FEMOTSCOND RF GUN BASED MEV ELECTRON DIFFRACTION

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Abstract

A time-resolved MeV electron microscopy based on a photocathode rf electron gun is being developed in Osaka University to study the structural dynamics and ultrafast processes in materials. A new structure normal-conducting rf gun has been developed to increase the accelerating Q-value and reduce the dark current from the field emission in the rf cavity. A low-emittance femtosecond-bunch electron beam has been generated successfully in the rf gun. 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. An ultrafast electron diffraction based on photocathode rf gun has developed in Osaka University. The single-shot and time-resolved measurements were succeeded.

INTRODUCTION

Ultrafast phenomena, including dynamic processes in material system and chemical/physical reactions, have been largely investigated using femtosecond laser pump-probe or femtosecond laser pump and short-pulsed X-ray radiation probe technique. Ultrashort-bunch electron beams are essential to reveal the hidden dynamics of intricate atomic processes in materials or ultrafast reactions in physics, chemistry and biology. Because of the electron beam as a charged particle source, the ratio of inelastic-/elastic-scattering events in materials for the electron beam is lower than that for the photons or X-rays. The energy deposited per elastic scattering event is 1000 times higher for the photons or X-rays. It is well-known that the electron beam is a powerful tool for the observation of the atomic structure in materials using electron microscopy technique.

In radiation chemistry and biology, many of ultrafast radiation-induced reactions, i.e. solvation, geminate recombination, and radical reactions in the time region from femtosecond to picoseconds, were discovered and understood by an electron pulse radiolysis technique [1,2]. In pulse radiolysis, a short electron bunch is used as a pump source. The radiation-induced reactions are analyzed by an ultrashort probe light such as femtosecond lasers using a stroboscope technique. Recently, a single electron bunch of the order of 100 fs with beam energy of 32 MeV has been generated to be utilized in this technique [3].

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Ultrashort-bunch electron beams are also indispensable for ultrafast electron diffraction (UED) and ultrafast electron microscopy (UEM). In UED and UEM, the short-bunch electron beam is used to a probe source. The ultrafast phenomena initiated with ultrashort light pulses are observed by monitoring the electron diffraction or image in the pump and unpump states. Most of the conventional UED experiments [4,5] have been constructed using 30-100 keV pulsed photocathode electron guns driven by femtosecond lasers. A high time resolution in UED has been achieved by operating in the non-space-charge-limited regime with thousands of electrons per pulse or less. The diffraction patterns are observed by integrating over many pulses to obtain an acceptable signal-to-noise. However, there are no spatial resolutions in UED systems. While UED is a powerful tool for sensing the spectrum of atomic spacing in the sampled volume, there are many scientific investigations that benefit from real-space imaging. The imaging affords a more direct interpretation of the defect structure than does diffraction. Currently, the UEM with the nanosecond time resolution has been achieved in conventional TEM through the use of photo-activated electron source driven by a nanosecond laser [6]. To obtain a high time resolution, a stroboscopic imaging of periodically driven processes [7] was preformed. In this configuration, a time resolution of 200 ps was achieved for processes up to 100 MHz, which called the single-electron-pulse method. These techniques were applied to ultrasonically driven disruption of crystals and magnetoelastic effects and magnetic-field-induced oscillations of the domain magnetization of domain walls and of their substructures.

In 2006, a MeV photocathode rf electron gun was firstly considered for UED [8]. The demonstration of methodology was carried out. In the photocathode rf guns, 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. A rf gun based ultrashort electron beam at the energy of 1~3 MeV, the emittance of 0.1 mm-mrad, the bunch length of 100 fs and the electron charge of ~1 pC is approached in Osaka University. From 2006, several groups have developed and demonstrated new MeV UED systems using the photocathode rf guns [9-11]. The studies indicate and suggest that an acceptable femtosecond-pulse electron beam with megavolt beam energy is achievable with the photocathode rf gun driven by a femtosecond laser light. Recently, a femtosecond time-resolved MeV electron microscopy using the rf gun has been proposed in Osaka University to study the atomic dynamics of phase transitions in solids. Here, we report the developments of a near-relativistic femtosecond electron rf gun and the design of a MeV UEM system using the photocathode rf gun. The results of beam study of femtosecond electrons in the rf gun and the demonstrations of MeV electron diffraction and imaging measurements are presented.

