportunity for a complete determination of the transient structures with atomic level detail [2]. A 100-fs-long bunch electron beam is essential to measure the ultrafast atomic motions on the fundamental time scale of a single atomic vibrational period (100 fs to ~1 ps) for the study of complex phase transient phenomena in solids, the kinetic pathways of chemical reactions, and the biological functioning processes.

In order to produce low-emittance short-bunch electron beams, a technology of laser-driven photocathode rf guns has been studied. The rf gun generates short electron bunches with short laser pulses. The electrons with low energy-spread and low space-charge induced emittance are emitted from the photocathode with a strong rf electric field. By using the photocathode rf gun, a low transverse emittance was obtained to 3.2 mm-mrad at 1 nC with a 5 ps long Gaussian laser pulse [3], and 2.4 mm-mrad at 0.9 nC by using an uniform spatial the laser beam [4]. The lowest normalized transverse emittance was achieved to 1.2 mm-mrad at 1 nC by using a square laser pulse shape with pulse length of 9 ps [5]. As the reason, we proposed and developed a 1.6-cell rf gun with a space-charge emittance compensation solenoid magnet to generate the femtosecond electron beam. The dynamics of the femtosecond electron beam in the rf gun was studies.

FEMTOSECOND ELECTRON GUN

Figure 1 gives the low-emittance femtosecond-bunch electron generation system. A new 1.6-cell S-band (2856 MHz) rf gun, designed at BNL [6, 7] and improved at KEK, is used. At the level of < 1 mm-mrad, the normalized emittance can be affected by a number of small contributions like field asymmetries or the thermal emittance of the electrons at the cathode, rather than being dominated by a single effect. In order to reduce field asymmetries, the following improvements were carried out: the laser injection ports were removed; a new turner system and a new insertion function of the photocathode were designed and installed as shown in Fig. 1. The photocathode is removable. A good-symmetry solenoid magnet was mounted at the exit of the rf gun to compensate the transverse emittance growth due to space charge effect. The cathode magnetic field was measured to be <10 G at the maximum field of 3 kG in the solenoid magnet, resulting in a negligible emittance growth due to the cathode magnetic field.

The rf gun is driven by a femtosecond Ti:Sapphire laser. In the laser system, the Ti:Sapphire oscillator (Tsunami, produced by Spectra Physics Co.) is mode-locked with a frequency of 79.33 MHz, the 36th sub-harmonic of the 2856 MHz accelerating rf. The outputs of the oscillator laser pulses are captured by a Pockels cell and amplified up to 1mJ in a regenerative amplifier. The repetition rate of the amplifier is 1 kHz. The amplified pulse is

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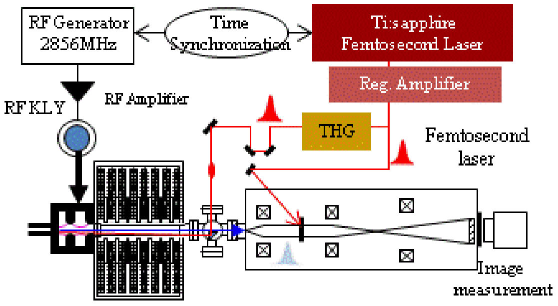
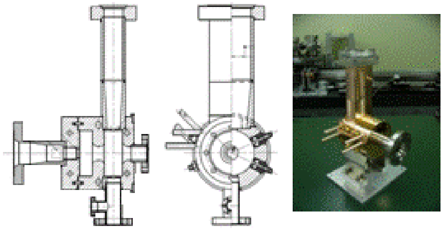
converted to the ultraviolet (UV) light using two nonlinear crystals with the maximum energy of 0.2mJ. The UV light is injected on the cathode surface at an incident angle of approximately 2^{o} along the direction of the electron beam using a prism placed downstream of the gun. The minimum pulse width of the UV light is 170 fs for the 100-fs amplified laser pulse input.



Femtosecond electron diffraction (UED)



Femtosecond photocathode rf gun

Figure 1: Femtosecond photocathode rf gun system

FEMTOSECOND BEAM DYNAMICS

The beam dynamics in the femtosecond photocathode rf gun have been studied by the space-charge tracking code PARMELA. The effects of the laser injection phase, the laser spot size, the laser pulse width, the accelerating rf field, and the bunch charge on the emittance, the bunch length and the energy spread were studied.

