# SUBPICOSECOND BUNCH FORMATION BY TRAVELING WAVE UNDER HEAVY BEAM LOADING

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## *Abstract*

Simulation results of subpicosecond bunch formation due to a phase motion of electrons in a travelling wave are presented. It has been shown that at satisfying phase conditions of electron injection that are necessary for velocity bunching, relative phase velocity of the total wave excited both by RF generator and particles becomes different from unit increasing bunch compression. Simulation of transportation of obtained 8.9 MeV bunches through undulator with a period of 108.5 mm and estimation of bunch form-factor at 446 harmonic of bunch repetition rate of 2797.15 MHz also was carried out. The data obtained allow to expect coherent radiation from undulator at wave-length of 240 μm.

## INTRODUCTION

Recently, the terahertz frequency range (from 100 GHz to 10 THz) has been rapidly elaborated due to the development of various sources of coherent radiation (see, e.g., [1]). Use of spontaneous coherent radiation of short relativistic electron bunches is one of the directions in creation of such sources [2]. Velocity bunching of particles in travelling wave field is promising method for subpicosecond bunch formation [3]. At moderate requirements on the transverse beam emittance (e.g., at generation of terahertz coherent radiation) traditional injectors that form one bunch in each period of the accelerating field can be used. The paper devoted to study phenomena concerning influence of beam loading effect on velocity bunching by travelling wave field. In addition preliminary evaluation of possibility to generate spontaneous coherent radiation at a wavelength of 240 microns has been carried out.

## METHODS OF SIMULATION

The SUPERFISH / POISSON group of codes was used to find the parameters of axially symmetric electrodynamic systems while the EGUN and PARMELA codes were used to simulate the particle motion. The method [6] was used to find the self-consistent field exited by the particles and an external generator. As a model of the linac we used a system consisting of an electron injector based on evanescent wave [7] and a short travelling wave section with phase advance of 2π/3 per cell [8] (see Fig. 1). The injector consists of 5 on-axis coupled cylindrical cavities and a Pierce type diode gun. Radii of the cavities are chosen in such a way to form exponential rise of on-axis field from the entrance of the electron beam into the injector to it exit. Therefore the maximum value of an accelerated field is in the fifth cavity that is coupled with a RF feeder.

To reduce beam emittance degradation at bunch formation and acceleration the axially symmetric magnetic field was applied along the linac. At this phase of the study the on-axis magnetic field distribution was simulated by a set of coils with current.

In the simulation we used the following parameters of the undulator: period was 108.5 mm, undulator parameter was 1, gap was 20 mm, the field was 0.098 T, the number of periods was 11. The total length of the installation from the cathode to the exit of the undulator was 3.22 m.

Our point of interest was steady state solution therefore beam current pulse was chosen as short as possible just to reach that solution (about 1.3 μs) in order to save simulation time. The simulation results are given below.

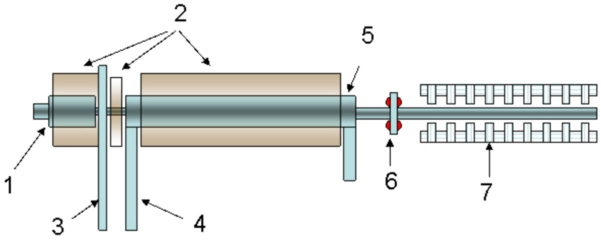

Figure 1: Linac layout. Injector (1), magnetic focusing system (2), injector waveguide (3), accelerating section waveguide (4), travelling wave section (5), quadruple (6), undulator (7).

## SIMULATION RESULTS

Simulation of self-consistent particle dynamics in the injector showed that the 1.56 MW of RF power supply is optimal value at accelerating beam with current of 1 A. The simulation at different configurations of the magnetic field has shown that to ensure small transverse emittance at the output of the injector it is necessary to keep small beam size at the entrance of the fifth cavity. Similarly, to have small transverse emittance at the output of the accelerating structure it is necessary to keep small beam size at the entrance of the section. One of the possible configurations of the on-axis magnetic field that gives a small deterioration in the transverse emittance of the beam is shown in Fig. 2.

Parameters of the injector with the chosen configuration of the magnetic field and RF power supply of 1.56 MW are given in Table 1. It should be noted that at the transverse emittance preservation the bunch length becomes about twice as large. Apparently, this happens due to the increase of the space charge forces with increasing density of the particles. However, the distribution of particles in the phase-energy plane has the crowding (see Fig. 4), which can be used for formation of femtosecond bunches.

