PRE-MODULATED ELECTRON BUNCH SEQUENCE

Dan Wang#, Lixin Yan
Department of Engineering Physics, Tsinghua University, Beijing, 100084, P.R.China

Abstract

We modulate electron bunch sequence of 0.1 ~ 1nC total charge, after photocathode RF acceleration of 68 ~120MV / m, 3m long travelling-wave accelerating tube for the overall velocity compression. PARMELA simulation results prove that the bunch of high relativity can reach high charge and have short longitude rms length, less than 1ps of each single bunch and picoseconds interval at the accelerating tube exit. Taking use of the pre-modulated bunch sequence, we can do further research in CTR, CSR and FEL radiation.

THEORY ANALYSE

In accelerator physics, the large charge of ultra-short electron bunches is necessary for coherent enhancement of the radiation. Pre-modulated electron bunch is of important application over the study of mechanism in CTR, CSR and FEL radiation [1].

Concerned about the longitudinal bunch distribution, we introduce the form-factor F(f) to measure the bunch longitudinal rms length and interval, which is defined as the modulus squared of Fourier transform of the longitudinal distribution of the whole bunch [2]. Here the whole bunch, will be discussed as the situation of single-cycle and multi-cycle bunch.

Considering a single bunch of Gaussian distribution, the corresponding single bunch form-factor F_s (f) is:

$$F_S(f) = \frac{\exp(4\pi^2 f^2 t_s^2)}{2}$$

where the bunch longitudinal rms length t_s is of ps, so the radiation frequency f= 1/ t is in the THz range. The form-factor is of exponential decay as the square of the frequency. Define cut-off frequency f_c as: $f_c = 1/(2\, t_s)$.

For multi-cycle bunch sequence, the form-factor becomes:

$$F(f) = F_S(f) \bullet F_b(f) \qquad (1)$$

with $$F_b(f) = \left| \frac{\sin(N_b \pi f / f_b)}{N_b \sin(\pi f / f_b)} \right|^2$$

where N_b is the number of bunches, with uniform interval t_b.

Figure 1 shows the shape of $F_b(f)$ and the overall form-factor F(f). Demonstrates that the overall form-factor's envelope will be decided by single bunch form-factor, and appear single-frequency peaks at the harmonic position nf_b (n = 1, 2, 3 ...).

In radiation spectrum the Peak Interval $f_b=1/t_b$, and the Peak FHWM $\Delta f=1/(2t_b \bullet N_b)$.

#correspondence author:wangdan07@yahoo.cn

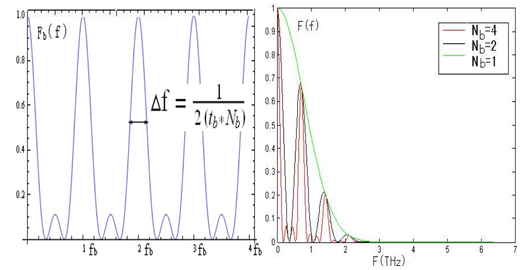

Figure 1: Shape of form-factor in theory.

SIMULATION

In the PARMELA simulation [3], we use 2 to 10 million macro particles to make the results of mesh convergence. And we take the effects of space charge force into account.

Figure 2 shows the simulation model diagram, with Tsinghua University Accelerator Laboratory's parameters, taking full account of the effect of space charge force. Due to photoelectric effect, the laser beam hits the photocathode and produce electron bunch with some initial distribution. However, as space charge force is proportional to the impact factor $1/\beta\gamma^2$ (γ is the Lorentz factor), so low speed bunch sequence distribution is extremely easy to be destroyed by charge force effect. Improvement of the photocathode cavity field is a valid way to avoid the effect. That is, the greater the photocathode field strength is, the more effective bunch pre-modulated we get. In actual photocathode chamber, the high-voltage ignition makes the RF Gun field strength be limited.

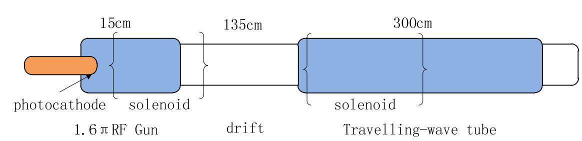

Figure 2: Pre-modulation simulation model.

Single Bunch

For pre-modulation of single bunch, the photocathode cavity field strength can reach 68 MV / m in laboratory conditions, avoiding high voltage ignition phenomenon. But for 4-bunch or 8-bunch, simulation proves requirement of higher cavity field strength for effective pre-modulation.

