GENERATION OF LONG BUNCH TRAIN USING RF GUN

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Abstract

At Laser Undulator Compact X-ray Source (LUCX) facility at KEK, we have developed a RF gun with increased mode separation. Using this RF gun we have successfully generated a bunch train of 300 bunches per train with 160 nC total charge and with peak to peak energy difference less than 0.85% at 5.2 MeV. We plan to generate and accelerate 8000 bunches per train with 0.5 nC per bunch. These bunches will then collide in the collision chamber with laser pulses to produce soft x-ray. After successful results from above work, we take next step and are now designing and fabricating a new 3.5 cell RF gun and a high gradient standing wave linac to achieve 50 MeV beam with 8000-bunches per train. This compact source will be used for future research. This paper details achieved results with existing gun for generation of long bunch train and lists out proposed activity.

INTRODUCTION

At KEK we have designed and developed an S-band 'Laser Undulator Compact X-ray Source' called as LUCX. This test bench has a RF photocathode gun to inject a low emittance, multi-bunch beam with bunch spacing of 2.8 ns into a 3 m long S-band travelling wave linear accelerator (linac). The linac then accelerates these bunches up to 50 MeV energy with peak-to-peak energy difference less than 0.5 % using Delta T compensation technique. This high energy beam then goes through a quadrupole doublet to reach a beam size of the order of 30 μm at the collision point. The collision point is inside a super-cavity where the beam interacts with pulsed laser to produce intense X-rays by Inverse Compton scattering principle. We have demonstrated 30 keV X-rays with a flux of 1.2×10^5 photons per train [1]. To achieve a further higher flux, increasing the number of bunches per train is very crucial and hence we planned to study the multi bunch beam loading compensation in detail and make use of the Delta T method effectively to achieve a low peak to peak energy difference for the bunch train.

In our setup we have a standing wave photo cathode RF gun followed by a 3 meter long travelling wave constant gradient linear accelerator. The beam loading mechanism for both the accelerating structures was studied and we found that the heavy beam loading in the linac makes it tough to accelerate long bunch train through the travelling wave linac. We used the linac to accelerate 100-bunches per train up to 41 MeV [2]. For longer bunch trains, we removed the linac and inserted a long drift tube and used the same setup to accelerate 300-bunches per train. In this paper we present the methods of experimentation and the results for the 300-bunches per train acceleration. The final target is to accelerate 8000-bunches per train with low peak to peak energy difference.

DELTA T (ΔT) METHOD FOR STANDING WAVE RF GUN

In this section we briefly review the □T method for beam loading compensation in the standing wave gun. The following equation gives the energy gain for the RF gun [2].

$$V_{RFG}=\frac{2\sqrt{\beta P_C Z}}{(1+\beta)}(1-e^{-t/T_a})-\frac{\omega_0 Zq}{2Q_0}\left[\frac{(1-e^{-(t-t_{inj})/T_a})}{(1-e^{-t/T_a})}+\frac{1}{2}\right]$$

Where, V_{RFG} is the energy gain for RF gun, β is the coupling factor, P_c is the cavity power. Z is the effective shunt impedance, Q_0 is the unloaded quality factor and ω_0 indicates the cavity frequency. The bunch charge is given by q while t_{inj} is the injection time for first bunch and T_a is the filling time.

Figure 1 shows the calculated energy gain for our standing wave RF gun. The first term in above equation is the unloaded energy gain which indicates the maximum energy that can be achieved if there is no loading. If we launch a single bunch beam near the crest, then we can achieve this high energy. Off-crest acceleration will result in slightly less energy but much lower energy spread. In our experimental setup, as the initial setting, we set the laser injection phase so as to achieve minimum energy spread. We can see the beam profile on a screen after the bending magnet and the correlation to the energy spread. Thereafter, we can change the injection phase and achieve the optimum phase corresponding to least the energy spread.

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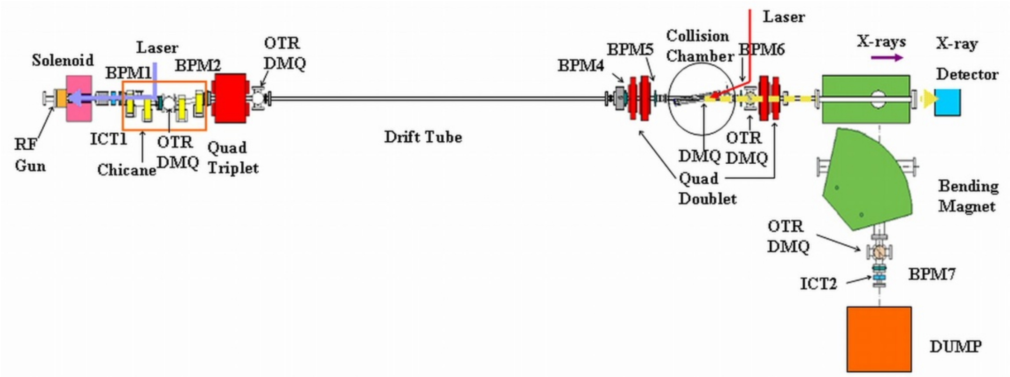

Figure 2: The LUCX setup for low energy beam. The linac is replaced by long drift tube.

