# GENERATION AND ACCELERATION OF HIGH BRIGHTNESS ELECTRON BUNCH TRAIN AT ATF OF KEK*

Shengguang Liu#, Masafumi Fukuda, Sakae Araki, Nobuhiro Terunuma, Mikio Takano, Junji Urakawa, KEK, Tsukuba, 305-0801, Japan
Koichiro Hirano, Japan Atomic Energy Agency, Ibaraki, 319-1184, Japan

*Abstract*

Laser Undulator Compact X-ray source (LUCX) is a test bench for compact high brightness X-ray generator at KEK in order to demonstrate the possibility on K-edge digital subtraction angiography, based on the Compton Scattering. For this project, one of the challenging problems is to generate and accelerate high brightness multi-bunch electron beams, compensating the energy difference due to beam loading effect. In this paper, we calculate the transient beam loading voltage and energy gain from RF field in standing wave gun cavity and traveling wave accelerating tube for multi-bunch train, considering the process of propagation, buildup of RF field in them and the special RF pulse shape. We generated and accelerated 100 bunch electron beam train with 50nC, which beam loading effect was compensated effectively by adjusting the laser injection timing. By BPM and OTR system, we measured the electron beam energy bunch by bunch. The average energy of 100 bunch train is 40.5MeV and maximum energy difference bunch to bunch is 0.26MeV, the relative energy spread of single bunch is about 0.13%. The transverse emittance can be optimized roughly to 3.6 pimm.mrad.

## INTRODUCTION

At present, International Linear Collider (ILC), Compton scattering and free electron laser based on self-amplified spontaneous emission (SASE FEL) are all the highlights in the accelerating field. For them, it is the most essential to generate and accelerate multi bunch electron beam with high brightness. With the development of the photocathode RF injector, including the short pulse laser technology as well as the semiconductor cathode with high quantum efficiency, we have generated high charge multi bunch electron beam from the photo cathode RF gun [1].

For the multi bunch train with high charge, the energy of electron bunch decreases differently from the first bunch to the last bunch due to the beam loading effect. We must compensate the energy difference for the bunch train. There are several energy compensation technologies [2] [3][4][5] have been applied or discussed for different accelerating setups. LUCX has only one klystron and two different accelerating structures, a standing wave gun and a traveling wave accelerating tube. Using ΔT compensation method, we generated 100-bunch 50nC electron bunch train and compensated the beam loading successfully.

*Work supported by JSPS research foundation, Japan
#liushg@post.kek.jp

As shown in Fig.1, a 1.6cell photo-cathode RF gun is the electron source with emittance compensation solenoid. A chicane composed of 4 dipole magnets allows the laser irradiation on the $Cs_2Te$ cathode perpendicularly. The electron beam is accelerated further by a 3-meter constant gradient S-band structure.

One klystron (Toshiba E3712) provides RF power for the two accelerating structures. One is standing wave gun cavity; another is a traveling wave structure accelerating tube (KEK/ATF type A) whose filling time is 830ns. Klystron can generate 4μs, 80MW RF pulse. For this accelerating tube, RF pulse that is longer than the filling time does not contribute the energy gain of electron beam. A traveling wave type RF pulse compressor [6] is used to convert 4μs RF pulse into 1μs slope pulse. The enhanced RF power from the RF compressor distributes into the gun and the accelerating tube.

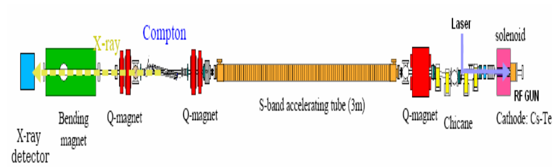


Fig.1 LUCX beam line

## PRINCIPLE OF BEAM LOADING COMPENSATION FOR MULTI BUNCH

When electron bunches pass through the accelerating structures, wake field is excited. Wake field decreases the accelerating field gradient in the structure, which is beam loading effect. The effective field in the structure can be assumed as superposition of RF field and wake field. We can compute the beam energy gain in the structure from the RF field and wake field separately, then to add them up to get the total beam energy. As above describes, LUCX has two accelerating structures. So the total energy gain can be calculated by the following four parts: Energy gain from the RF field in the gun $V_{RF\_GUN}$; Energy gain from the RF field in the accelerating tube $V_{RF\_Acc}$; Energy loss due to the wake field in the gun cavity $V_{beam\_Gun}$; Energy loss due to the wake field in the accelerating tube $V_{beam\_Acc}$.

