Femtosecond Electron Beam Generation by S-Band Laser Photocathode RF Gun and Linac


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Abstract. A laser photocathode RF electron gun was installed in the second linac of the S-band twin linac system of Nuclear Engineering Research Laboratory (NERL) of University of Tokyo in August in 1997. Since then, the behavior of the new gun has been tested and the characteristic parameters have been evaluated. At the exit of the gun, the energy is 3.5 MeV, the charge per bunch 1~2 nC, the pulse width is 10 ps (FWHM), respectively, for 6 MW RF power supply from a klystron. The electron bunch is accelerated up to 17 MeV and horizontal and vertical normalized emittances of 3 × mm.mrad are achieved. Then, the bunch is compressed to be 440 fs (FWHM) with 0.35 nC by the chicane-type magnetic pulse compressor. The linac with the gun and a new femto- and picosecond laser system is planned to be installed for femtosecond pulseradiolysis for radiation chemistry in 1999.

INTRODUCTION

A laser photocathode RF electron gun is one of the most attractive electron sources since it can supply the relativistic electron bunch of high quality both transversely and longitudinally. Namely, low transverse and longitudinal emittances are advantageous for the brightness of synchrotron radiation and bunch compression, respectively. Especially, those features are inevitable for X-ray free electron laser (FEL) such as SASE[1]. Several works have been done for its development aiming the application to FEL and linear collider[2, 3, 4, 5]. We installed a new S-band laser photocathode RF electron gun in the second S-band twin linac system[6] in August in 1997. The gun was constructed by KEK, Brookhaven National Laboratory (BNL) and Sumitomo Heavy Industries based on much experiences at BNL[7]. The purpose is to apply it to the joint research project on laser wakefield acceleration and femtosecond X-ray generation via Thomson scattering among Nuclear Engineering Research Laboratory of University of Tokyo, High Energy Accelerator Research Organization (KEK), and Japan Atomic Energy Research Institute [8, 9], the picosecond pulseradiolysis for radiation chemistry and the picosecond time-resolved X-ray diffraction. The main subject here is to produce a femtosecond low emittance electron bunch and to enhance the quality and stability of the gun. Technical
feasibility and reliability of the gun are totally accomplished considering the scope of the applications. Updated results are presented in this paper.

**PERFORMANCE OF LASER PHOTO-CATHODE RF GUN**

Upgraded twin S-band linac linac system with the laser photocathode RF gun is depicted in Fig. 1. We also constructed the chicane-type magnetic pulse compressor. Two 6 MW S-band klystrons feed RF power to the RF gun and accelerating tube individually.

![FIGURE 1. Upgraded subpicosecond S-band linac in the twin linac system.](image)

The 90 kV thermionic electron gun, subharmonic buncher and two prebunchers were replaced with the RF gun so that the injector section becomes very simple. The cavity of the gun has S-band 1.6 cells. 10 ps (FWHM) light pulse is produced by the fourth harmonics (263 nm) of the YLF laser (1.05 μm) and irradiates the copper cathode at 68 degree angle at 10-50 Hz. Since the basic mechanism of electron emission is photoelectric, the lifetime of the copper cathode is intrinsically unlimited. The work function of copper is 4.6 eV (270 nm). The quantum efficiency around the work function is 1 x 10^-6. 6 MW RF power is fed to the cavity to induce the field gradient close to 100 MV/m. The time-duration of the fed RF is 4-8 μs. The peak energy at the exit of the gun is 3.5 MeV. The solenoid magnet is attached to the cavity for transverse emittance compensation against space charge effect. The emittance is measured by the conventional quadrupole scanning. Horizontal and vertical emittances are uniformly 3 μm.mrad in normalized rms. Here we controlled transverse laser spot to be circular at the cathode even for oblique injection. Then, we had uniform emittance for both directions. If we do not perform the above treatment, the emittance becomes not uniform and the lowest horizontal emittance of 1 μm.mrad is achieved while the vertical one is 7 μm.mrad. The beam spot is 3 mm. Maximum charge per bunch is 2 nC for 75 μJ laser energy at the cathode. Then, the low emittance electron beam is accelerated up to 17 MeV and simultaneously its energy profile is modulated for the magnetic pulse compression in the accelerating tube where the maximum field gradient is 8.5 MV/m.