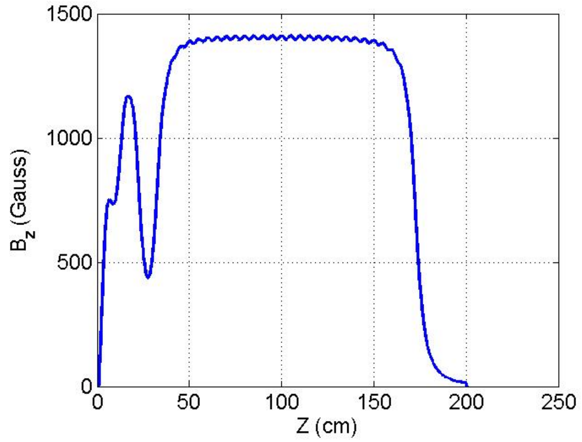

Figure 2: On-axis magnetic field distribution.

Table 1: Injector parameters

| Parameter | Value |
|---|---|
| Operating frequency, MHz | 2797.15 |
| Initial beam energy, keV | 25 |
| Initial beam current, A | 1.1 |
| Maximal on-axis field, MV/m | 43 |
| Output beam energy, MeV | 1.065 |
| Energy spread (70% of beam particles), % | 2.8 |
| Bunch length (70% of beam particles), ° | 19 |
| Transversal beam emittance, $(1\sigma)$, mm·mrad | 9 |

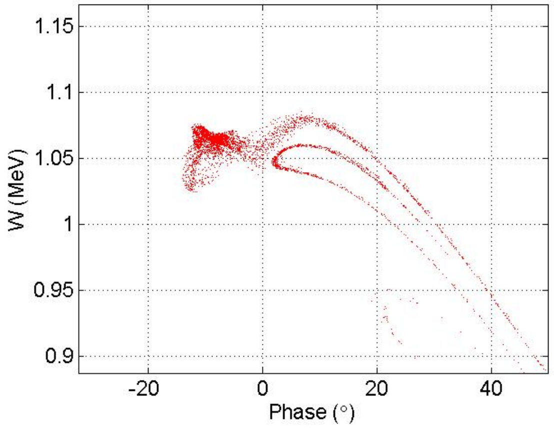

Figure 3: Phase-energy distribution of particles at the injector exit.

Simulation of the particle dynamics at different phase shifts between fields in the injector and accelerating section showed that the minimum duration of bunches is achieved at bunch injection into practically zero field of a travelling wave. Fig. 4 shows the steady state (about 1.6 μs from the beginning of the microwave pulse) distribution of phase and amplitude of the accelerating space harmonic, which is a superposition of fields excited both by an external microwave generator with power of 12 MW, and accelerated particles. Despite the fact that at the operating frequency the phase velocity of wave in a section is equal to the velocity of light, phase velocity of the resulting wave is different from the velocity of light, as it follows from Fig. 4. Due to this effect bunches perform phase oscillations relatively the wave (see Fig. 5).

Fig. 6 shows the distribution of particles in the phase-energy plane after the first cell of the section and at the section output. Particle phases are counted relatively to the crest of the total wave in the section. Analysis of similar dependencies in intermediate points of the section showed that the core of the bunch commits some more than a quarter of the phase oscillation. Head of the bunch is moved toward the crest of the wave in an initial part of the section, and then direction of the motion is changed outward of the crest. This may indicate that the head of the bunch would move along a closed trajectory in the long enough system.

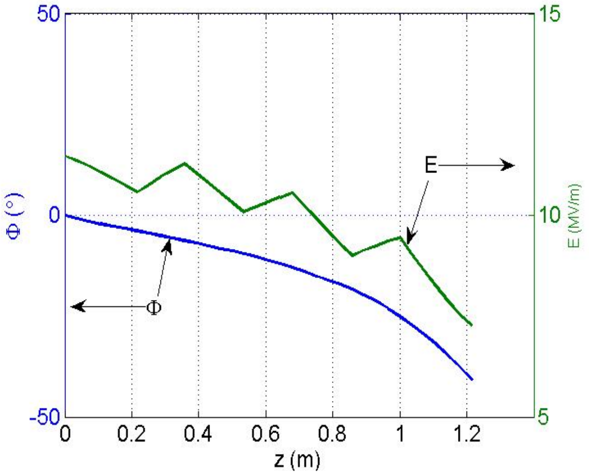

Figure 4: Accelerating field amplitude (E) and phase (Φ) along the accelerating section.

