FEMTOSECOND PHOTOCATHODE ELECTRON GUN FOR TIME-RESOLVED ELECTRON DIFFRACTION

J. Yang[#1], N. Naruse[1], Y. Murooka[1], Y. Yoshida[1], K. Tanimura[1], J. Urakawa[2], [1)]The Institute of Scientific and Industrial Research, Osaka University, 8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan; [2)]The High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki, Japan

Abstract

Ultrafast time-resolved electron diffraction based on a photocathode rf electron gun is being developed in Osaka University to reveal the hidden dynamics of intricate molecular and atomic processes in materials. The photocathode rf gun generates a femtosecond-bunch electron beam by femtosecond laser driving. The transverse emittance, bunch length and energy spread were measured. The growths of the emittance, bunch length and energy spread due to the rf and the space charge effects in the rf gun were investigated by changing the laser injection phase, the laser pulse width and the bunch charge. The demonstration of the electron diffraction measurement was reported.

INTRODUCTION

The ultrafast electron diffraction (UED) or ultrafast electron microscopy (UEM) provides a unique opportunity for a complete determination of the transient structures with atomic level detail [1]. In UED, a short electron bunch is used as a probe source. The ultrafast phenomena initiated with ultrashort light pulses are observed by monitoring the electron diffraction patterns in the pump and unpump stats. Most of the conventional UED experiments [2,3] have been constructed by using dc or pulsed photocathode electron guns with beam energy of 30-60 keV. Unfortunately, the space charge effect (Coulomb repulsion) within the pulse for low energy, and the initial kinetic energy distribution of the photoelectrons act to broaden the electron pulse as it propagates. Those made it difficult to obtain pulse much shorter than 1 ps containing the electron number of 10^4 or more. To generate a femtosecond electron beam for UED, one could use low electron charge, i.e. ~1000 electrons per pulse or less. Recently, the shortest width of the electron pulses used in UED is 600 fs containing 6000 electrons at 30 keV, and 400 fs containing 1000 electrons at 60 keV. Alternatively, it is possible to increase the extracting electric field inside the electron gun, while the space charge effect is reduced. However, this approach is limited by the maximum electric field for vacuum breakdown (12 and 25 MV/m for the dc and pulsed, respectively).

As these reasons, in 2006, a MeV photocathode radio-frequency (rf) electron gun was firstly considered for UED [4,5]. The demonstration of methodology was carried out. In the photocathode rf guns, which have been constructed for new development of accelerator physics, the electrons emitted from the photocathode surface are accelerated rapidly with a strong rf electric field (~100 MV/m or more) to reach relativistic speeds within a few millimeters. The increases in the pulse duration, emittance and energy spread due to the space charge effect are thus reduced to the minimum. An ultrashort electron beam at the energy of MeV with low emittance and high electron charge is thus generated. As a typical example of a 1.6-cell 2856-MHz (s-band) rf gun developed in Brookhaven National Laboratory [5,6], the transverse normalized emittance of 1.2 mm-mrad at bunch charge of 1 nC was obtained by using a square laser pulse [7]. The previous studies indicate that a low emittance femtosecond-pulse electron beam with megavolt beam energy by injecting a femtosecond laser light on the cathode is achievable by using the rf gun. It provides a big choice to construct megavolt electron diffraction. Here, we approach femtosecond time-resolved electron diffraction using the rf electron gun, with the aim of obtaining single-shot diffraction patterns on a 100 fs time scale, to study the atomic dynamics of phase transitions in solids.

However, in order to develop time-resolved electron diffraction based on the use of the rf gun and to improve the time resolution into the order of 100 fs, it is necessary to fully understand the beam dynamics of femtosecond electrons in the rf gun. The space charge effect on the number of electrons, electric field, initial pulse duration, and beam size are important consideration in the design of the optimal electron source. In this article, we report the developments of a near-relativistic 100-femtosecond rf electron gun and femtosecond megavolt electron diffraction system, and the studies of beam dynamics of femtosecond electrons in the rf gun. The growths of the emittance, bunch length and energy spread due to the rf and space charge effects are discussed.

FEMTOSECOND ELECTRON GUN

Figure 1 shows the femtosecond photocathode rf gun and time-resolved megavolt electron diffraction system. At the level of <1 mm-mrad, the emittance can be affected by a number of small contributions like field asymmetries or the thermal emittance of the electrons at the cathode. To generate low-emittance femtosecond-pulse electron beams, a new 1.6-cell S-band rf gun has been developed under the KEK/Osaka University

[#]yang@sanken.osaka-u.ac.jp

collaboration with many improvements: (1) the conventional laser injection ports in the half cell were removed to reduce field asymmetries; (2) a new turner system was designed to adjust precisely the electric field balance in the half and full cells; and (3) a new insertion function of the photocathode was installed as shown in Fig. 1 to reduce the field emission. The field emission due to the strong electric field is the biggest problem for the use of a low-charge electron beam in UED or other applications. To minimize the field emission from the cathode, a copper photocathode is used; however, the photocathode is removable. At the exit of the rf gun, a good-symmetry solenoid magnet is mounted to compensate the transverse emittance growth due to space charge effect.