After this setting, we launch the multi bunch beam. When the first bunch passes through the structure, some power in the cavity goes to the bunch and the cavity power reduces. Hence, the next bunch in the train will see less power and thus have slightly less energy than the first bunch. This pattern can continue and thus we have a bunch-to-bunch energy difference. This situation is indicated by Curve 1 in the Fig.1.

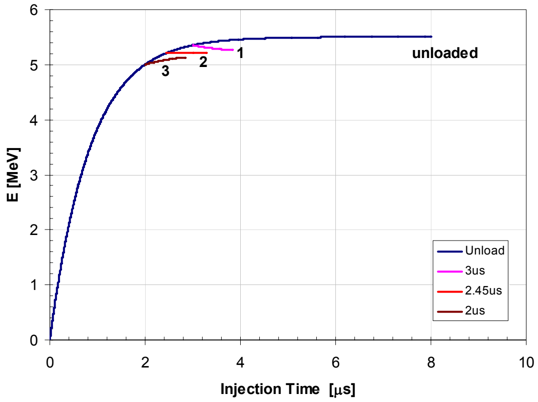

Figure 1: Beam loading compensation for standing wave RF gun. Curve 1 and Curve 3 indicate late and early injection and show large peak-to-peak energy difference. Curve 2 is launched at such a time to achieve best beam loading compensation and results in least energy difference.

On the other hand, if we launch the first bunch much earlier, then the first bunch gets low energy and takes away some part of the cavity power. By the time the next bunch arrives, the cavity power is enhanced due to filling of power and the subsequent bunches will have more energy. In this case, as well, we get a bunch-to-bunch energy difference. This is indicated by Curve 3 in Fig. 1. If the bunch injection time is adjusted such that by the time the next bunch arrives, the loss in power is compensated by the filling power, then the next bunch will have same energy as the preceding bunch. Hence all the bunches in the train can have more or less same energy and the bunch-to-bunch energy difference will be less. This case is indicated by Curve 2 in Fig. 1. The method is called ΔT method of beam loading compensation. We use this method for our setup.

“LUCX” LOW ENERGY SETUP

Figure 2 shows the experimental setup used for the measurement of the multi bunch beam. The RF gun is on the left end and a peak power of 10 MW with 2 μs pulse width is input to the gun. We get a 5.2 MeV energy beam which goes through the chicane magnet, the quadrupole magnets and through the bending magnet to the dump. The bending magnet is used to measure the energy of the bunch. As discussed before, once we fix the initial parameters, the multi bunch beam is launched. In this case, we can not measure bunch-by-bunch energy spread. Instead we use the bending magnet, the OTR screen and the beam position monitor (BPM) near the screen to check the energy variations during the passage. For 4-bunch mode, we know the average energy. The BPM indicates the position of the bunch for the case of 4-bunch mode. When the multi bunch beam is passed, some bunches have different energy than the average energy due to the variation of the beam loading. We maintain the bending magnet current and so bunches with different energy traverses a different trajectory through the magnet and the BPM indicates shift in the bunch position. We can correlate the deviation in position from the average trajectory to the change in energy and thus find the bunch energy as a function of bunch number. This gives us the peak-to-peak energy difference. By carefully adjusting the injection timing, we can then minimize the energy difference. We demonstrate the results for 300-bunch per train generation, later in the paper.

MULTI BUNCH BEAM GENERATION

The purpose of this experiment was to study the long pulse train acceleration [3]. So we decided not to use the power multiplier “Resonant Ring Compression Scheme” (RRCS) and instead input entire klystron output pulse to the RF gun [4]. In reality this resulted in heavy out gassing and hence we restricted to 2 μs pulse width. Figure 3 shows the input power waveforms. The (top) dark blue line is the forward power going to the RF gun while the (middle) light blue line is the reflected waveform. The (lower most) pink curve is the cavity power waveform. From the cavity power waveform, the filling time can be evaluated. We found that the filling time for this measurement was 0.76 µs. After careful tuning, the beam was successfully accelerated to the dump with no beam loss. However we found that the beam had a long tail due to dispersion in the bending magnet.

