ANALYSIS OF SHORT ELECTRON BUNCHES SHAPING IN A LINAC

M.I. Ayzatsky, K.Yu. Kramarenko, V.A. Kushnir, V.V. Mytrochenko, A.M. Opanasenko, S.O. Perezhogin

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

E-mail: mitvic@kipt.kharkov.ua

The features of short electron bunche shaping via velocity bunching are explored. The basic possibility to obtain bunches with duration less than 1 ps at the LUE-40 linac is shown.

PACS: 41.75.Ht, 25.20.-x

INTRODUCTION

Production of short, intense electron bunches is one of the most dynamic branch in the physics of charged particle beams. Application of relativistic electron beams to generate short-wave electromagnetic radiation, including various types of free-electron lasers and x-ray sources based on inverse Compton scattering of laser radiation, requires high-energy electron bunches with unique properties. There are various schemes for obtaining short bunches (see, for example, [1, 2]). One of the promising methods of ultrashort bunch formation is the use of phase motion of particles relative to the wave in the accelerator section or so called velocity bunching [3]. An analysis of works concerning the velocity bunching showed that theoretical bases of the method do not consider the influence of fields generated by accelerated bunches on the beam dynamics. Such approach is justified for bunches obtained at the output of photoinjectors whose average beam current is rather low.

We have theoretically shown [4] that at the velocity bunching under conditions of a significant beam loading, the phase velocity of the total wave, that is a superposition of waves excited by the RF power generator and bunches, differs from the speed of light. This can increase the efficiency of the bunching.

In this paper, we present the results of a study of this method in the LUE-40 linac [5]. The linac consists of an evanescent wave injector [6] and two accelerating sections of the Kharkov-85 type [7].

1. METHODOLOGY OF RESEARCH

To find the parameters of axially symmetric electrodynamic and magnetic systems, the SUPERFISH / POISSON group of codes [8] were used, as well as the EGUN [9] and the PARMELA [10] codes were used to simulate the particle motions. The technique [11] was used to find self-consistent fields along the linac.

The simulation was carried out for the following parameters. The beam current and energy of particles at the gun exit were equal to 250 mA and 25 keV, respectively; the beam current after the collimator installed at the injector exit was 68.5 mA, the current pulse length was 1.85 μs, the RF pulse length was 3 μs, the current pulse delay with respect to the RF pulse was 0.82 μs, the injector input RF power was 0.75 MW, the first accelerating section input RF power was 15 MW. As an indicator of phase motion of bunches relatively the accelerating wave we used a phase of the first harmonic of beam current relatively the wave crest in centers of section cells (the bunch phase thereafter). The phase motion and beam characteristics at various phases of the first section RF power supply were studied in the steady state (at a time 1.75 μs from the beginning of the microwave pulse). The bunch phase in the first accelerating section cell φ_i was a parameter of the study.

The simplest method that can be used in our conditions for estimation of the length of bunches that can be obtained at the exit of the linac is the so-called "zero phasing" method [12 - 14]. The essence of the method is that the electron beam to be analyzed is passed through the accelerating section in such a phase that the average beam energy does not change (zero crossing) but a phase correlated energy deviation is applied to the bunch particles. To estimate the phase length of the bunches, the results of the paper [14] were used because in contrast to the papers [12, 13], they take into account the initial slope of the ellipse on the phase plane of "longitudinal coordinate-energy" $\Delta W/\Delta z$. If the length of bunches is much smaller than the wavelength of the field in the section, the particle energy deviation has a linear dependence on the phase of the particles in the bunch. In this case, it is possible to operate with a linear slope of the field $\pm 2\pi eV/\lambda$, were electronvolt is the maximum beam energy gain in the section (acceleration on the wave crest), λ is the wavelength, sign ± corresponds to zero crossings with oposite slopes separated by ±90° from the wave crest.

If we neglect the influence of the initial beam size on the measurement of the energy spectrum with a magnetic analyzer and the uncorrelated energy spread of the beam in comparison with the correlated one that introduces the measuring section, the phase length of the bunch in degrees $\Delta\phi_{\mathrm{FWHM}}$ (here and hereafter we assume a values of full width at a half of magnitude of the spectrum – FWHM if other does not mentioned) can be found from the formula:

$$\Delta\phi_{\mathrm{FWHM}} = 360\frac{\Delta W^{+}_{\mathrm{FWHM}} + \Delta W^{-}_{\mathrm{FWHM}}}{4\pi eV}, \qquad (1)$$

where $\Delta W^{\pm}_{\mathrm{FWHM}}$ are the absolute values of beam energy spreads at the two zero crossings.