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 to amplify the laser pulse with a high-stability in the pulse energy. However, a part (10Hz) of the amplified pulses is used to produce the electron beam. The amplified pulse is converted to the ultraviolet (UV) light using two nonlinear crystals with the maximum energy of 0.15 mJ. The femtosecond 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 in full-width at half-maximum (FWHM) for the 100-fs amplified laser pulse input. The laser shaping of the UV light in the spatial and temporal directions is considered to reduce the space-charge force in the bunch.

The femtosecond laser pulse split from the output of the laser amplifier is used as a pump pulse. The femtosecond electron beam produced from the rf gun for obtaining the diffraction patterns is propagated to the sample with a magnetic lens besides the solenoid magnet. This magnetic lens, which is located at a distance of 1 m from the cathode, is used to make a parallel electron beam with the minimum divergence on the sample. The sample is located at a distance of 25 cm from the magnetic lens. The diffraction patterns in the sample are magnified with two magnetic lenses downstream of the sample. The two magnetic lenses are installed downstream of the sample: the first lens (diffractive lens) is located at the position of 25 cm from the sample, while the second lens (projective lens) is located downstream of the diffractive lens. The distance between two lenses is adjustable from 20 to 30 cm to magnify the diffraction patterns by changing the position of the projective lens. The size of the three lenses is 20 cm in diameter and 10 cm in thickness. The diameter of hole in the center of the lenses is 2 cm. The magnified diffraction patterns are measured by an emulsion plate which is located at a distance of 1.4 m from the sample. The highly sensitive emulsion plate is firstly proposed to record the electron diffraction pattern, but it is used successfully to measure the track of small numbers of particles in the elementary particle and nuclear physics.

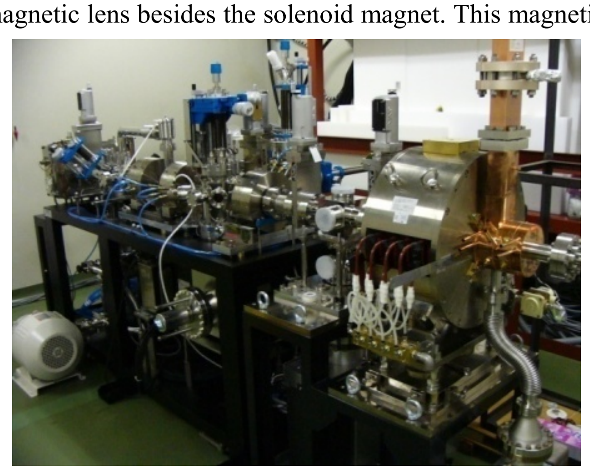

Figure 1: Femtosecond MeV electron diffraction based on photocathode rf gun.

BEAM DYNAMICS OF FEMTOSECOND ELECTRONS

Another important advantage of using the rf gun to produce femtosecond electron pulse is its capability of compressing the pulse duration as it is being accelerated in the time-dependent rf field. This permits the use of a longer laser pulse and further reduces the space charge effect near the cathode region. The beam simulation indicates that the pulse compression due to the rf is occurred at <60^o. A 50-fs electron bunch can be generated at 30^o by using a 100-fs laser pulse. The low energy spread of UED also can be obtained at the low laser injection phase because of the phase compression in the longitudinal phase space, i.e. 10^{-4} at <30^o. The low transverse emittance of ~0.02 mm-mrad (not including the thermal emittance) is achieved under 70^o; but there are no large changes of 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 force) 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. The laser injection phase was fixed to 30^o in the simulation.

Generally, the space charge effect is dominant in the femtosecond electron beam. However, for the MeV beam with the electron charge of a few pC, the dependence of the pulse width on the charge is not strong (not affect for generating a 100-fs electron pulse), but the transverse emittance and the energy spread increase largely with the bunch charge due to the space-charge effect. As the simulation results for increasing the electron charge from 0.1 to 2 pC, the bunch length is only increased from 50 to 70 fs. The energy spread is increased from 0.01% to 0.08%. The normalized transverse emittance is increased from 0.01 to 0.12 mm-mrad.

