DEVELOPMENT OF FEMTOSECOND PHOTOCATHODE RF GUN

J. Yang[#1], K. Kan[1], T. Kondoh[1], Y. Yoshida[1], S. Tagawa[1], K. Tanimura[1], J. Urakawa[2], [1]The Institute of Scientific and Industrial Research, Osaka University, Japan, [2]High Energy Accelerator Research Organization

Abstract

Femtosecond-bunch, low-emittance electron beams are essential 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 a photocathode rf gun were studied. 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. Finally, a femtosecond electron source based on the photocathode rf gun is proposed for the time-resolved pulse radiolysis and the time-resolved electron diffraction. The beam simulation indicates that an MeV sub-100-fs electron beam with the normalized transverse emittance of less than 0.1 mm-mrad (the thermal emittance of the cathode is not included) and the relative energy spread of 10^{-4} at bunch charge of 0.1-1pC is achievable in the photocathode rf gun driven by a femtosecond laser light.

INTRODUCTION

High-brightness electron sources, producing short, intense, low-emittance electron bunches, are key elements for new developments in accelerator physics. These sources are essential for future high-energy electron-positron colliders, laser or plasma wake-field acceleration, and new femtosecond x-ray free electron lasers (FELs) based on self-amplified spontaneous emission (SASE), such as the x-ray FEL project at DESY, LCLS and SPPS at SLAC. Typically, a femtosecond-bunch electron beam with a normalized emittance of 1 mm-mrad at bunch charge of 1 nC is desired to reach saturation in a single pass at 1.5 angstroms [1].

Femtosecond electron bunches, of the order of 100 fs in duration, are also essential to reveal the hidden dynamics of intricate molecular and atomic processes in materials through experimentation such as time-resolved pulse radiolysis [2] or time-resolved electron diffraction [3]. In the pulse radiolysis, 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 of a few tens MeV is very important to be utilized in this technique for observing information of the most basic reaction mechanisms in physics, chemistry and biology (e.g. excitation, ionization, and relaxation of atoms and molecules) on the femtosecond time scale. The time-resolved electron diffraction provides a unique opportunity for a complete determination of the transient structures with atomic level detail. 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 new phases in solids, the kinetic pathways of chemical reactions, and the biological functioning processes.

In order to produce such 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 surface with a strong rf electric field (higher than 100 MV/m). As a typical example, a 1.6-cell rf gun with a space-charge emittance compensation solenoid magnet has been developed in Brookhaven National Laboratory (BNL). A transverse normalized rms emittance of 3.2 mm-mrad with 1 nC of bunch charge was obtained in the rf gun with a 5 ps long Gaussian laser pulse [4]. The normalized transverse emittance was reduced to 2.4 mm-mrad at 0.9 nC by using an uniform spatial the laser beam [5]. 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 in full-width at half-maximum (FWHM) [6].

In the rf gun, phase compression in the longitudinal phase space occurs at low laser injection phase because the electrons come out photocathode are nonrelativistic. This process was studied theoretically for the generation of a sub-picosecond electron beam. At the low injection phase in the rf gun, the actual 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.

However, the studies of both transverse and longitudinal beam dynamics of the femtosecond electron beam in the rf gun would be important. Optimization of operating parameters of the rf gun, such as the gun phase, the electric field, the space charge compensation and so on, would be required for new developments in accelerator physics and new beam applications. In this paper, the growths of beam 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. Finally, an MeV femtosecond electron source

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

based on the photocathode rf gun is proposed for the time-resolved pulse radiolysis and the time-resolved electron diffraction.

FEMTOSECOND ELECTRON SOURCE

Photocathode RF Gun

Figure 1 gives the femtosecond time-resolved electron diffraction system with a low-emittance, femtosecond-bunch electron gun. An 1.6-cell S-band (2856 MHz) rf gun, which was produced by the collaboration of ISIR and KEK, was used for electron bunch generation. The rf gun was consisted of two cells: a half cell and a full cell. A metal photocathode (such as Cu, Mg, CsTe) was located on the side of the half cell. The length of the half cell was designed to be 0.6 times the full-cell length to reduce the peak electric field on the iris of the cavity. The beam divergence was thus reduced. A magnetic coupling located in the full cell was utilized to couple rf power between the waveguide and the cavity. The coupling between the cells was accomplished via the iris of the cavity. The peak on axis electric fields in the rf gun was 40-80 MV/m to generate 1-4 MeV electron beams by adjusting the peak input rf power.

A single 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.