Photocathode cavity has a horizontal focusing solenoid, the proper focus adjustment can make the bunch into the acceleration cavity at the position of bunch waist (150 cm vicinity), to ensure particles do not lost in the 3m long acceleration tube. At 68 MV / m field strength, the bunch energy will reach 3.2 MeV at the exit of RF Gun. Without velocity compression, the maximum energy is up to ~32 MeV. While after velocity compression, that is, the bunch go into the accelerating cavity not at maximum velocity phase but the vicinity of cos (-90 °). The bunch tail is

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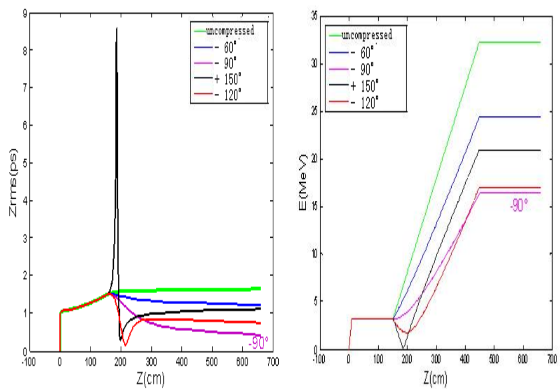
greater accelerated than the head, leading the tail catch up with the head, and the bunch length becomes shorter, while the energy growth is smaller. Different compression phases make different compression ratios of bunch length and final energy, shown in Figure 2.



a)Longitudinal rms length b)Energy

Figure 3: Curves under different compression phases.

Theory [4] and simulations prove the existence of the optimized compression phase allowing the bunch length as short as possible.

Figure 4 shows the simulation results of the scan. For a single bunch, making the bunch into the accelerator in the vicinity of cos (- 90 °), there are optimized experimental conditions and parameters.

Table 1 gives the parameters and results of modulation. Under the conditions of the laboratory's existing photocathode cavity 68 MV / m, even for a large charge (800 pC) of the bunch, single bunch can be compressed to ~0.2 ps rms length.

Table 1: Single Bunch Modulation

Parameters			
Initial transverse rms size	0.05 mm		
Initial longitudinal rms	0.6 ps		
RF Gun phase	30°~ 40°		
Focus current of RF Gun	~90 A		
Focus current of accelerator tube	300 ~400 A		
Results			
Charge(pC)	**200**	**400**	**800**
Z_{rms}(ps)	0.07 ~0.12	0.09 ~0.12	0.24

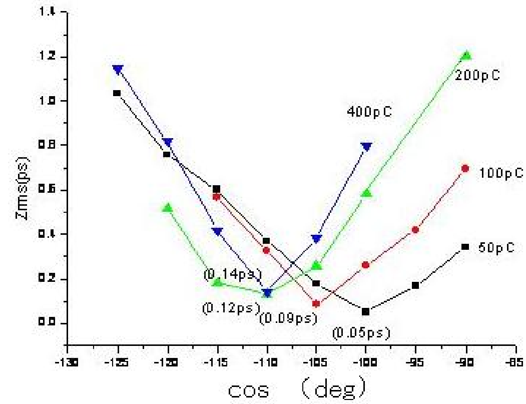
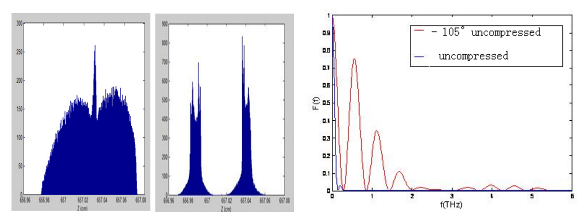


Figure 4: Optimized compression phase scan.

Multi-cycle Bunch

Double-bunch

In 68 MV / m field strength, under the overall compression of double-bunch in the vicinity of optimized compression phase, figure 5 shows that each bunch can be compressed vertically, and has much better form-factor and much wider spectrum at last.



a) Before / after compression b)Form-factor

Figure 5: 2- bunch result with velocity compression.

Four or eight-bunch

For more bunches (4 and 8), the initial single bunch length is 0.6 ps, interval is 5 ps for 4 bunches and 2 ps for 8 bunches, so that the whole length is not too long. Because we need to control the bunch intervals of consistency, and to reduce the randomness of the spectrum, it is necessary to control space charge effect at low power stage by improving the photocathode cavity field. Our simulation use 120 MV / m field strength, results are show in figure 6.

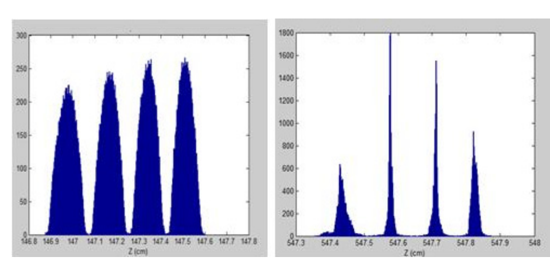


Figure 6: 4 × 200 pC bunch distribution before/ after velocity compression.

