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# FUNDAMENTAL LIMITS OF BALLISITC BUNCHING OF HIGH-BRIGHTNESS ELECTRON BEAMS

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*Abstract*

The interest in superradiant THz sources based on coherent transition, synchrotron or undulator radiation grows continuously and such sources require high-quality electron bunches with low emittance, high charge and sub-picosecond (sub-ps) duration. Since accelerator-based THz sources are usually driven by relatively low energy electron bunches of a few tens of MeV, space-charge makes bunch compression to sub-ps level very challenging. In the present work we investigate the feasibility of ballistic bunching down to ps duration while preserving the transverse phase-space quality. We found that in order to compensate for the nonlinear dependency of the arrival time on the energy as well as bunch deformations induced by space-charge effects, one needs to apply a nonlinear energy chirp.

## INTRODUCTION

In view of the growing interest in THz radiation, the Swedish FEL Center and FREIA Laboratory are working on the conceptual design of a compact user-oriented THz/X-ray source for multidisciplinary research. Such a source composed of an undulator based THz source and an X-ray source requires high-brightness short electron bunches. The THz source is planned to be operated not only as an FEL oscillator but also in the SASE mode. Ultra-short THz pulses (super-radiant source) will be generated in a bending magnet. A compact X-ray source may be accomplished using inverse Compton scattering. The requirements on the electron beam quality for different modes of operation of the THz/X-ray source are summarized in Tab.1. These stringent requirements make the design of a linear accelerator-driver (linac-driver) and, in particular, of an electron source very challenging.

Table 1: Main Beam Parameters

| Beam | Oscillator + Compton | SASE+ Compton | Super-radiant + Compton |
|---|---|---|---|
| energy, MeV | 15 | 15 | 15 |
| rms energy spread, % | 0.5 | 1 | 1 |
| charge, pC | 250 | 250 | 100 |
| rms duration, ps | 5 | 1 | 0.1 |
| rms emittance, μm | 2 | 2 | 2 |

One of the possible solutions for the electron source is a superconducting continuous wave (CW) RF gun with a photo-cathode. But such a gun, which can directly generate electron bunches of a few ps and ultra-low emittance, involves a quite complicated technology for a small university facility. Another possible solution is to use a low-frequency thermionic CW RF gun with a pulsed gate electrode proposed at ANL [1]. The drawback is very long electron bunches of around 1 ns duration. Therefore, in this paper we study the feasibility of compression of ns electron bunches down to a few ps duration by means of ballistic bunching while preserving the transverse phase-space quality.

## RF LINAC LAYOUT

A working layout of an RF linac-driver is schematically shown in Fig. 1 [2]. This configuration is motivated by the fact that it allows the realization of the ballistic bunching, the velocity bunching in RF fields [3] and the magnetic bunch compression. The thermionic RF gun, which is similar to that proposed in Ref. [1], makes use of a normal conducting 117.4 MHz resonant cavity with a pulsed gate electrode. The beam dynamics in the RF gun was simulated using the codes CST Studio, EGUN, SUPERFISH and PARMELA. The gate electrode has a single on-axis, circular opening that allows the electron beam to be injected into the gun cavity on the flattop of 1 ns, 17.85 kV pulse generated by a fast high-voltage (HV) pulser. The HV pulse induces an electric field of 10 MV/m in the gap between the cathode and the gate electrode. The thermionic $CeB_6$ cathode at a temperature of 1773 K gives an emission current density of 20.5 $A/cm^2$ resulting in a beam current of 0.65 A. In order to mitigate the effect of wakefields of the circular opening the beam is injected through, we shaped the cathode, which resulted in a reduction of the slice rms normalized beam emittance at the exit of the RF gun from 2 mm·mrad to 0.4 mm·mrad. In order to reach the minimum of the phase-correlated energy spread and transverse emittance, the bunch is accelerated on-crest. The accelerating gradient of 20.25 MV/m results in the beam energy of 0.448 MeV.

The phase-dependent transverse emittance and energy spread induced in the RF gun cavity can be compensated by means of the energy monochromator cavity operating at the third harmonic, 352.2 MHz. This allows to generate 1 ns bunches with a charge up to 0.65 nC and an average energy of 397 keV with the width of uncorrelated energy

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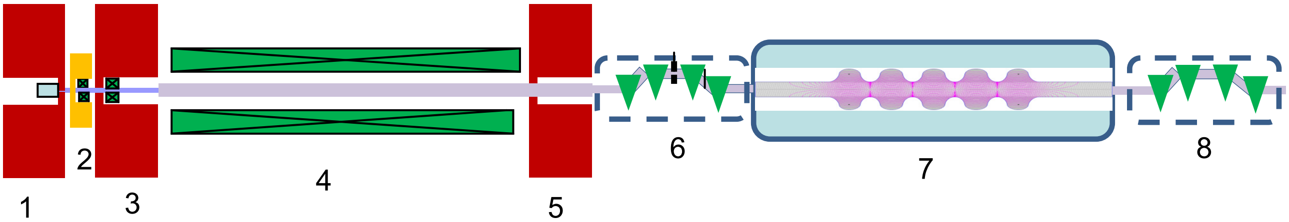


Figure 1: General layout of the RF linac. 1: 117.4 MHz RF gun with gate electrode and thermionic cathode; 2: 352.2 MHz energy monochromator; 3: 117.4-MHz buncher; 4: focusing solenoid in drift space; 5: 117.4 MHz booster; 6: chicane-based chopper; 7: 704.4 MHz accelerating SC RF cavity; 8: chicane-based bunch compressor.

spread no more than 0.5 keV and an rms normalized emittance of 0.9 mm·mrad.