### *Beam Loading in gun and Accelerating Tube*

For the bunch injecting the gun at time *t* in an electron bunch train, taking account of the decay of wake field and all wake field induced by previous bunches passing through the gun, the effective beam loading voltage can be expressed as

 

$$V_{beam\_Gun} = -\frac{\omega_0 R_0 T^2}{2Q_0}\cdot q\cdot\left[\frac{1-e^{-(t-t_1)/t_{fG}}}{1-e^{t_b/t_f}}+\frac{1}{2}\right] \quad (1)$$

$t_b$ $t_1$ is bunch train duration and the injection time of the first laser pulse, the value "$\frac{1}{2}$" corresponding the energy loss due to the beam loading by the bunch itself.

In the accelerating tube, taking account of the decay of wake field and all wake field induced by previous bunches and the concern bunch itself, the beam-loading voltage for the bunch injecting the accelerating tube at time $t$ (the first bunch injects in at time $t_2$) in electron bunch train is as the formulas (2) expresses

$$V_{beam\_ACC} = -\frac{i_0 R_a}{2(1-e^{-2\tau})}\left[1-e^{-2\tau\frac{(t-t_2)}{t_{fA}}} - 2\tau e^{-2\tau}\frac{t-t_2}{t_{fA}}+\tau(1-e^{-2\tau})\frac{t_0}{t_{fA}}\right] \quad (2)$$

Where $R_a$, $i_0$, $t_{fA}$, $t_2$, $t_0$ is the shunt impedance, the average current during the multi bunch train, the filling time, the first electron bunch injection time and bunch spacing respectively. Taking LUCX as example, for 50nC/100 bunch electron train, the energy loss due to the beam loading for the last bunch is 4.7MeV.

### *Energy Gain from RF Field in Gun and Accelerating Tube*

In the gun, RF field build up on "time" which can be expressed by following formulas

$$V_{RF\_Gun} = \frac{2\sqrt{\beta P_G R_0 T^2}}{1+\beta}(1-e^{-t/t_{fA}}) \quad (3)$$

Where β $P_G$ is coupling factor, RF power forwards into gun cavity.

RF pulse forwarded into the gun cavity is slope one. We must consider the RF pulse shape in the process of field build-up.

Generally, RF pulse is square and electron beam injects into accelerating tube after the RF field fills up the whole structure. Energy gain from RF field can be calculated by formula

$$V_{RF\_ACC} = \sqrt{R_a P_A (1-e^{-2\tau})} \quad (4)$$

Where $R_a$ $P_A$ $\tau$ is the shunt impedance, the forwarded RF power to the accelerating tube, attenuation factor. For LUCX, the accelerating tube is a constant gradient traveling wave structure. RF field builds up on "space". Along the axes of structure, the group velocity of RF waveform decreases. We generate and accelerate multi bunch trains on LUCX facility, electron beams entering the structure before RF field filling the whole structure. We must take account of the transient process of field build-up in the structure and the special shape of RF pulse. A function $V(t)$ is introduced to describe the energy gain as

$$V_{RF\_ACC} = \sqrt{R_a P_A (1-e^{-2\tau})}\times V(t) \quad (5)$$

In fact, $V(t)$ is normalized energy gain. Taking LUCX operation as example, 4μs square RF pulse is converted into 1μs slope RF pulse by the RF pulse compressor; filling time of accelerating tube is 830ns. $V(t)$ has been calculated and plotted as Fig.2, The dashing curve shows the corresponding RF pulse. The energy multiplication factor $M$ is 1.54. The peak value of $V(t)$ occurs at t = 3.75μs, at which the RF field has not filled the whole structure.

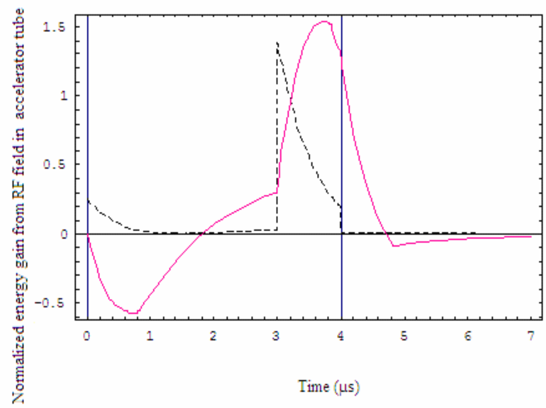


Fig.2 Energy gain from the slope RF power

### *Beam Loading Compensation*

From above analysis, we can calculate the total unloaded energy gain as a function of injection time during 3.0μs< t < 4.0μs. Black curve in Fig.3 shows the total unloaded energy gain for the LUCX operation

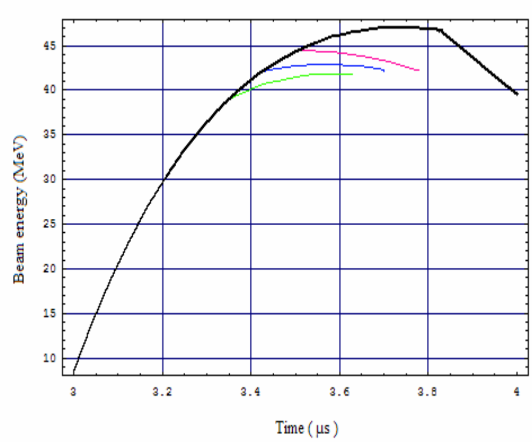


Fig.3 Energy gain without and with beam loading at different injection timing

conditions. We can find a time region, in which the total unloading energy increases with time, the energy loss due to the beam loading can be compensated roughly.