Let's estimate how the assumptions made above, are fulfilled in the case of LUE-40 linac.

The element σ^{1}_{11} of the sigma beam matrix in the analysis plane of the magnetic analyzer (square of the beam size in the bending plane) was found using the TRANSPORT code [15]):

$$\begin{aligned} \sigma^{1}_{11} &= 3.08\cdot 10^{-4}\sigma^{0}_{11} + 0.0468\sigma^{0}_{12} + \\ &+1.772\sigma^{0}_{22} + 0.314\sigma^{0}_{66}, \end{aligned} \qquad (2)$$

where $\sigma_{11}^0, \sigma_{12}^0, \sigma_{22}^0, \sigma_{66}^0$ are the squares of the transverse beam size in the bending plane, the correlation between the size and slope of the trajectory, the slope of the trajectory, the beam energy spread at the entrance of the magnetic analyzer, respectively (under the dimensions we mean the FWHM values). With characteristic parameters of the beam at the exit of the linac, namely, the transverse normalized emittance – 60 mm·mrad and the transverse beam size of 5 mm, the beam size in the analysis plane does not exceed 1.3 mm. At a half width of the analyzing slit equals 1.3 mm, the resolution of the analyzer is 0.13%. Thus, when the energy spread of the particles is about 1% or more, the dimensions of the beam can be neglected.

2. SIMULATION RESULTS

At simulations, φ_i was changed in the range from 86 to 15° by a phase change of the first section RF power supply. We chose the start value of the φ_i = 15°, since at this phase the minimal width of the energy spread was observed. At φ_i = 86°, the smallest phase length of bunches was reached.

Analysis of the obtained data showed the following. To ensure the minimum energy spread of beam particles at maximum average energy gain, it is necessary to inject bunches before the crest of an externally excited wave ($\varphi_i \approx 15°$). In this case, the wave that has the speed of light overtakes bunches at the output of the accelerating section. Beam particles are accelerated mostly around the wave crest so energy spread is small. Build up of a wave associated with bunches affects only the amplitude of the externally excited wave (so called effect of beam loading). With further increase of φ_i a superposition of the radiation field of bunches and the externally excited field is a wave with a phase velocity that is smaller than velocity of bunches at the exit of the section. In proximity of the section entrance the bunches move toward the wave crest and then with the radiation field build up they slip toward zero crossing (Fig. 1).

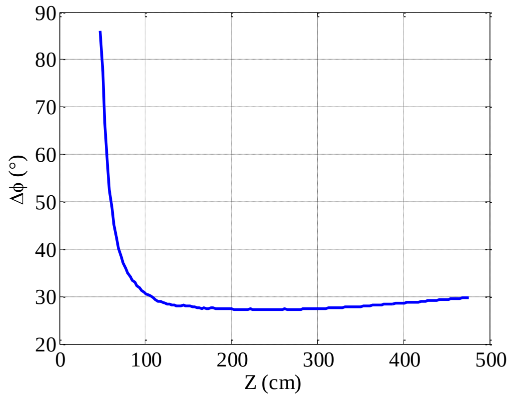

Fig. 1. The bunch phase along the first accelerating section (zero on the vertical axis corresponds to the crest of the accelerating wave) at the shortest bunch formation

At the same time, particles of the bunches are rotating in a phase-energy plane, so the energy spread for 70% of the particles $\Delta W_{70\%}/W$ increases while the phase length (at list for 70% of the particles $\Delta\phi_{70\%}$) decreases. At φ_i = 86° (Table 1), the energy spread again becomes small that may indicate a dense bunch formation (phase length of the bunches reaches sub-picoseconds values and $\Delta\phi_{FWHM}$ becomes less than one degree).

It also should be noted that for the particles from a head of the bunches under the increase of φ_i, the decrease of the energy gain is observed. At φ_i close to 90° they even decelerated in several initial cells of the section. Such deceleration gives a sharp increase of the root mean square size of the beam x_{rms}, y_{rms} and, consequently, an increase of the normalized transverse emittance of the beam $\varepsilon_{n\,rms\,x,\,y}$. In practice, this can lead to loss of beam particles and decrease the output current *I*.