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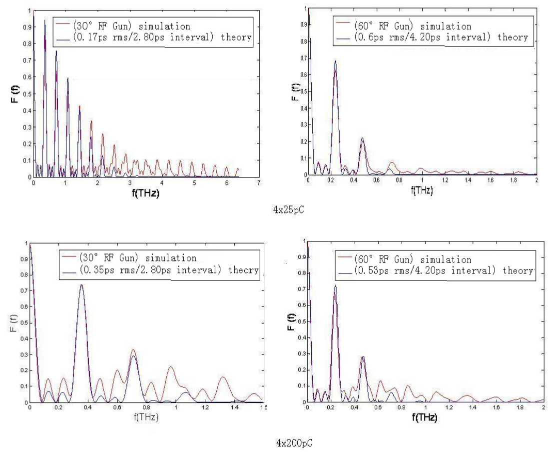


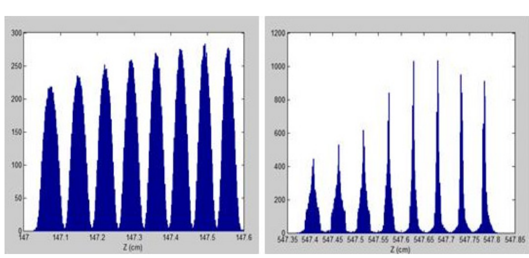
Figure 7: 4-bunch pre-modulation simulation result.

Figure 6 demonstrates that under high field strength of photocathode cavity, the bunch interval can be kept uniform, while the bunch length growth is inevitable. Still by overall velocity compression of travelling-wave accelerating tube, we can achieve a whole bunch of compression, which allows the length of each bunch to be reduced drastically.

Figure 7 shows simulation form-factor compared with the theoretical results. Conclusions are that the total charge of 800 pC can be compressed to 4-bunch, with average length of 0.6 ps rms or less, and greatly widening the radiation spectrum.

At the same time, the phase of RF Gun is important in deciding the bunch interval show as figure 7. The greater the phase is, the bigger the intervals are.

Results of 8-bunch are as shown in figure 8. The conclusion is that with very high field strength, and overall velocity of compression of whole bunch, we can get effectively pre-modulated bunch sequence.



Before (0.65ps rms/2.28ps interval) After (0.3ps rms/2.80ps interval)

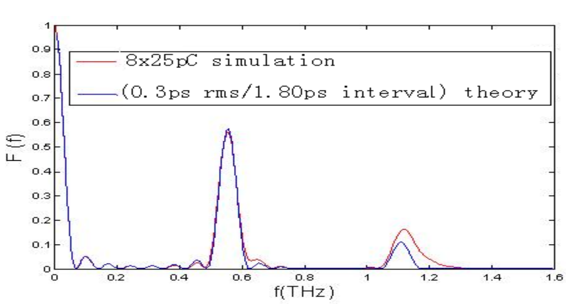


Figure 8: 8×25pC bunch pre-modulation simulation.

FEL APPLICATION

Study from the form-factor for the FEL undulator.

Space integral, single-electron spectrum can be obtained as [5]:

$$U_{bunch}(f) = U_e(f) \bullet \left[N^2 \bullet F(f)\right]$$

Integrated over the space angle Ω, we can obtained for the single-electron spectrum.

$$U_e(f) = e^2 N_u^2 \gamma^2 \eta \int_0^{\pi} \frac{a_u^2}{(1+a_u^2+\gamma^2\theta^2)^2} \sin\theta \, d\theta \times \left\{\frac{\sin[N_u \pi (f/f_r - 1)]}{N_u \pi (f/f_r - 1)}\right\}^2 \qquad (2)$$

where e is the electron charge, N_u is the total number of the undulator periods, a_u is the undulator parameter, and $\eta=377\,\Omega$ is the intrinsic wave impedance, θ is the radiation angle with respect to the electron axis, and f_r. is the resonant radiation frequency.

For common parameters, N_u=50, γ=30, a_u=0.98, the result of formula (2) is a sinc(x) function which can reach the amount of 10^{-32} at the frequency f_r.

If we modulate the bunch and make $nf_b=f_r$, we can get a very high peak spectrum at f_r. For sinc(x) is much narrow than FHWM △f in form-factor, The total spectral shape is the shape of sinc(x).

If we integrate $U_e(f)$ over frequency f around f_r=1THz in sinc(x) function, the total U_e reaches about 10^{-21} J.

100 pC corresponds electron numbers N ≈ 6.25 × 10^8, because of factor N^2, 100 pC (0.1 nC) of charge of the theory of single bunch detection power is amount of tens of μJ. Because FEL radiation is in the picoseconds process, the magnitude of radiation power is up to MW~GW. It is a significant THz source design.

REFERENCES

[1] J.H. Han, "Production of a sub-10 fs electron beam with 10^7 electrons'', Physical Review Special Topics-accelerator And Beams, 14, 050101(2011)

[2] A. Gover, "Superradiant and stimulated-superradiant emission in pre-bunched electron-beam radiators. I. Formulation'', Physical Review Special Topics Accelerators And Beams, March 2005, 8, 030701 (2005)

[3] L.M. Yong, "PARMELA Los Alamos National Laboratory report'', LA-UR-96-1835(Received April 22, 2003)

[4] S.G. Anderson, "Velocity bunching of high-brightness electron beams'', Physical Review Special Topics Accelerators And Beams, 2005,8 ,014401(2005)

[5] Y.C. Huang, "Desktop megawatt superradiant free-electron laser at terahertz frequencies'', Appl. Phys. Lett., 2011, 96,231503(2011)

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