We are always making efforts to reduce dark current by baking for high vacuum in the cavity and the RF aging, and observing its behavior. It is very important to reduce the dark current because it would be rather harmful for the applications such as FEL and pulseradiolysis from several aspects of noise or sample damage. The dark currents are multi-bunches existing in the traveling accelerating RF phases. Therefore, each peak
current is negligible while the total charge during the whole RF pulse is more than photoelectrons. So far, its charge per 4 μs RF pulse is 2 nC at 50 Hz. When the RF pulse is elongated to 8 μs, it increase to 26 nC. We are going to continue the efforts.

**BUCK COMPRESSION FOR FEMTOSECOND SINGLE BUNCH**

The chicane-type magnetic pulse compression was designed by using PARMELA. It consists of four identical bending magnets. In order to compensate the nonlinearity of the energy modulation in the accelerating tube, we optimized the longitudinal length of the magnet and the gap between the magnets. Calculated longitudinal phase space distribution of electrons and pulse shape are shown in Fig.2. Its pulse width is 200 fs at FWHM.

The pulse shapes of the bunches with and without compression were measured by a single shot by the femtosecond streak camera (FESCA-200, HAMAMATSU PHOTONICS), which time-resolution is 200 fs, via Cherenkov radiation emitted in a Xe-gas chamber attached at the end of the linac. Measured pulse shapes of the bunches before and after the compression are shown in Fig.3. It is observed that 13 ps (FWHM) bunch is compressed to 440 fs (FWHM). The average charge of the compressed bunches is 0.35 nC. This reduction of charge is mainly due unoptimized optics and alignment of the linac, which should be improved. We carried out the calibration of the time-resolution of the camera using a 100 fs Ti:Sapphire laser after the beam experiment. We found out that the error at FWHM of the camera at that time is 370 fs assuming the Gaussian error function and the law of error propagation. When we subtract the error from 440 fs, it become 238 fs at FWHM, which agrees well with the numerical result. Again here the advantage and effectiveness of the low emittance beam from the laser photocathode RF gun was confirmed.

There are several discussions about the precision of the space charge force of PARMELA as for such a ultrashort bunch. Actually the noninertial space charge force
and the coherent radiation force[10,11] in a bending magnet are not considered in PARMELA. Recently, a preliminary numerical simulation of our bunch compression in the chicane was carried out and the effect of the above forces on the pulse length was calculated to be negligible[12]. We are going to measure the emittance growth due to the effect in the chicane.

![Uncompressed pulse](image1)

![Compressed pulse](image2)

**FIGURE 3.** Measured pulse shapes with and without compression.

**SYNCHRONIZATION BETWEEN LASER AND ELECTRON**

We are investigating the precision of synchronization between the laser and electron pulses. We measured it by the femtosecond streak camera. About 100 data of streak measurements were accumulated and the time-interval between the two pulses was evaluated. Its histogram is given in Fig.4. If we assume the distribution to be Gaussian, the standard deviation is 3.5 ps. This linac can be synchronized with the femtosecond T3 (Table-Top Terra-Watts) laser and has been applied to laser wakefield acceleration and femtosecond X-ray generation via the head-on Thomson scattering[13]. Further, a new femto- and picosecond laser system is going to be installed for femtosecond pulseradiolysis for radiation chemistry in 1999.
There are two promising methods to evaluate pulse shape of femtosecond electron bunch. The first one is to measure Cherenkov radiation or optical transition radiation emitted by the electron bunch by the femtosecond streak camera. The second one is the coherent far-infrared transition radiation interferometry [14,15,16]. It is important to compare the results by the two methods in order to confirm the precision of both methods[17,18,19]. First we performed the measurement at the first linac where the 90 kV thermionic electron gun and achromatic-arc-type compressor were installed.