Femtosecond Laser

The rf gun was driven by a femtosecond laser. The laser was consisted of a femtosecond Ti:Sapphire laser oscillator, a pulse stretcher, an amplifier, a pulse compressor and a frequency converter. The oscillator generated a 50 fs long laser pulse with a central wavelength of 800 nm and a spectral width of 15 nm FWHM. The oscillator was mode-locked with a frequency of 79.3MHz, the 36th sub-harmonic of the 2856MHz accelerating rf, by adjusting the cavity length of the oscillator. In order to reduce the time jitter between the laser pulse and the electron bunch, the oscillator will be synchronized the accelerating rf by phase-locking the 36th harmonic output of the laser oscillator with the 2856MHz accelerating rf. The time jitter between the oscillator output and the accelerating rf signal is expected to <10 fs.

The laser pulse output of the oscillator was stretched up to 150 ps in the pulse stretcher and amplified in the regenerative amplifier. The amplified pulse was compressed in the pulse compressor, and then frequency tripled to 266 nm UV light in a pair of nonlinear crystals. The UV light was injected onto the cathode surface at an angle of an approximately 2^{o} along the direction of the electron beam using a prism placed downstream of the rf gun.

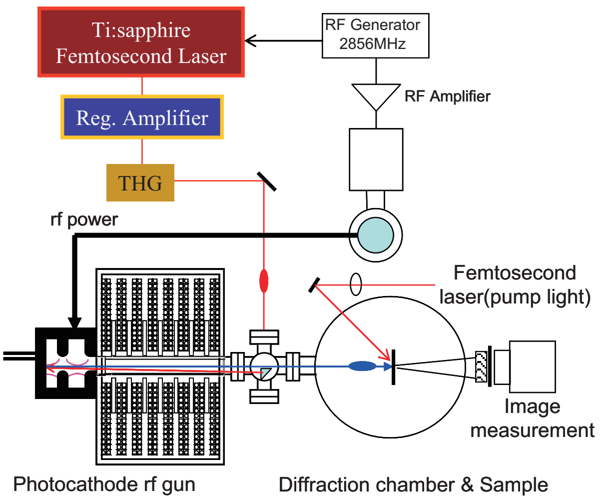

Fig. 1 The ultrashort-bunch electron linear accelerator

BEAM DYNAMICS IN RF GUN

Both the transverse and longitudinal dynamics of femtosecond electron beam in the rf gun were studied by particle simulation included space-charge effect calculation. 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. Figure 2 gives the bunch length and the relative energy spread as a function of the laser injection phase at a constant bunch charge of 0.1pC and a constant solenoid field of 1.84 kG (minimum emittance at 0.1 pC). The injection laser pulse width was fixed to 100fs. The data indicates that the short bunch length is observed at small gun phase (laser injection phase) because of the rf bunch compression inside the rf gun. The optimal gun phase was 30-degree, because the minimum relative energy spread and low transverse emittance are obtained at 30-degree. In the simulation, the beam energy at exit of the gun was 4 MeV. It can be changed to 1-4 MeV by adjusting the input rf power of the gun.

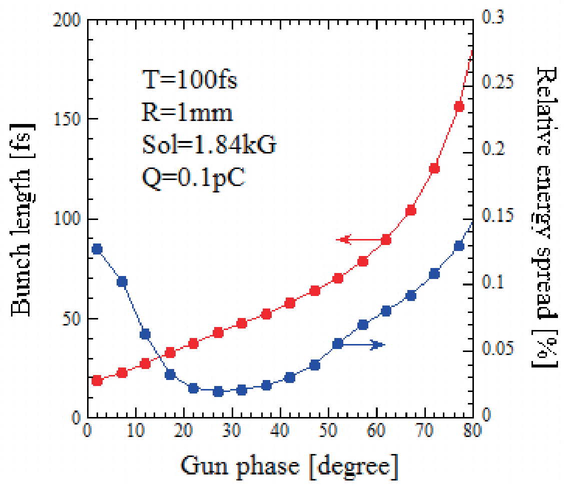

Fig. 2 Bunch length and relative energy spread versus laser injection phase

Figure 3 gives the dependences of the electron bunch length and the energy spread on the injection laser pulse

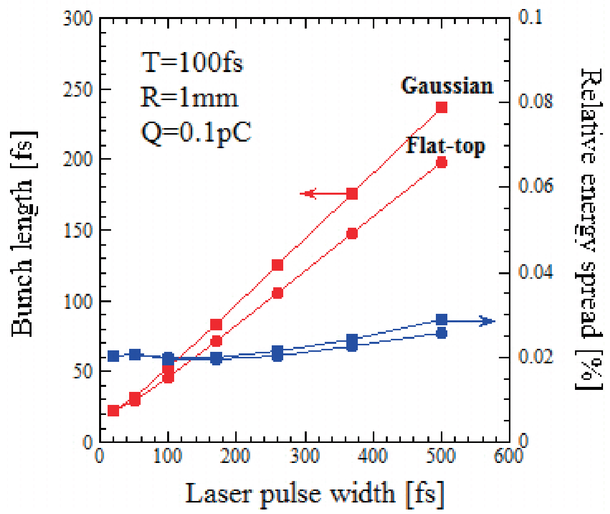

Fig. 3 Relative energy spread and bunch length versus injection laser pulse width