The above results show that with the existing injector we can get subpicosecond bunches at the exit of the LUE-40 linac.

Table 1

Dependence of beam parameters on the bunch phase

φ_i (°)	86	72	58	44	30	15
I (мА)	61	62.8	62.4	63.2	63.4	63.3
$\Delta\phi_{FWHM}$ (°)	0.65	1.03	0.94	13.6	22.8	23.5
$\Delta\phi_{70\%}$ (°)	3.44	3.31	9.5	16.6	21.7	25
W (MeV)	40.2	39.8	39.7	46.5	49.1	49.1
$\Delta W_{70\%}/W$ (%)	3.0	5.6	12.1	11.6	5.7	2.9
x_{rms}, y_{rms} (mm)	11.5	8.1	4.5	2.8	3.0	3.5
$\varepsilon_{n\,rms\,x,y}$ (mm·mrad)	58	13	7	6	6	8

To study the details of using the above-mentioned method for measuring the phase length of bunches, an appropriate simulation was carried out. The main goal of the simulation was to study influence of beam loading on the results of the measurement.

The simulations was carried out in several stages. At the first stage the shortest bunches from the first accelerating section were injected into the second section that was not powered. In a steady state, the phases of the field that was excited by the beam along the section, was studied. Then, the section was fed with a RF power of 15 MW. The phase of the RF power supply was adjusted in such a way that the field in the last cell was opposite to the field excited by the bunches (the phase of the RF power supply was -97°). In this case particles from the bunch centers get the maximal energy gain (acceleration on the crest). Next, the phase of the RF power supply was shifted by ±90° (the phases were -7 and 173° respectively) that corresponds to “acceleration” at zero crossings. The influence of the second section on the energy spectrum and average beam energy is shown in Fig. 2 for these cases.

As it can be seen from the Fig. 2, when bunches are injected into the zero crossing the average energy of particles is changed in the steady state. It looks like increasing of beam loading. The change is insignificant, so we can assume that the core of the bunches is placed within the linear part of the sinusoid.

We also studied the influence of the second section on distribution of particles in the phase plane of longitudinal coordinate – energy. As it can be seen from Fig. 3, the slopes of bunch core are changed on this plane.

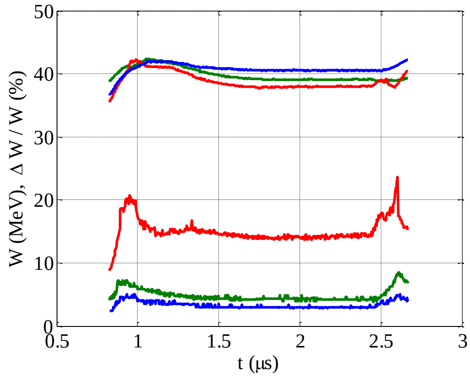

Fig. 2. The change in the energy and energy spread of the electron beam within the current pulse. A green curve corresponds to the phase of the second section of -7°, a red curve corresponds to the phase of the second section 173°, a blue curve corresponds to the first section exit. The upper curves are energies; the lower curves are the energy spreads

Moreover, with the injection of bunches in the phase of +90°, the slope of the distribution is decreased, while when the bunches are injected in the phase of -90°, the slope is increased. At acceleration on the wave crest, the energy of particles at the spread pick is increased by 47 MeV in a steady state mode (Table 2).

Table 2

Results of spectral processing at the exit of the second section

Injection	On crest	-90°	+90°
Initial energy, MeV	40.2	40.2	40.2
Energy gain, MeV	47	-1.1	-2.2
Energy spread ΔW_{FWHM}, MeV	-	0.4	0,47
$\Delta W_{70\%}$, %	0.8	4.3	14.0

Using Fig. 3 one can find the initial slope of distribution of particles from the bunch core on the phase plane of longitudinal coordinate – energy. In our case, it is -1600 MeV/m.

