COMPUTER SIMULATION OF TRANSIENT SELF-CONSISTENT DYNAMICS OF INTENSE SHORT-PULSED ELECTRON BEAMS IN RF LINAC

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Abstract

The electron injector for a storage ring is one of numerous applications of the RF linacs of intensive short-pulsed beams with duration about 100 ns, current about 1 A and energy of particles of a few tens of MeB. Since acceleration of intensive short-pulsed beams takes place in transient mode, then the energy spread is determined by both intro- and multi- bunch spread. Obtaining the energy spread less than 1% is the actual problem. In this work we consider numerically unsteady self-consistent beam dynamics in one section RF linac. For transient beam loading compensation a method of delay of a beam with respect to RF pulse is applied. The simulation takes into account influence on the beam dynamic of such factors as: initial energy and phase spread; sliding of particles on a wave in the initial part of accelerating section; temporal dependence of phase and energy of bunches at the section enter; space charge fields.

INTRODUCTION

The electron injector for a storage ring is one of numerous applications of the short-pulsed RF linacs. Acceleration of high intensive short-pulsed beams with charge about 100 nC to energies of a few tens of MeV with spread less than 1% is an actual problem at the present time. Thus the development of both bunching system, providing a small energy and phase spread, and beam loading compensation techniques are required. Obtainment of a small energy spread is restricted by as transient beam loading so a lot of others factors, namely: energy and phase spread of bunches injected in a accelerating section and their temporal dependences of average phase and energy; sliding of particles with respect to wave phase; space charge effects. The purpose of this paper is numerically to study capabilities to attain the minimum possible beam energy spread in one section S-band RF linac operating in short-pulsed mode. In Fig.1 it is sketchy illustrated the design of the RF linac which consists of a 25 keV thermionic electron gun, the compact evanescent oscillations (CEO) buncher [1], and a traveling wave (TW) constant-impedance (CZ) accelerating section with 20 MW RF feed.

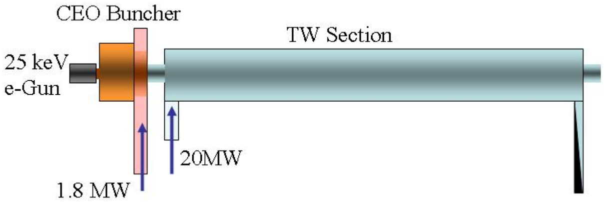

Figure 1: Layout of the one section RF linac.

SIMULATION TECHNIQUES

In order to simulate transient beam dynamics in the buncher and the traveling wave section we use the unsteady self-consistent technique that incorporates codes, PARMELA [2]. A motion of charged particles at each integration time step is simulated by the PARMELA codes that allows to take into account bunch space charge fields. This technique is based on unsteady theory of excitation of resonators and inhomogeneous traveling wave accelerating structures. To calculate eigen-fields and the characteristics of the buncher and the TW section, we use the SUPERFISH codes. The thermionic electron gun is designed by the well-known EGUN codes.

OPTIMIZATION OF THE BUNCHER

First of all, we must to obtain beam parameters close to optimal at the buncher exit. Feature of the buncher based on evanescent oscillations is that the longitudinal electric field exponentially increases along an axis that provides effective bunching of an initially continuous electron beam and its acceleration to relativistic velocities at the enough short length of the buncher comparable to wavelength in free space. The operating frequency of the CEO buncher is 2797 MHz. An electron source is the 25 keV thermionic electron gun which generates a current pulse with linear rise and fall time of 20 ns and the 80 ns duration of flat top. The beam current at the flat top equals to 1.1 A. By matching both a beam time delay with respect to a pulse of RF power and level of the RF power we try to reach both the minimal energy spread within the beam pulse and the minimal phase volume of a bunch. The calculated beam parameters at the buncher exit are represented in Table 1.

Table 1: The Buncher Beam Parameters

Input RF Power	1.8 MW
Beam delay	504 ns
Beam current at the flat top	0.7 A
Average energy	1.13 MeV
Energy spread (70% of particles)	4.3 %
Bunch phase length (70% of particles)	16.9 degree
RMS normalized emittance	31 π·mm×mrad
RMS beam size	2 mm

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The time dependence of the beam average energy is shown in Fig.2. As it can see from this figure, the energy spread due to transient beam loading is not more than 2%, whereas the energy spread within a bunch amounts to 4.2%. The bunch energy-phase picture is imaged in Fig.3.

