FEMTOSECOND ELECTRON BEAM DYNAMICS IN PHOTOCATHODE ACCELERATOR

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Abstract

Ultrashort-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 ultrashort electron beam in a photocathode linear accelerator were studied for femtosecond electron beam generation. 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 dependences of the emittance, bunch length and energy spread on the booster linac rf phase were measured. Finally, a 100 fs electron source based on the photocathode rf gun with a femtosecond laser injection is proposed for time-resolved pulse radiolysis and time-resolved electron diffraction. The femtosecond beam dynamics in the rf gun was investigated by simulation.

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 or time-resolved electron diffraction. In the pulse radiolysis [2, 3], 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 [4].

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) [5, 6]. 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 [7]. The normalized transverse emittance was reduced to 2.4 mm-mrad at 0.9 nC by using an uniform spatial the laser beam [8]. 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) [9].

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 experimental studies of both transverse and longitudinal beam dynamics in the rf gun would be important to generate a high-brightness electron beam. Optimization of operating parameters of the rf gun, such as the gun phase, the space charge compensation and so on, would be required for new developments in accelerator physics and new beam applications.

ULTRASHORT ELECTRON LINAC

Figure 1 gives the low-emittance, ultrashort-bunch electron generation system [7]. A 1.6-cell S-band (2856 MHz) rf gun as the Gun IV type at BNL [5, 6], is used for electron bunch generation. The rf gun was consisted of

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two cells: a half cell and a full cell. A copper photocathode used for the study of the beam dynamics 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 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.

The rf gun was driven by an all solid-state LD-pumped Nd:YLF picosecond laser. 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 with a semiconductor saturable absorber mirror (SESAM). The time jitter between the oscillator output and the reference 79.3 MHz rf signal was measured to be <0.5 ps using a phase detector technique. The ultraviolet (UV) light, which was frequency quadrupled to a 262 nm using a pair of nonlinear crystals with the maximum energy of 0.3mJ, was 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 electron beam produced by the rf gun was accelerated up to 32 MeV with a 2 m long travelling-wave booster linac. The linac was located at a distance of 1.2 m from the cathode surface. The peak rf inputs of the rf gun and the linac were 10 MW and 25 MW, respectively, which was produced by a 35 MW Klystron. The peak on axis electric fields in the rf gun and the linac were approximately 115 and 20 MV/m, respectively. The repetition rate of the operation was 10 Hz in the experiment.

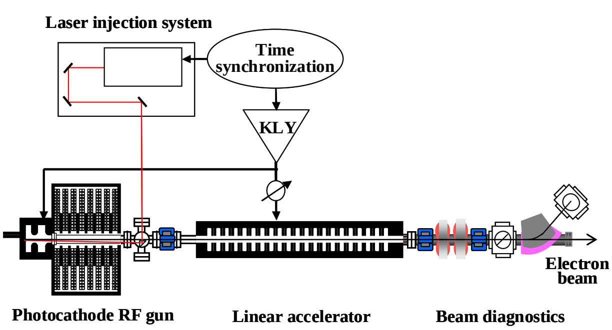

Fig. 1 The ultrashort-bunch electron linear accelerator

BEAM DYNAMICS IN RF GUN

Figure 2 gives the transverse emittance as a function of the laser injection phase at a constant solenoid field of 1.71 kG (minimum emittance at 1 nC [7]). The data was measured at the constant booster linac phase of 84-degree and constant laser energy of 0.18 mJ. The bunch charge at each laser injection phase was different. The rf induced emittance growth increases with the laser injection phase.

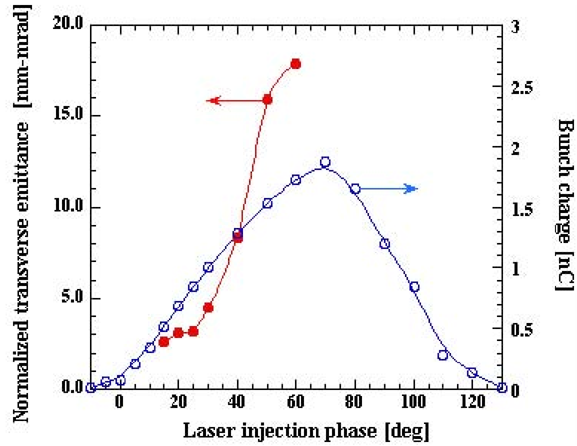

Fig. 2 Transverse emittance versus laser injection phase

The emittance growth due to the space charge effect also occurs at higher injection phase because of the bunch charge increase due to Schottky effect. However, the normalized transverse emittance increases slightly from 2.6 to 3.2 mm-mrad with changing the injection phase from 10 to 30 degree.

The dependences of the bunch length and the relative energy spread on the laser injection phase are shown in Fig. 3. The linac phase was fixed 84-degree. Therefore, the effects of the bunch length and the energy spread on the linac phase are negligible. In Fig. 3, the constant laser energy of 0.18 mJ was used. The bunch charge was different at each laser injection phase as given in Fig. 3. The data in Fig. 3 shows that the bunch length of the electron beam decreases linearly with the laser injection phase. The phase compression inside the rf gun occurs at the laser injection phase of <40 degree, while the relative energy spread of the beam increases. A sub-picosecond electron bunch was observed in the rf gun at the low injection phase, i.e. <20 degree. The bunch length and the relative energy spread of the beam increased due to the longitudinal space charge effect at higher injection phase. The bunch length was longer than the incident laser pulse length at >50 degree.