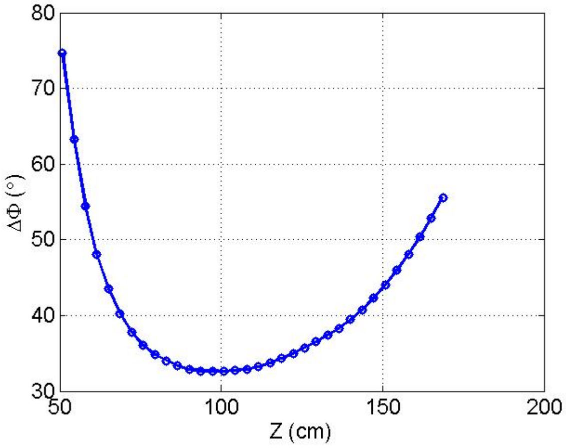

Figure 5: The phase difference between the wave and the first harmonic of beam current along the section.

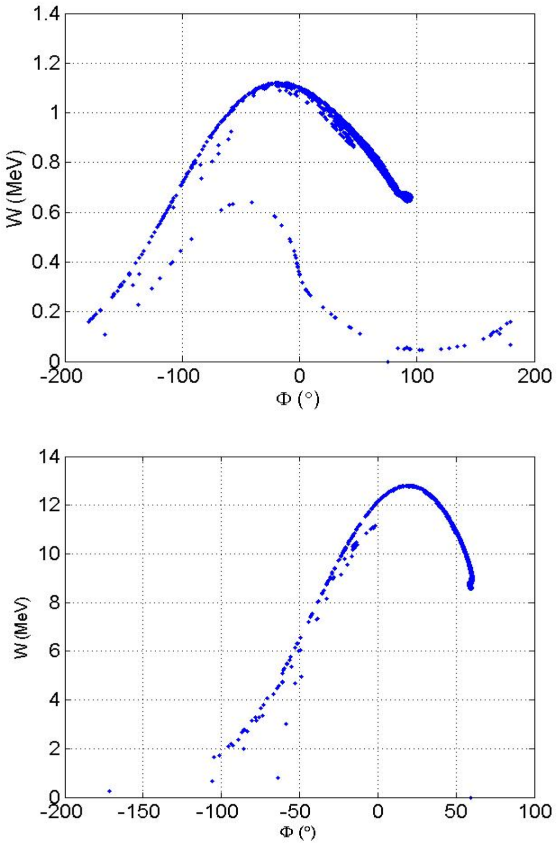

Figure 6: Phase-energy distribution of particles after the first cell of the section (top) and at the section output (bottom).

Analysis of the phase distribution of particles at the section output has shown that the distribution has a spike with a subpicosecond value of the phase length at a half of magnitude (FWHM). It should be noted that FWHM includes at least 45% of the beam. At the phase detuning between fields in the injector and accelerating section within ± 5° from the optimum the peak current becomes twice as little. Simulation of particle motions through the undulator without influence of the radiation has shown that the phase spectrum of the beam varies slightly. Generalized beam parameters at the exit of the linac for the steady state are given in Table 2.

Table 2: Linac beam parameters

| Parameter | Value |
|---|---|
| Particle energy, MeV | 8.9 |
| Beam current, A | 0.93 |
| Peak current, A | 300 |
| Bunch length (FWHM), fs | 400 |
| Phase interval that includes 70% of particles, ° | 1.5 |
| Transversal beam emittance, (1σ), mm·mrad | 15 |
| Transversal beam size, mm | 3.7 |

As is known, a measure of coherence is the form factor of the bunch, which can be expressed as the square of the relative current harmonic at the frequency of radiation. If we want to observe the radiation at a wavelength of 240 microns, then we must consider the 446-harmonic of repetition frequency of bunches, which is equal to the operating frequency of the accelerator 2797.15 MHz. Calculations showed that in our case, this value is 0.035. Thus, when the number of particles in the bunch is $2 \cdot 10^9$ one can expect the power of coherent radiation will be seven orders of magnitude greater than the power of spontaneous emission.

## SUMMARY

Study of features of formation of sub-picosecond electron bunch in the accelerating section with a phase velocity equal to the velocity of light has been carried out with numerical simulation of self-consistent particle dynamics. It was shown the principal possibility of subpicosecond bunch formation with peak current of 0.3 kA and the normalized brightness of $1 \cdot 10^{10}$ A/m$^2$ using the injector with the Pierce type diode gun. Such bunches can be used to study the generation of terahertz radiation. The data obtained on the bunch form factor allow to expect the coherent radiation from the undulator at a wavelength of 240 microns, which corresponds to the 446 harmonic of the linac operating frequency.

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