Effect of Laser Injection Phase

In the rf gun, phase compression in the longitudinal phase space occurs at low laser injection phase (launch phase) because the electrons come out photocathode are non-relativistic. This process has been studied theoretically for the generation of a sub-picosecond electron beam. Figure 2 shows the dependence of the bunch length on the laser injection phase. The laser pulse width was 100 fs in rms, the rms spot radius was 1 mm, the peak rf field was 100 MV/m and the bunch charge of 0.1 pC. The simulations were ended at a 1-m distance point away from the cathode without any solenoid fields. The data indicate that the bunch compression due to the rf is occurred at < 60^{o}. A 50-fs electron bunch can be generated at 30^{o} with a 100-fs laser injection. The low energy spread also can be obtained at the low laser injection phase because of the phase compression in the longitudinal phase space. There are no large changes on the transverse emittance with changing the injection phase from 20^{o} to 60^{o}.

However, at the low injection phase in the rf gun, the actual electric field (effective electric field) at the cathode decreases. The longitudinal self-field of the electron bunch (i.e. longitudinal space charge effect) is dominant in the rf gun. In order to reduce the longitudinal space charge effect, the rf gun should be operated with a high-power rf to increase the electric field, or should be operated at a low bunch charge.

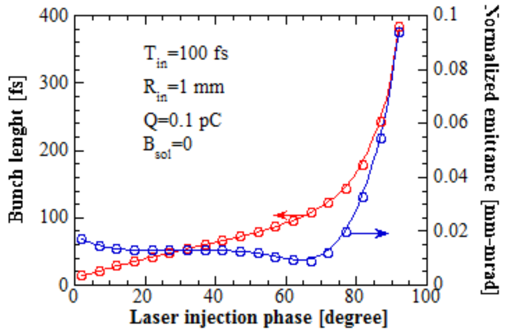


Figure 2: Bunch length and energy spread versus laser injection phase. Laser pulse width T_{in}=100fs, laser spot radius R_{in}=1 mm, bunch charge Q=0.1 pC.

Effect of Laser Spot Size

Figure 3 shows the bunch length and the transverse emittance changing with the laser beam spot size. The longitudinal space-charge effect causes the increase on the bunch length at the small laser spot. On the other hand, the rf effect is dominant at the large laser spot, resulting in the increases of the bunch length and the transverse emittance. The minimum bunch length of 50 fs is achieved at the laser spot radius of 0.7 mm for the laser pulse width of 100 fs at the bunch charge of 0.1 pC. It is depended with the laser pulse width and the bunch charge.

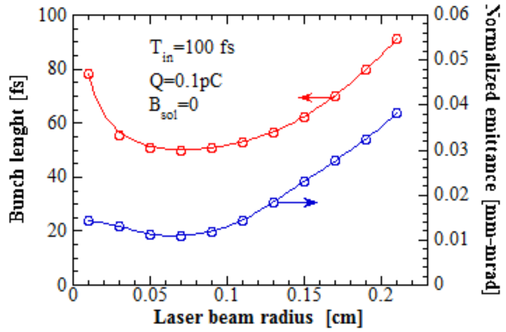


Figure 3: Bunch length and normalized transverse emittance versus laser spot radius.

The space-charge or rf induced transverse emittance is negligible at low bunch charge. In the case, the thermal emittance of the electrons at the cathode is dominant the beam transverse emittance. In order to reduce the thermal emittance, a copper cathode was used in the rf gun, because the work function of the copper is near the UV light energy. The thermal emittance of the order of 0.1

mm-mrad is achievable by reducing the laser beam size or the effective electric field at the cathode.

Effect of Laser Pulse Width

Figure 4 gives the effect of the bunch length, the energy spread and the transverse emittance on the laser pulse width. The bunch length of the electrons increases linearly with the laser pulse width at 0.1 pC. The bunch is compressed to be two factors comparing with the input laser pulse because of the injection of 30° used. A 100-fs electron bunch can be generated in the rf gun with a 200-fs laser pulse injection. The slight increase on the transverse emittance with the laser pulse width is caused by the rf effect.