Radiations from a relativistic electron bunch such as synchrotron radiation, transition radiation, Cherenkov radiation etc. have broad spectrum. In case that the wavelength of the radiation is shorter than the electron bunch length, the phase of radiation emitted by the electrons is different from one another so that the radiation is incoherent. On the other hand, in case that the wavelength is longer than the bunch length, the phase becomes almost the same so that the radiation is coherent. This is called the temporal coherence of radiation. The coherent radiation yields the interferogram when we use an interferometer such as the Michelson interferometer. The information of the electron bunch can be deduced from the interferogram. Another important feature of coherent radiation is the dependence of the power on the number of electrons in the bunch. The following theory shows that the power of the incoherent radiation is linear to the number while that of the coherent radiation is linear to the square. From the interferogram of the light intensity of two interfered coherent radiation pulses, the longitudinal bunch distribution are given in the following procedure.
When the cross section of the beam is small and the observation point is far from the source point, the intensity of the transition radiation is expressed by the analogy of the intensity of coherent synchrotron radiation as,

\[ I_{\text{coh}}(\nu) = N[1 + (N - 1)f(\nu)]I_0(\nu), \]  

(1)

where \( N \) is the number of electrons in the bunch, \( \nu \) is the wave number which is the inverse of the wavelength of the transition radiation and \( I(\nu) \) is the transition radiation intensity emitted from a single electron. The first term of Eq.(1) expresses the incoherent transition radiation while the second term the coherent transition radiation. The quantity \( f(\nu) \) is the bunch form factor which is given by the Fourier transform of the distribution function, \( S(\hat{r}) \), of the electron in the bunch,

\[ f(\nu) = \int S(\hat{r}) \exp\left[i2\pi(\hat{n} \cdot \hat{x})\nu\right] d\hat{x}, \]  

(2)

where \( \hat{n} \) is the unit vector directed from the center of the bunch to the observation point and \( \hat{x} \) is the position vector of the electron relative to the bunch center. Since \( N >> 1 \), we approximately have,

\[ I_{\text{coh}} = N^2 f(\nu)I_0(\nu). \]  

(3)

The form factor \( f(\nu) \) can be divided into two parts, the longitudinal bunch form factor \( f_L(\nu) \) and the transverse bunch form factor \( f_T(\nu) \) as follows,

\[ f_L(\nu) = \int h(z) \exp\left[i2\pi\cos \theta / \nu\right] dz, \]  

(4)

\[ f_T(\nu) = \int g(\rho) J_1(2\pi\rho\sin \theta \nu) \rho d\rho, \]  

(5)

where \( h(z) \) and \( g(\rho) \) are the longitudinal(\( z \)) and transverse(\( \rho \)) distribution function of the electron bunch, respectively. The transverse bunch form factor is obtained by measuring the transverse distribution of the electron bunch. When we observe the transition radiation from the on-axis or nearly on-axis direction, i.e., \( \theta^2 >> 1 \), \( \cos \theta \) and \( \sin \theta \) can be unity and zero, respectively.

From the experiment, the interferogram of the light intensity of the two interfered coherent transition radiation pulses as a function of the moving mirror position of the interferometer is obtained. By definition the interferogram can be written,

\[ S(\delta) - 4\pi \int |RT|E(\omega) e^{-i2\pi\delta / \nu} d\nu, \]  

(6)

where \( S(\delta) \) is the intensity of the interfered radiation intensity at the detector for the optical path difference \( \delta \) minus the intensity at \( \delta \rightarrow \pm \infty \), \( E(\omega) \) is the Fourier transform of the electrical field of the transition radiation and \( R, T \) are the coefficients of reflection and transmission at the beam splitter, respectively. Solving for \( \left| E(\omega) \right|^2 \) yields,
Using Eq. (3) and the relation \( I_{\text{c.m.}}(\nu) = |\tilde{E}(2\pi c \nu)|^2 \), the bunch form factor can be obtained by,

\[
|\tilde{E}(\nu)|^2 = \frac{1}{4\pi|RT|^2} \int_{-\infty}^{\infty} S(\delta) e^{-i2\pi c \nu t} d\delta.
\]  

Finally the Kramers-Kronig relation and inverse Fourier transform gives the longitudinal bunch distribution \( h(z) \) from the longitudinal bunch form factor as follows[20],

\[
h(z) = \int_{-\infty}^{\infty} g(\nu) \exp\left[i(\phi_s(\nu) - 2\pi z \nu)\right] d\nu,
\]

\[
g(\nu) = f''(\nu),
\]

\[
\phi_s(\nu) = -2\nu \left| \int_{-\nu}^{\nu} \frac{\ln|g(\nu')/g(\nu)|}{\nu'^2 - \nu^2} d\nu' \right|.
\]