This time region depends on RF power, beam current and the bunch train duration. By adjusting the injection timing of electron train, the beam energy loss can be compensated mostly as the blue curve in Fig.3 shows, in which the first bunch and the last bunch has the same energy and the bunch in the middle of the train has the maximum energy. If the electron train is injected early, beam loading would be compensated overly as the green curve in Fig.3 shows; if the electron train is injected late, beam loading would not be compensated enough as the pink curve in Fig.3 shows.

## MULTI BUNCH ENERGY MEASUREMENT

### *Measurement Setup*

A bending magnet and a set of Profile & OTR plus CCD cameral are employed to measure the energy and energy spread. But for multi bunch case, because the bunch spacing is only 2.8 ns, Profile & OTR plus CCD system can not react quickly enough to distinguish bunch by bunch. So a BPM is installed just beside the Profile & OTR as figure 4 shows. By Profile & OTR, we can get the average position and the average energy of the multi bunch train. By the BPM, we can get the position offset of each bunch to the average position. Then the energy difference of each bunch to the average value can be calculated.

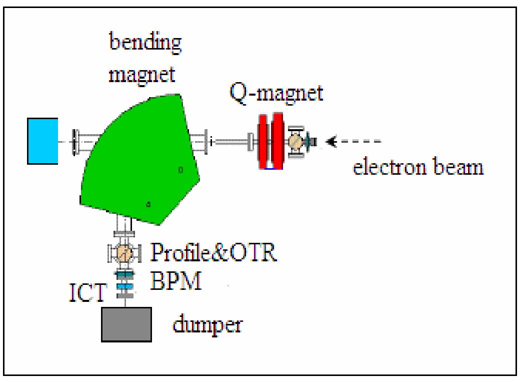


Fig.4 Energy measurement setup

### *Experimental Results*

We have generated 100 bunches with 50nC electron bunch train on LUCX facility successfully. The distribution of bunch charge in the train depends on the laser train shape. RF gun phase and accelerating RF phase setting is for minimum energy spread. BPM is of button type which has four buttons. BPM signals from the two vertical buttons display on the oscilloscope with 2.8ns/70 time resolution, which is fast enough to record all the peak values excited by bunches in 100 bunches train. From the performance of BPM, the position offset for every bunch in a train can be calculated. By the position of beam and the current setting of the bending magnet, the average energy of the bunch train can be calculated. By the position offset of each bunch, the energy offset to the average energy can be calculated then.

For 50nC/100 bunch train, we adjust the laser injection time by injection timing module TD4 in order to compensate the energy loss due to the beam loading. We get the expected compensation results shown in Fig.5. The yellow curve corresponds the optimized injection time, in which the head parts and the tail parts of bunch train has the same energy mostly; the blue curve corresponds the injection time 44.8 ns later than the yellow curve corresponds, in which the head parts of bunch train has higher energy than the tail parts. The reason is that during this time region, beam loss from the beam loading effect can not be compensated enough; the pink curve corresponds the injection time 14 ns early than the yellow curve does, in which the tail parts of electron bunch train has much more energy than the head parts. That means, during the beam train time region, the energy loss from the beam loading is compensated overly.

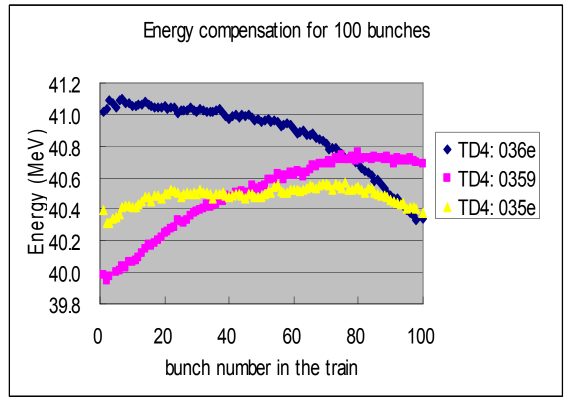


Fig. 5 Energy compensation for 100 bunches

## CONCLUTIONS

We have generated 100 bunches with 50nC electron bunch train. By optimizing the injection time, the beam loading has been compensated effectively. Energy difference peak to peak between 100 bunches is 0.26MeV. RMS energy difference is only 0.01%. In the near future, we plan to increase the RF power for the gun and for the accelerating tube to generate and accelerate 100 bunches with 200nC electron bunch train for X ray Compton scattering experiments.

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