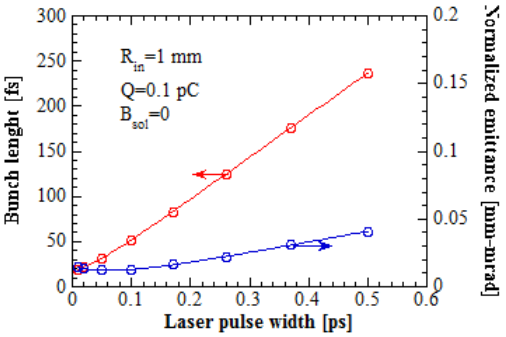


Figure 4: Bunch length and normalized transverse emittance versus laser pulse width.

Dependence on Bunch Charge

If increase the bunch charge from 0 to 2 pC, the bunch length is only increased from 50 to 70 fs, but the transverse emittance and the energy spread increase largely with the bunch charge due to the space-charge effect, as shown in Fig. 5. In UED or UEM, the ultralow energy spread beam is required. The bunch charge of 1 pC is suitable for the generation of a sub-100-fs electron beam with the relative energy spread of 0.05%, and 0.1 pC for the generation of a femtosecond beam with the energy spread of 0.01%.

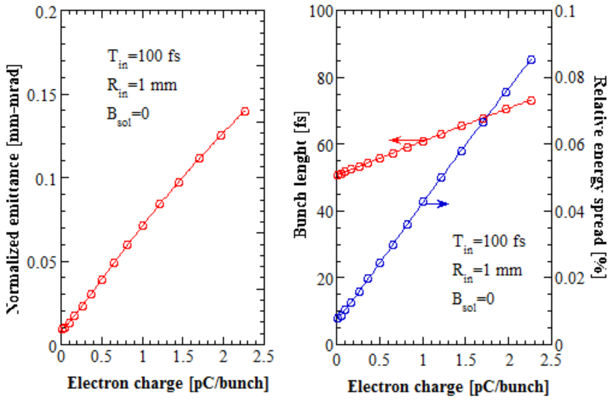


Figure 5: Normalized transverse emittance, bunch length and energy spread versus bunch charge.

Dependence on Acceleration Field Gradient

In UED or UEM, a low-energy electron beam is suitable for the diffraction measurement. The beam energy generated in the rf gun can be varied by adjusting the acceleration field gradient. However, the large growths of the bunch length, the emittance and the energy spread are occurred with decreasing the field gradient because of the space-charge effect. To reduce the growths, it would be selected a low bunch charge. As given in Fig. 6, a low-emittance electron beam with charge of 0.1 pC, beam energy of 2 MeV, bunch length of 100 fs and energy spread of 0.03% is achievable in the rf gun.

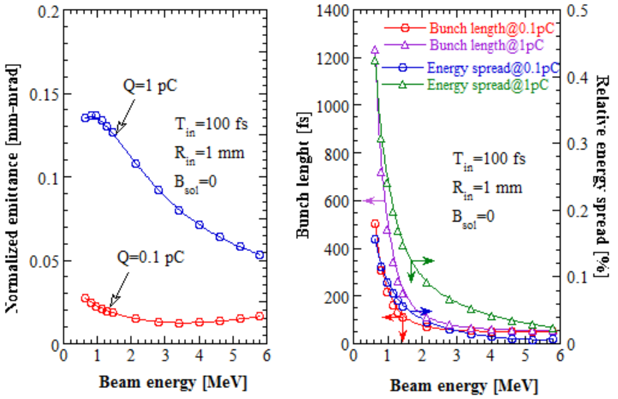


Figure 6: Normalized transverse emittance, bunch length and energy spread versus beam energy.

CONCLUSSION

A photocathode-based low-emittance femtosecond-bunch electron source was reported. The femtosecond beam dynamics in the rf gun was studied by particle simulation. The data indicates that a sub-100-fs MeV electron source with the normalized emittance of 0.1 mm-mrad and the relative energy spread of 10^{-3}~10^{-4} at bunch charge of 0.1-1pC is achievable in the photocathode rf gun driven by a femtosecond laser light.

The produced femtosecond electron beam is able to be used in the time-resolved pulse radiolysis for observing information of the most basic reaction mechanisms on the femtosecond time scale. It is also suitable in ultrafast electron diffraction or ultrafast electron microscopy. It is a powerful candidate to improve the time-resolution of UED or UEM into the order of 100 fs time region.

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