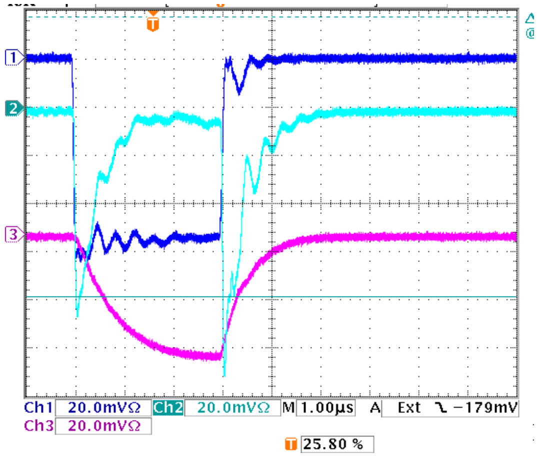

Figure 3: Power waveform for low energy experiment. Power multiplier scheme is turned off.

After these initial settings, we planned the final experiment for 300 bunch beam. The Pockels cell for laser is capable of generating long pulse trains, however above 300 pulses, the waveform showed ringing and hence we can not use it for longer pulse train more than 300. For more bunches per train a new Pockels cell was required. So we decided to limit the experiment up to 300 bunches. The beam was carefully tuned starting from 4 bunch mode and gradually the bunch number was increased to 36, 100, 150, and 230 and then finally to 300 bunches. Careful tuning was done at each stage to ensure that the beam goes to the dump. The charge of bunch was then gradually increased to 0.55nC per bunch. Figure 4 shows the results for 100-, 230-, and 300-bunch mode operation. Figure 5 shows the measured waveforms.

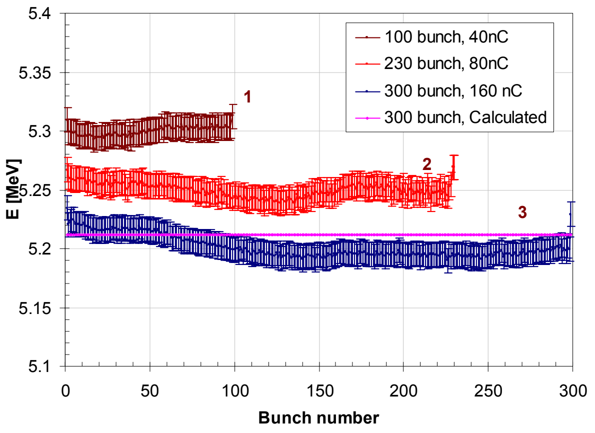

Figure 4: Curves 1, 2, and 3 show results for 100-bunch mode at 40 nC, 230-bunch mode at 80 nC, and 300-bunch mode at 160 nC, respectively.

The 100-bunch mode was performed at a charge of a 40 nC charge, the 230-bunch mode at 80 nC and the 300-bunch mode at 160 nC. The results are shown in Table 1.

Table 1: Measurement Results for Multi Bunch Beam

Number of bunches	**100**	**230**	**300**
Energy [MeV]	5.3	5.25	5.2
Total Charge [nC]	40	80	160
Peak to peak energy difference [%]	0.36	0.58	0.85

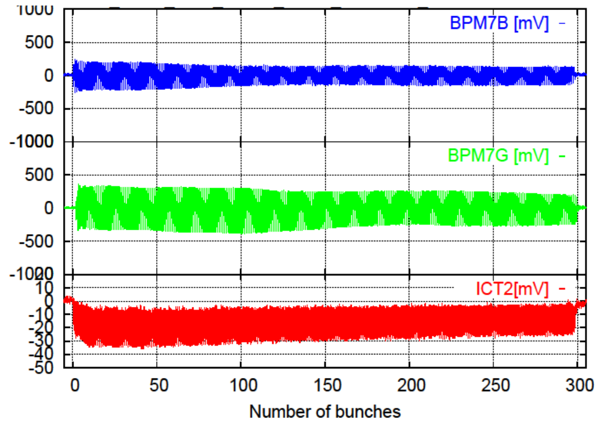

Figure 5: Oscilloscope waveform for 300-bunch generation. The upper two waveforms indicate position of bunches in the BPM while the last curve shows the current transformer waveform.

CONCLUSIONS

We successfully accelerated a long pulse train with 300 bunches per train with 160 nC total charge and achieved a low peak to peak energy difference of 0.85%. The limitation of 300-bunches came from the Pockels cell of the laser system and we have now modified the laser system. We will achieve 8000-bunches per train with 4 µC total charge in near future. There after we will collide these bunches with laser pulses and produce soft X-rays with high flux. We already made a 3.5 cell RF gun and now we are making a high gradient standing wave linac to achieve 50 MV/m gradient. These two systems together will make it possible to have 50 MeV beam with 8000-bunches per train and there after increase the X-ray flux dramatically. This research will make our system much more compact and with a high flux.

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