The beam energy generated in the rf gun can be varied by adjusting the acceleration field gradient. However, the large growths of the pulse width, the emittance and the energy spread are occurred with decreasing the field gradient, especially at beam energy of <1.5 MeV as given in Fig. 2, because of the space-charge effect. In the simulation, the parameters in the simulation are: 100fs (laser pulse width), 1 mm (laser spot radius), 30^o (laser injection phase) and 0.1 pC (electron charge). The simulations were ended at a 1-m distance point away from the cathode without any solenoid fields. To reduce the growths, one could use a low bunch charge, i.e. 0.1 pC. However, by using the rf gun, an intense electron beam, which is three orders of magnitude higher than that produced by the conventional dc or pulsed guns, can be generated for UED. The theoretical studies indicate that a 100-fs electron beam with the energy of 1.5-4 MeV, the transverse emittance of 0.02-0.1 mm-mrad and the relative energy spread of 10^{-3}-10^{-4} at bunch charge of 0.1-2 pC(10^6-10^7 electrons per pulse) is achievable.

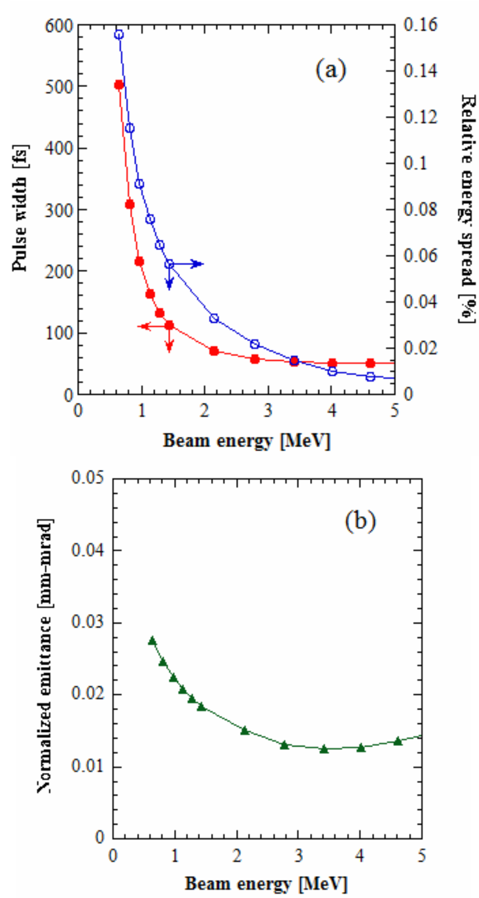

Figure 2: Simulation results of pulse width, energy spread and transverse emittance versus beam energy.

CONCLUSION

A near-relativistic 100-femtosecond rf electron gun was presented for femtosecond megavolt electron diffraction. The femtosecond beam dynamics in the photocathode rf gun was studied theoretically by particle simulation. The growths of the emittance, pulse width and energy spread due to the rf and space charge effects were investigated by changing the laser parameters, field gradient and electron charge. The theoretical studies indicate that a 100-fs electron beam with the energy of 1.5-4 MeV, the transverse emittance of 0.02-0.1 mm-mrad (excluding the thermal emittance) and the relative energy spread of 10^{-3}-10^{-4} at bunch charge of 0.1-2 pC (10^6-10^7 electrons per pulse which is three orders of magnitude higher than that produced by the conventional dc or pulsed guns) is achievable.

However, the thermal emittance of the electrons on the cathode should be reduced because the total emittance causes the blotting of the diffraction pattern on UED. The previous theoretical studies [8] indicate that the diffraction will be detectable if the beam divergence is 0.1 mrad or small. The thermal emittance can be minimized by reducing the incident laser sport size and by optimizing the electric field on the cathode [9]. Recently, the emittance (~ thermal emittance) of 0.12 mm-mrad was achieved experimentally for the Cs_2Te cathode under the peak electric field of 40 MV/m and the bunch charge of 6 pC by using a 262 nm laser light with the rms laser sport size of 0.05 mm [10]. The researches in PSI-XFEL group [9] indicated that, for the copper cathode, the thermal emittance can be obtained to be 0.12 mm-mrad at the rms laser sport size of 0.33 mm and the peak electric field of 40 MV/m. It can be reduced to be 0.1 mm-mrad or low by using a laser spot size of small than 0.3 mm.

Therefore, by using the rf gun, a 100-fs electron beam with the energy of 1.5-4 MeV, the total transverse emittance of 0.1 mm-mrad and the relative energy spread of 10^{-4} at bunch charge of 0.1 pC is achievable for obtaining the diffraction patterns on UED. The use of the rf electron gun is a powerful candidate to improve the time-resolution of UED into a 100-fs time region.

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