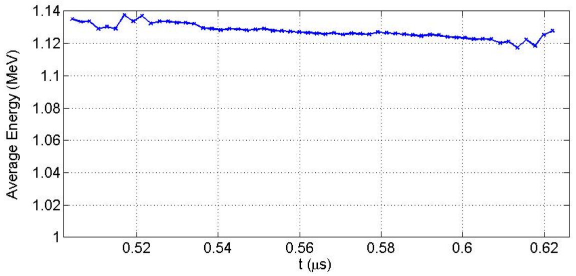

Figure 2: Beam average energy v.s. time.

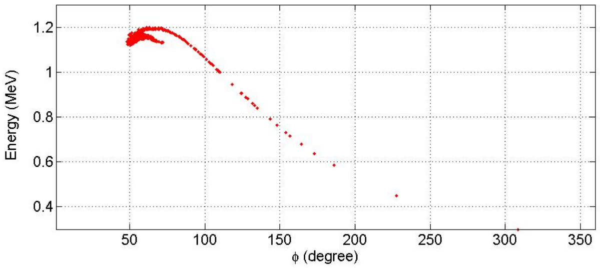

Figure 3: An energy-phase map of a bunch.

OPTIMIZATION OF THE SECTION

For compensating transient beam loading in the TW section we utilize the combination of two variants of the ΔT schemes described in [3]. According to this technique a beam is switched on before when a RF wave-front crosses the end cell of the accelerating structure, but is switched off at being crossed. The chosen ΔT scheme provides the maximum energy gain, but is sensitive to dispersive effects. So that in order to exclude the contribution of the wave-front phase modulation, due to the dispersion, to the energy spread we consider a TW constant impedance structure with π/2 phase advance per a cell. The basic parameters of the RF structure are given in Table 2.

Table 2: TW Section Parameters

Operating frequency	2797 MHz
Shunt impedance	47.7 MΩ/m
Group velocity	0.04*c*
Attenuation factor	0.27
Filling time	362 ns
Length	4.4 m

The optimization of beam dynamics parameters is carried out in two stages.

The First Sage of Optimisation

At first using the analytical ratios derived for the ultra-relativistic point bunch approximation in [3], we can to estimate the combination of optimum values of such parameters as average energy gain, a beam current, an RF power by choosing the beam time delay with respect to an RF waveform. We suppose that the accelerating structure is supplied by the RF power of 20 MW with the 180 ns rise time. In the issue the average energy gain of the beam as function of time has the form shown in Fig.4. This temporal energy gain distribution provides the multi-bunch RMS energy spread of about 0.6%. The energy gain plotted in Fig. 4, unlike the similar dependence obtained in [3] with the zero duration of rise and fall of a current pulse, has the "mustache" of low energy (leading bunches) and high energy (trailing ones), due to taking into account the finite time (20 ns) of rise and fall of the simulated current pulse.

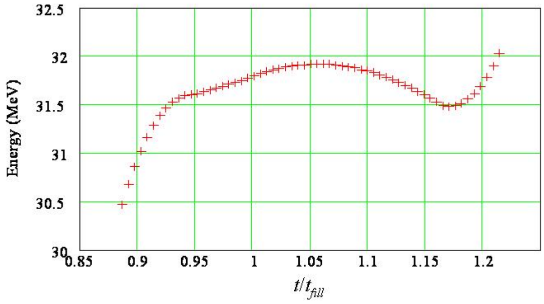

Figure 4: A loaded accelerating energy gain as a function of time with beam compensation.

The Second Sage of Optimisation

At the second stage we refine on the acceleration characteristics estimated above by the numerical simulation of transient self-consistent beam dynamics. This simulation takes into account the following effects: 1) sliding of bunches with respect to the phase of an accelerating wave in the head of the section; 2) the finite energy and phase spreads of the bunches; 3) temporal dependences of average phase and energy of the bunches injected in the section; 4) transverse beam dynamics; 5) space-charge fields.

At the beginning, the optimal wave phase with respect to bunches is established by phasing the input RF field at the given beam delay preliminary obtained in the first stage. The results of the phasing are demonstrated in Fig.5. Here the dependences of the energy spread for 70% of beam particles and the FWHM of the energy spectrum are shown as functions of the phase of an input RF field. For the phase at which the minimum energy spread is attained we refine the beam injection time by matching it. The outcome of these simulations are illustrated in Fig.6. It can be seen from this figure that the best results, namely 2.9% of the energy spread for 70% of particles and 1% of the FWHM are obtained at the beam delay of about $0.87t_{fill}$. The others beam parameters for this optimal injection time can be seen in Table 3.