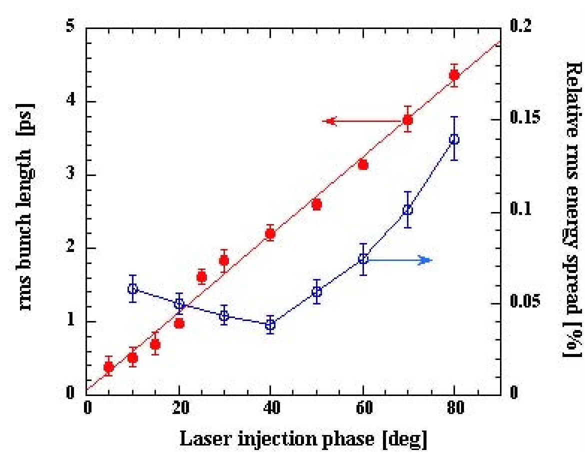

Fig. 3 Energy spread and bunch length versus laser injection phase

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BEAM DYNAMICS IN BOOSTER LINAC

Figure 4 gives the normalized transverse emittance at bunch charge of 1 nC as a function of the rf phase of the linac. A constant solenoid field of 1.71 kG and a constant laser injection phase of 30 degree were used in the measurements. A large rf induced emittance growth was observed at the linac of >88 degree, where the energy spread was increased due to the rf effect, as shown in Fig. 5. However, a slight dependence of the bunch length on the linac phase was observed. The electron bunch will compress in the linac at the low phase, i.e. <90 degree, the tail of the beam gains more energy and moves faster than the head. The bunch will expand at >90 degree, the head of the beam moving faster than the tail.

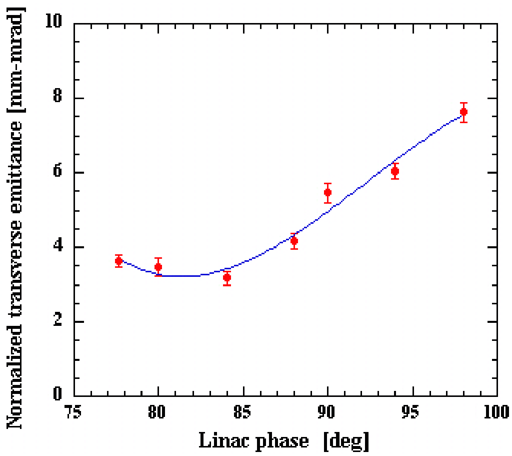

Fig. 4 Transverse emittance versus linac phase

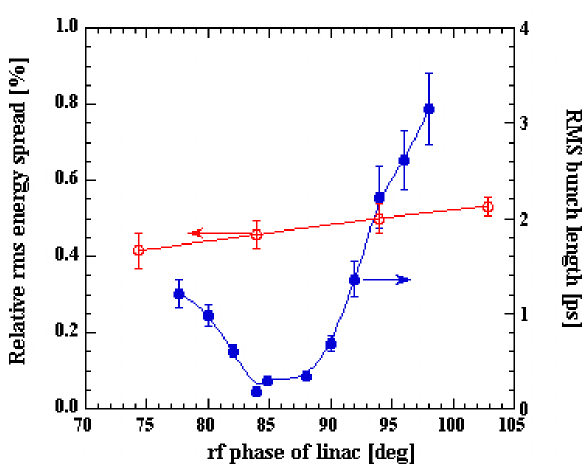

Fig. 5 Energy spread and bunch length versus linac phase

A 100-FEMTOSECOND ELECTRON SOURCE

By using the rf bunch compression in the rf gun, operating under the lower gun phase, as shown in Fig. 3, a

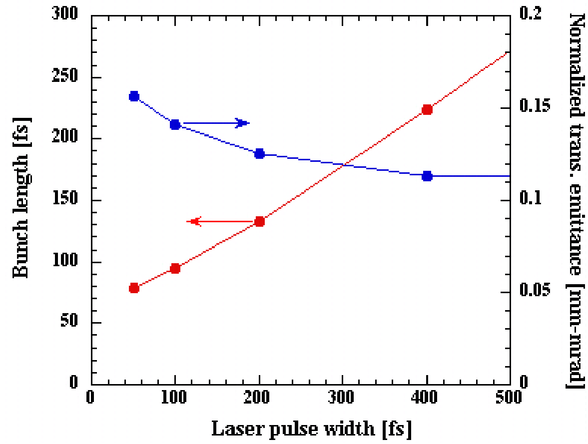

Fig. 6 Bunch length and transverse emittance versus incident laser pulse width

sub-picosecond electron beam with bunch length of a few hundreds femtosecond can be generated in the rf gun with a picosecond laser injection. However, it is difficult to generate a femtosecond electron beam with bunch length of 100 fs or shorter than 100 fs. The technique of magnetic bunch compression is powerful to compress the picosecond electron bunch into femtosecond by using a chicane downstream of the linac. However, the energy spread would be larger than 1%, which is not suitable for the electron diffraction.

In this paper, a 100 fs electron source based on the photocathode rf gun is proposed for time-resolved pulse radiolysis and time-resolved electron diffraction. In the source, a femtosecond laser was used to generate the femtosecond electron beam in the photocathode rf gun. A 100 fs electron beam with transverse emittance of <1 mm-mrad and energy spread of <0.1% was achieved in the simulation. Figure 6 gives the dependences of bunch length and emittance on the laser pulse width at bunch charge of 1 pC. The laser injection phase was fixed to 30 degree. The thermal emittance is not included in Fig. 6.

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