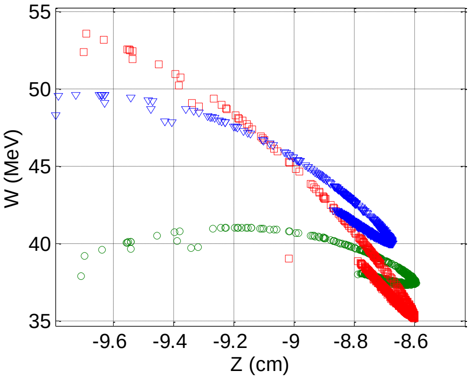

Fig. 3. The distribution of particles in the plane of the longitudinal coordinate is energy. Rings – injection in the phase of +90 ° from the crest, squares – injection in the phase -90 ° from the crest, triangles – beam at the exit of the first section

From the maximal gain of particles in the second section of 47 MeV, the linear slope of the field in this case is ± 2760 MeV/m. That is, these values differ only by 1.7 times. As the distribution of particles is complex, the above-mentioned method can be used only for obtaining rough estimates in our case. For a more accurate measurement, it is necessary to apply the tomography method [16], but it requires a long time for measurements. Insufficient stability of the accelerator does not allow realizing it now.

In any case, substitution data on energy spreads from Table 2 into (1), we find that the phase length of the bunches is equal to 0.53°. From Table 1, one can see that this value is 0.65°. In re-account for the time, we have the following results: 530 fs against 645 fs. The difference is about 115 fs or 18%. Thus, the accuracy of the method is quite satisfactory, taking into account the assumptions that have been made.

3. EXPERIMENTAL STUDIES

Due to the structure of the RF power supply system, it was impossible to get reliable readouts from the phase shifter feeding the injector. To measure the phase difference between the fields of the injector and the first section, a circuit consisting of a double balanced mixer ZEM4300+ and a calibrated coaxial phase shifter was used. The signals from the RF field probe in the first cell of the injector and from the directional coupler installed in the feeder line of the first section were fed to the inputs of the mixer. When the phases between the injector and the section were changed, the signal at the output of the balance mixer was kept at zero by means of a phase shifter. Phase change was readout from the phase shifter scale.

The process of estimating the phase length of the bunches was as follows. At first, the temperature of the second section was reduced by more than 10°C in order to prevent coherent energy losses when transporting the beam from the output of the first section to the magnetic analyzer. The phase of the RF power supply of the injector was tuned to obtain the minimum energy spectrum. The reference phase shift between the injector and the section was fixed. Further, the phase was shifted by a certain amount that was determined during previous studies. After measuring the energy spectrum, the temperature of the second section was set equal to the working one, RF power was fed into this section and three energy spectra were measured. The first spectrum was taken for the "on crest injection" and the other two were measured for the "zero crossing injection". The "on crest injection" was identified by the maximum energy. The "zero crossings injections" were identified as minimal influence of the second section on an average energy of the beam.

Three series of such measurements were carried out for the calibrated phase shifter readouts Φ from 10 to 36°. The results of measurements and processing of spectra according to the formula (1) are given in Table 3.

It can be seen from Fig. 2 that the simulated transient process is practically independent of the injection phase of the bunches into the second section. For any injection phase, approximately 650 ns after the injection of the beam, a steady state sets in. The analysis of the experimental data showed another behavior. The steady-state mode does not occur at all, and the transition depends on the injection phase of the bunches into the second section. The phase shift between the bunches and the wave changes during the whole current pulse.

Table 3

Results of measurements and spectral processing

Φ, degr.	10	23	36
Initial energy, MeV	38.2	37.1	37.1
Energy gain, MeV	34.2	33.4	36.2
Beam current, мA	47.5	46.7	45.9
Energy spread ΔW^{+}_{FWHM}, MeV	1.9	1.5	0.55
Energy spread ΔW^{-}_{FWHM}, MeV	3.7	3.2	1.9
$\Delta\phi_{FWHM}$, degr.	5	4	2

Therefore, when the slope of the field of the second section changes sign, we get a different form of the transient process (Fig. 4). It can be seen in the top graph that the energy increases with time, and in the lower graph it decreases. The measurements of the phase shifts between the signals at the output of the first section klystron and the outputs of both sections showed significant changes during RF pulses, especially at the output of the second section where this change reached 35°. Most likely this is due to the imperfection of the high-voltage pulse of klystron modulators (typical dependence is 5…6°/%). In principle, this can be used to reduce the influence of the transient on the beam spectrum, under certain phasing conditions of the sections. But when taking measurements of the phase length of the bunches, this makes difficult to interpret the results.