PHOTOCATHODE RF GUN FOR UEM

For single-shot UEM studies with nm-ps space-time resolution, the characteristics of the electron beam can be determined in the case of use of an efficient 1000 x 1000 pixel charge-couple device (CCD) camera with 25 μm pixels:

(1) The number of electrons in pulse can be considered to $N \sim 10^8$ for the imaging and $N \sim 10^6$ for the diffraction, according to the Rose criterion (~100 electrons/ pixel).

(2) The normalized emittance of the electron beam generated from the rf gun is required to less than 0.14 mm-mrad for obtaining a focal spot size of 10 μm on the specimen.

(3) The energy spread should be of order of 10^{-4} to reduce the effects of spherical and chromatic aberrations in the electron optics.

(4) The final requirement is low dark current from the rf gun.

To achieve these requirements, a new 1.6-cell S-band rf gun has been developed under the KEK/Osaka University collaboration with many improvements: (1) a spherical shape cavity was used in both the half and full cells; (2) 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 to reduce the field emission. The photocathode is removable. The asymmetry on the rf field is reduced to be minimum in geometry. The emittance growth due to the field-asymmetry can be improved. The dark current from the rf gun is also expected to be reduced. The Q-value of the cavity was achieved to 16,300 which is increased 25% comparing with the old rf gun. Figure 1 shows the structure of the rf cavity and the picture of the rf gun.

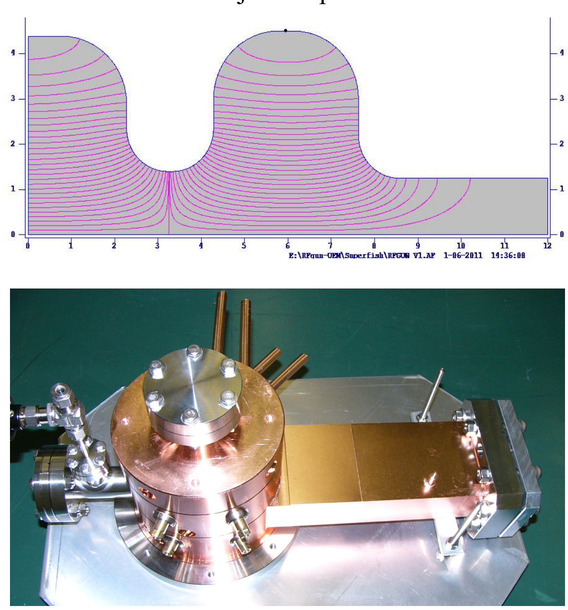

Figure 1: The structure of the rf cavity and the picture of the completed rf gun.

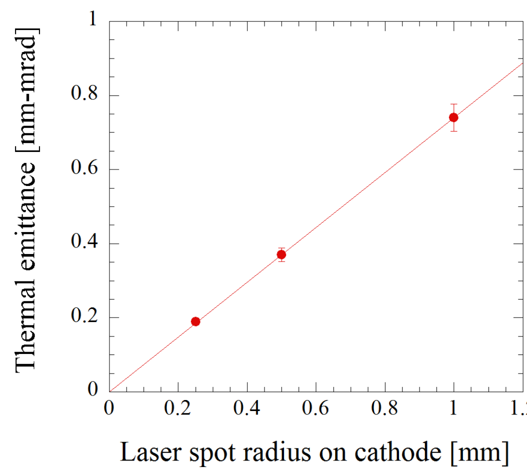

Figure 2: The thermal emittance as a function of laser spot radius on the cathode.

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 1 mJ with a regenerative amplifier. The amplified pulse is converted to the ultraviolet (UV) light with the maximum energy of 40 μJ. The pulse width of the UV light is 200 fs in FWHM. The femtosecond UV light is injected on the cathode surface at an incident angle of approximately 2° along the direction of the electron beam using a vacuum mirror placed downstream of the gun. To achieve a small focal spot size of the electron beam on the specimen, the back-injection method and a transmission cathode is also approached in UEM system.