**Experiment**

We performed this comparison at the first linac where the achromatic-arc-type magnetic pulse compressor was installed. In the experiment the longitudinal bunch distribution was controlled by tuning the energy modulation of the bunch in the accelerating tube for the magnetic pulse compression. We chose femto- and picoseconds (FWHM) pulse widths.
and performed the comparison between the femtosecond streak camera and the Michelson coherent transition radiation interferometry measurement as shown in Fig. 5. We measured the transition radiation in the far-infrared region emitted by an electron bunch at the Al-foil put in air after the 50 μm thick Ti window at the end of the linac. We used liquid-He-cooled Si bolometers as a detector for the far-infrared radiation. The major beam parameters are as follows: the energy was 32 MeV, the pulse length is 500 fs to 1.7 ps (FWHM) and the electron charge per single pulse is 30 to 250 pC. On the basis of the procedure of analysis as mentioned before, we have analyzed these pulses from the interferograms which we have got by the Michelson interferometer. Because of nonuniform transparency of the 100 μm-thick Mylar beam splitter and diffraction loss of long wavelength components, the bunch form factor was obtained within rather limited range. Therefore we had to use theoretical bunch form factor assuming the Gaussian or exponential distribution out of the range.

Results and Discussion

The interferogram of the subpicosecond electron pulse is shown in Fig. 6.

![Interferogram of the subpicosecond electron pulse.](image)

The experimental result of the bunch form factor is shown by the solid curve and that of theoretical by dashed curve in Fig. 7. In the figure, we chose the Gaussian distribution as the theoretical curve, since the exponential function has unphysical long tails in both sizes and the observation of the bunch shapes by the streak camera done just beforehand indicates that the Gaussian is closer to the real bunch distribution.

The dashed curves in Fig. 7 represent those of three bunch lengths of 400, 500 and 600 fs at FWHM. We used the measured bunch form factor from 9.5 to 18 cm⁻¹ range and the theoretical bunch form factor out of the range for the analysis. In this case, we adopt the bunch form factor of 500 fs bunch length and extrapolate this to the range under 9.5 cm⁻¹ and over 18.0 cm⁻¹.
Finally, we got the bunch distribution from the interferogram as shown by the solid curve in Fig. 8. The dashed curve in the figure is one of the pulse shape taken by the streak camera. The result by the interferometry gives 550 fs bunch length at FWHM while that by the streak camera becomes 650 fs. The calibration of the camera was also performed by using a Ti:Sapphire laser. Then the error at FWHM was found out to be 370 fs assuming the law of error propagation. After the above error is substrated, the net pulse length becomes 550 fs. These results agree with each other and it is therefore clear that the reliability of the method to measure subpicosecond electron pulse has been confirmed.

We are going to perform the same measurement at the second linac where the laser photocathode RF gun and chicane are installed.

With the choice of thinner beam splitter which determines the appropriate spectrum window of the interferometer, we expect the method is promising even for the shorter bunch (100 - 200 fs FWHM) with better resolution. This is also because the spectrum shifts from the far-infrared region to the infrared region where the sensitivity of the Si-bolometer becomes better.
CONCLUSION

The new laser photocathode RF electron gun and the chicane-type magnetic pulse compressor were installed in the second S-band linac in the twin linac system. The details of their characteristics were measured and evaluated. Horizontally and vertically uniform emittance is 3 n mm.mrad in normalized rms with 3.5 MeV and 1 nC. After acceleration up to 17 MeV, 13 ps bunch was compressed to 440 fs (FWHM) with 0.35 nC. The femtosecond electron single bunch of the low emittance has been used for the laser wakefield acceleration and the femtosecond X-ray generation via the head-on Thomson scattering. Both advantages and drawbacks of the gun continue to be checked including the technical feasibility and reliability for such applications.

We constructed the Michelson coherent transition interferometer for subpicosecond electron pulse shape measurement. From the comparison of the diagnostics by the interferometry with that by the streak camera, the reliability of the interferometric method to measure the subpicosecond electron pulse that are close to the time resolution of the femtosecond streak camera was confirmed. The design for 100 - 200 fs has started. Especially, a new pulseradiolysis for radiation chemistry in 1999.

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REFERENCES

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