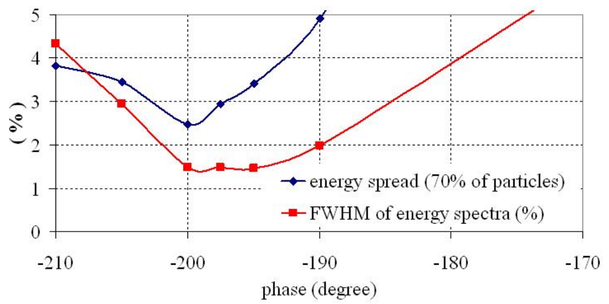

Figure 5: Energy spread versus phase of an input RF field.

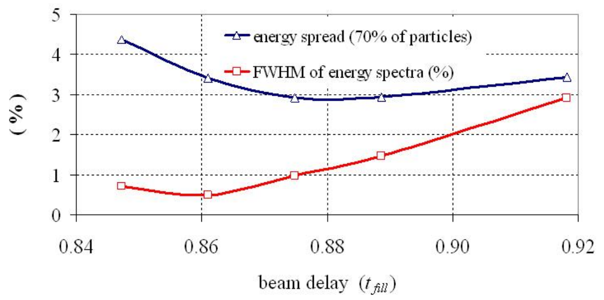

Figure 6: Energy spread versus beam delay relative to the filling time of the TW section.

Table 3: The Optimal Parameters of the Accelerated Beam

Beam delay	0.87 t_{fill}
Beam charge	67 nC
Beam current at the flat top	0.67 A
Average energy	31.0 MeV
Energy spread (70% of particles)	2.9 %
FWHM of energy spectrum	0.98 %
Bunch phase length (70% of particles)	13.0 degree
Beam size (70% of particles)	3.7 mm
RMS beam size	2 mm
RMS normalized emittance	25π·mm·mrad

It should be noted that the minimum energy spread reached by simulating, is 1.5÷ 2 times more than the expected value analytically calculated in the first stage optimization. To explain this result let us compare the temporally dependences of the average beam energy with the beam compensation which are represented in Fig. 4 and Fig.7. It is arguable that the analytical estimations (Fig. 4) good agree with the simulation result (Fig.7). Moreover the multi-bunch RMS energy spread resulted from the computer simulation is about 0.4% that is not more than the energy spread preliminary obtained from the analytical consideration. Thus the intro-bunch energy spread, due to finite bunch phase width, gives the considerable contribution to the total beam energy spread. Besides, comparing the dependences in Fig. 4 and Fig.7, a small beam-energy shortage can be observed in the case of the simulation. The cause of this energy shortage is the sliding of bunches with respect to the accelerating wave in the head of the accelerating section and the finite phase width of the bunches.

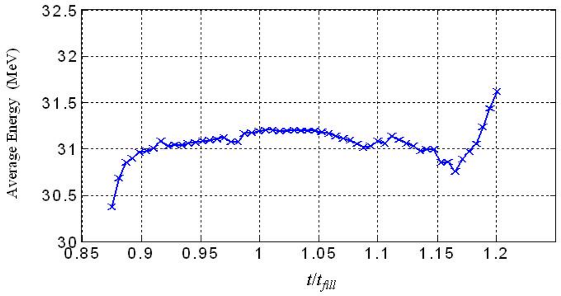

Figure 7: Average beam energy as a function of time with beam compensation.

SUMMARY

In this paper we have studied capability to attain the minimum possible beam-energy spread in the one section S-band RF linac loaded heavily by the beam of about 100 ns in macro-pulse length and a current about 0.7 Amps. We have shown that the utilization of the ΔT schemes of beam loading compensation for the TW constant impedance structure with π/2 phase advance per a cell provides the multi-bunch RMS energy spread less than 0.5%. However, the total energy spread, the sum of multi- and intro – bunch energy spread, is 1.5÷2 times more than this value due to the considerable contribution of the intro-bunch energy spread, which is caused by finite bunch phase width. Therefore the more effective phase compression bunches injected in the accelerating section is required to reduce the energy spread in the one section S-band RF linac.

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[3] A. Opanasenko, "Transient Beam Loading Compensation at RF Acceleration of Intense Short-Pulsed Electron Beams", IPAC'10, Kyoto, May 2010, TUPEA017, (2010); http://www.JACoW.org.