As the experiences, there is no problem to generate the required electron number using the rf gun. The dark current has been reduced successfully to be <0.1 pC per pulse with the above improvements in the new rf gun. However, at the level of <1 mm-mrad in the rf gun, the emittance can be affected by a number of small contributions like field asymmetries or the thermal emittance of the electrons at the cathode, especially for the thermal emittance. To reduce the thermal emittance, we used a small laser spot size on the cathode. Figure 2 given the dependence of the emittance on the laser spot radius. The emittance was measured at bunch charge of <2 pC. The emittance is thus dominated by the thermal emittance [12]. In the measurement, the copper cathode was used. The gun phase was 30°. The data indicates that a low thermal emittance of 0.1 mm-mrad can be obtained with the laser spot radius of less than 100 μm. Figure 3 gives the obtained longitudinal emittance and the bunch length. At the bunch charge of <10 pC, the rms bunch length and the longitudinal emittance were obtained to be 200 fs and 1.1 deg-keV, respectively. The bunch length is determined by the injection UV laser pulse width. The energy spread can be calculated to 2 x 10^{-3}. However, it is possible to reduce the energy spread to 10^{-4} through the injection electron optics of TEM with a condense beam aperture. The use of a short-pulse UV laser (i.e. <100 fs) is also essential to achieve a low-energy-spread electron beam with the rf gun.

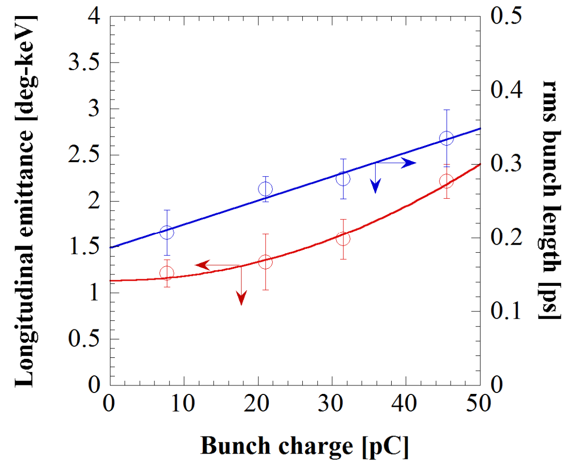

Figure 3: The longitudinal emittance and bunch length as a function of bunch charge.

MEV ELECTRON DIFFRACTION AND IMAGING

The femtosecond electron beam produced from the rf gun 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 first lens (objective lens) is located at the position of 25 cm from the sample, while the second lens (projective lens) is located downstream of the objective lens. The magnified diffraction patterns and imaging are measured by an CsI(Tl) scintillator and a CCD camera which is located at a distance of 1.4 m from the sample.

Figure 4 shows the photocathode rf gun based MeV UED system and the demonstrations of MeV electron diffraction and imaging. The diffraction was measured in a 180-nm-thick Si sample. The beam energy of the electrons was 2.95 MeV. The electron charge was 0.3 pC/pulse. The obtained distinct diffraction and imaging suggest that the rf gun is very useful for both UED and UEM.

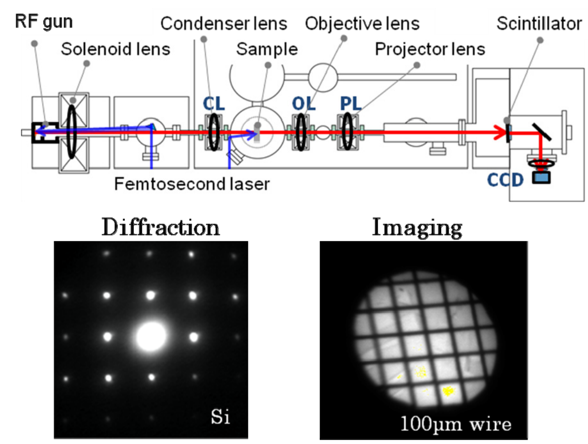

Figure 4: RF gun based MeV UED system, the electron diffraction and imaging obtained by 3 MeV electron beam.

The obtained distinct diffraction and imaging suggest that the rf gun is very useful for both UED and UEM.

CONCLUSION

A new structure rf electron gun was developed to generate a femtosecond megavolt electron beam. A time-resolved MeV electron microscopy based on a photocathode rf electron gun has been approached in Osaka University to study the dynamics of photon-induced structure change and electronic/atomic processes in materials. The transverse emittance, the bunch length and the longitudinal emittance were measured. The demonstrations of MeV electron diffraction and imaging based on the rf gun were carried out in Osaka University.

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