It can be seen from Table 3 that the phase length of the bunches is much smaller than the calculated one for the corresponding deviations of the bunch injection phase into the first section (see Table 1). This requires additional explanations.

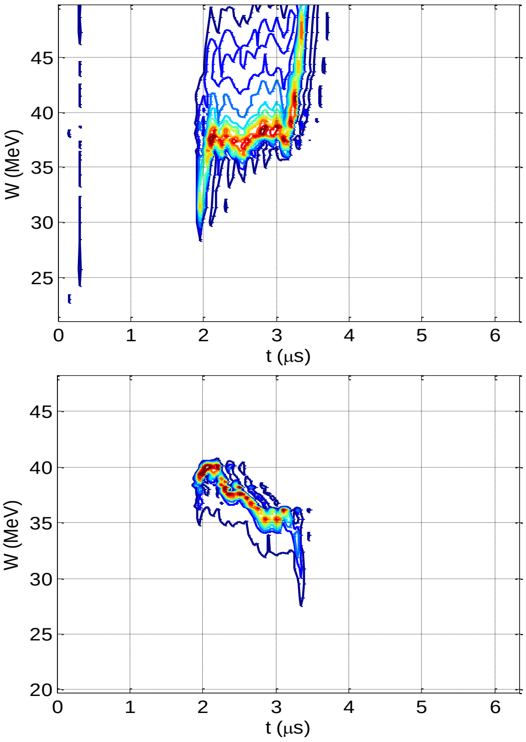

Fig. 4. Contour graphs of the electron energy at the exit of the second section for the shift of the bunch injection phase -90° (up) and +90° (below) from the wave crest (for case of Φ = 36°)

One of the reasons may be a different initial phase, from which the countdown is taken. Since the criterion for adjusting the phase between the injector and the first section is the energy spectrum, it is possible to select the value for the reference phase that corresponds to the regime of the velocity bunching. It can be seen from Table 1 that as the initial phase difference between the wave and the bunches increases, the energy spread first increases and then decreases. Thus, this criterion is ambiguous. Indirect evidence that the bunch injection phase in the first section corresponds to the velocity bunching mode is that the measured transverse beam emittance of 60 mm·mrad (see [5]) is very close to the calculated one in the above mode (see Table 1).

In the velocity bunching mode, the transversal emittance increases by an order of magnitude in comparison with that of the usual mode. As it was mentioned above, the reason is that particles from the head of the bunches are decelerated in the several initial cells of the section and obtain phase dependent transversal kick that causes increase of the root mean square size of the beam. Applying solenoidal magnetic field along an initial part of the section can diminish the kick providing small transversal beam size in the region of interest. With such improvement it is possible to enhance transportation of the beam along the linac and to increase the phase shift range between the injector and the section for bunch phase length measurements.

SUMMARY

The simulation of the process of electron velocity bunching was carried out. The distinguishing features of the process of forming and measuring of bunches with duration of less than 1 picosecond are investigated. The principal possibility of obtaining such bunches on the LUE-40 linac is shown. The carried out experimental studies confirmed of the main simulation results. At present, the minimum measured duration of bunches is 2000 fs. To further advance into the region of obtaining femtosecond bunches, it is necessary to update the linac systems, particularly, in order to increase the long-term stability of the beam parameters and automate the measurement of the energy spectrum.

REFERENCES

1. P. Piot. State-of-the-Art Electron Bunch Compression // *Proc. of the LINAC 2004.* Lubeck, Germany, 2004, v. 1, p. 528-532.
2. P. Emma. Issues and Challenges for Short Pulse Radiation Production // *Proc. of the EPAC 2004*. Luserne, Switzerland, 2004, v. 1, p. 225-229.
3. S.G. Anderson, P. Musumeci, J.B. Rosenzweig. Velocity bunching of high-brightness electron beams // *Physical review special topics – accelerators and beams.* 2005, v. 8, p. 014401.
4. N.I. Ayzatsky, V.F. Zhiglo, V.A. Kushnir, et al. On the question of the formation of femtosecond bunches of electrons at the output of a resonant linear accelerator on a traveling wave at a significant beam loading // *Problems of Atomic Science and Technology, Ser. "Nuclear Physics Investigations".* 2010, № 3, p. 72-75.
5. M.I. Aizatskyi, V.I. Beloglasov, V.N. Boriskin, et al. State and prospects of the linac of nuclear-physics

complex with energy of electrons up to 100 MeV // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2014, № 3, p. 60-63.