width. The laser spot size and the bunch charge were fixed to 1 mm radii and 0.1 pC in the simulation, respectively. The gun phase was 30-degree. The bunch length increases linearly with the injection laser pulse width for >50 fs. The energy spread is not dependent on the laser pulse width. The slight increase of the relative energy spread at the laser pulse of >200 fs was caused by the rf effect in the rf gun. There are not large differences of the bunch length and the energy spread for the Gaussian and flat-top laser shapes at the bunch charge od 0.1 pC. The transverse emittance dependence is shown in Fig. 4. The emittance growth due to the space charge effect was occurred at the laser pulse width of <100 fs (Gaussian) of <200 fs (flat-to). The growth of the emittance was taken place for using the long laser pulse because of the rf effect. The minimum normalized transverse emittance can be obtained at the laser pulse of .100 fs for the Gaussian distribution and 200 fs for the flat-top distribution.

Figure 5 gives the dependences of the bunch length and the relative energy spread on the bunch charge. The laser

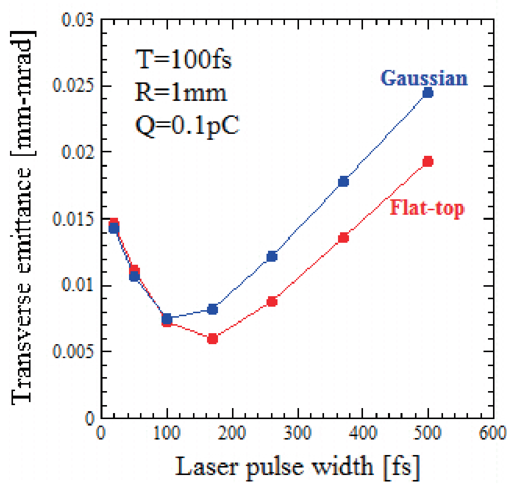

Fig. 4 Transverse emittance versus laser pulse width

pulse width was fixed to 100 fs. Both the bunch length and energy spread are increased with increasing the bunch charge. The simulation shows that a high-brightness electron beam with the bunch length of <60 fs and the relative energy spread of <0.1% is achievable at the bunch charge of <0.8 pC. The energy spread can be reduced to 10^{-4} by decreasing the bunch charge to 0.1pC.

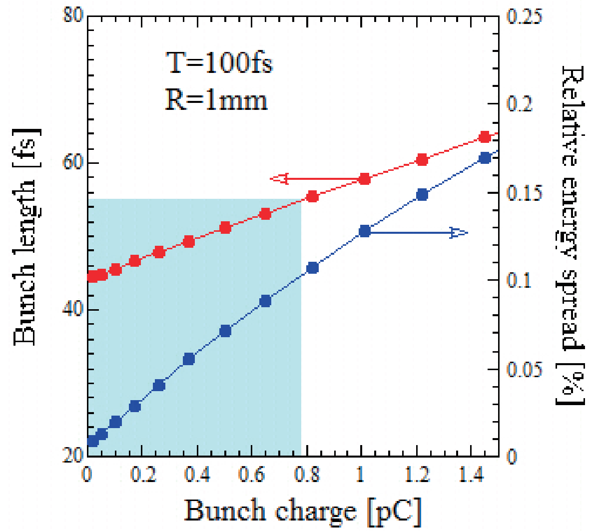

Fig. 5 Bunch length and relative energy spread versus bunch charge

SUMMARY

The transverse and longitudinal dynamics of femtosecond electron beam in a photocathode rf gun were studied. 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. Finally, a femtosecond electron source based on the photocathode rf gun was proposed for the time-resolved pulse radiolysis and the time-resolved electron diffraction. The simulation indicates that an MeV sub-100-fs electron beam with the normalized transverse emittance of less than 0.1 mm-mrad (the thermal emittance of the cathode is not included) and the relative energy spread of 10^{-4} at bunch charge of 0.1-1pC is achievable in the photocathode rf gun driven by a femtosecond laser light.

REFERENCES

[1] M. Cornacchia, et al. "Linac Coherent Light Source (LCLS) Design Study Report", Stanford University-University of California Report No. SLAC-R-521/UC-414, revised 1998.
[2] J. Yang, et al., Radiat. Phys. Chem., **75** (2006) 1034.
[3] W. E. King, et al., J. Appl. Phys. **97** (2005) 111101.
[4] J. Yang, et al., Jpn. J. Appl. Phys. **44** (2005) 8703.
[5] M. Babzien, et al., Phys. Rev. E, **57** (1998) 6093.
[6] J. Yang, et al., J. Appl. Phys. **92** (2002) 1608.