6. V. Mytrochenko, M.I. Ayzatskiy, I. Khodak, et al. Performance of compact electron injector on evanescent oscillations // *Proc. of the EPAC08*. Genoa, Italy, 2008, p. 790-792.
7. E.Z. Biller, A.N. Dovbnya, V.A. Kushnir, et al. Beam Current Enhancement in Kharkov Electron Linac // *Part. Accel.* 1990, v. 27, p .119-124.
8. J.H. Billen and L.M. Young. *Poisson/Superfish*. Los Alamos, 1996, LA-UR-96-1834.
9. W.B. Herrmannsfeldt. EGUN: Electron Optics Program Preprint. SLAC, SLAC-PUB-6729. 1994, 140 p.
10. L.M. Young. *PARMELA*: Preprint LA-UR-96-1835. Los Alamos, 1996.
11. V.V. Mytrochenko, A.N. Opanasenko. Study of transient self-consistent beam dynamics in RF linacs using a particle tracing code // *Nuclear Instruments and Methods*. 2006, v. A558, p. 235-239.
12. V.A. Vishnyakov, V.I. Beloglazov, A.V. Bondarenko, et al. The design and characterization of the injector accelerator with a steady change in the phase velocity of the wave // *Physical-technical institute of the Academy of Sciences of the Ukrainian SSR*. 1971, 22 p. (Kharkiv, rotary print of the FTI Academy of Sciences of the Ukrainian SSR, KPI 71-32).
13. L.Z. Gilavyan, V.A. Obozny, V.N. Ponomarev. Measurement of the phase extension of electron bunches of LUE-50 of the Institute of Nuclear Energy of the Academy of Sciences of the USSR // *Proceedings of Atomic Science and Technology. Ser. "Linear accelerators"*. 1976, issue 1 (2), p. 59-60.
14. D.X. Wang, G.A. Krafft, C.K. Sinclair. Measurement of femtosecond electron bunches using a rf zero-phasing method // *Phys. Rev. E*. 1998, v. 57, № 2, p. 2283-2286.
15. D.C. Carey, K.L. Brown, F. Rothacker. Third-Order TRANSPORT with MAD Input: A *Computer Program for Designing Charged Particle Beam Transport Systems*. Batavia, Illinois: Fermi National Accelerator Laboratory, 1998, 328 p. (FERMILAB-Pub-98/310).
16. S. Kashiwagi, M. Washio, X.J. Wang, et al. Photo-Electron Beam Longitudinal Phase Space Tomography Studies at the ATF // *XX International Linac Conference*. Monterey, California, August 21-25, 2000, p. 149-151.

Article received 26.02.2018

ИССЛЕДОВАНИЕ ФОРМИРОВАНИЯ КОРОТКИХ ЭЛЕКТРОННЫХ СГУСТКОВ В ЛИНЕЙНОМ УСКОРИТЕЛЕ

Н.И. Айзацкий, Е.Ю. Крамаренко, В.А. Кушнир, В.В. Митроченко, А.М. Опанасенко, С.А. Пережогин

Исследованы особенности формирования коротких сгустков электронов с помощью скоростной группировки и их измерения. Показана принципиальная возможность получения сгустков с длительностью менее 1 пс на ускорителе ЛУЭ-40.

ДОСЛІДЖЕННЯ ФОРМУВАННЯ КОРОТКИХ ЕЛЕКТРОННИХ ЗГУСТКІВ У ЛІНІЙНОМУ ПРИСКОРЮВАЧІ

М.І. Айзацький, Є.Ю. Крамаренко, В.А. Кушнір, В.В. Митроченко, А.М. Опанасенко, С.О. Пережогін

Досліджено особливості формування коротких згустків електронів за допомогою швидкісного групування і їх вимірювання. Показана принципова можливість отримання згустків з тривалістю менше 1 пс на прискорювачі ЛУЕ-40.