The 117.4 MHz bunching cavity introduces an energy chirp along bunches. The cavities are followed by a drift space for ballistic bunching. After the ballistic bunching, a normal-conducting booster cavity increases the bunch energy to 1 MeV with subsequent energy filtering in a chicane-based chopper that reduces the energy spread to the level tolerable by the photon source. Bunches are accelerated afterwards in a SC 704 MHz 5-cell elliptical cavity up to 15 MeV. The beam undergoes final compression in a chicane.

## BALLISTIC BUNCHING

In our design shown in Fig. 1, the first stage of compression is realized via the ballistic bunching. To this end, we introduce a velocity modulation along the bunch in the 117.4 MHz buncher so that the bunch head is made slower that its tail and the bunch shrinks as it propagates. For the sake of good beam transport in the drift region, we designed a focusing system consisting of a series of 11 short solenoids. In order to substantially reduce the transverse emittance, the emittance compensation method was applied, according to which each bunch slice must be as close as possible to a laminar Brillouin flow [4]. The resulting beam emittance is less than 2 mm·mrad. Meanwhile, an rms normalized emittance of 10 mm·mrad can be quite easily achieved.

Since in the linearized limit the longitudinal position of the maximum compression for ballistic bunching is inversely proportional to the relative energy modulation amplitude $\Delta\gamma_0/\gamma_0$, we chose $\Delta\gamma_0/\gamma_0 \approx 0.2$. Then, for our bunch parameters, the maximum bunching takes place at a distance of 3.3 m from the cathode. However, the nonlinear effects related to a large energy modulation plays a role and the resulting bunch shape is far from ideal. In order to clearly show this nonlinear bunch deformation, in Fig. 2 we present the longitudinal phase-space after the buncher and at the position of maximum bunching without taking into account space-charge effects. One can see that the compression rate is only one order of magnitude because of the arising "moustache", which results from the nonlinear dependence of the electrons arrival time $t_e$ into position $z$ of the drift space on their velocity $\upsilon$

$$t_e(z,t_0) = t_0 + \frac{z}{\upsilon(t_0)}. \quad (1)$$

Here, $t_0$ is the injection time of electrons into the buncher. One can show that at the position of maximum bunching, the arrival phase of electrons in the coasting coordinate systems reads

$$\varphi_e(\varphi_0) = \frac{3}{2\beta_0^2}\frac{\Delta\gamma_0}{\gamma_0}\sin^2\varphi_0, \quad (2)$$

where $\varphi_e = \omega t_e$, $\varphi_0 = \omega t_0$, $\beta_0 = \upsilon_0/c$ is the bunch velocity normalized to the speed of light $c$.

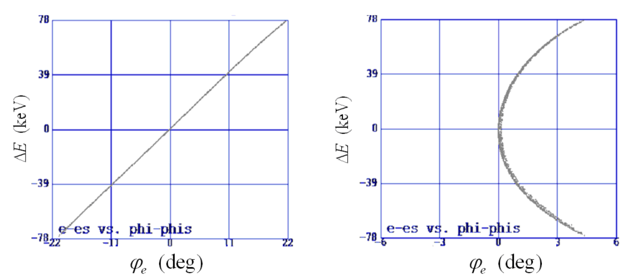


Figure 2: The longitudinal phase-space after the buncher (left plot) and at the position of the maximum ballistic bunching (right plot).

### *Optimum Ballistic Bunching*

The shown weak compression with a strong nonlinear deformation of the bunch raises a question of a maximum possible compression by means of ballistic bunching. There are three main factors that restrict one from achieving a high compression rate, namely, space-charge forces, energy spread and non-linearity of the arrival time of electrons. We will focus on the latter since it is crucial even for low charge quasi-monoenergetic bunches.

In order to obtain the initial velocity profile $\upsilon(t_0)$ that will give us the ideal bunching at some distance $L$ (the "moustache" in Fig. 2 would be leveled to a straight vertical line), let us find the derivative of the arrival time with respect the initial time $t_0$ and set it to zero at $z=L$, *i.e.*

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$$\left.\frac{dt_e}{dt_0}\right|_{z=L} \equiv 1-\frac{L}{\upsilon^2(t_0)}\frac{d\upsilon(t_0)}{dt_0}=0\,. \qquad (3)$$

A solution to Eq. (3) is the hyperbolic function of the electron velocity on the injection time

$$\upsilon(t_0)=\frac{\upsilon_0}{1-\upsilon_0 t_0/L}\,. \qquad (4)$$

In practice, this special initial velocity profile can be realized by using harmonics in the buncher cavity. However, the number of harmonics required to achieve an ideal hyperbolic velocity profile is more than a dozen. At the same time, by applying only the fundamental and third harmonic one can substantially improve the bunching. The results of PARMELA simulations of the longitudinal phase-space for a 100 pC electron bunch at the exit of the RF buncher and at the position of the maximum compression are shown in Fig. 3. More than half of electrons are compressed down to around 5 ps that corresponds to a compression rate of around 200. Other beam parameters such as the phase spectrum, transverse distribution, longitudinal phase-space and energy spectrum are shown in Fig. 4 from left to right. All space dimensions and particle coordinates are in cm, the electrons energy is in keV with respect to 372 keV, which is the energy of the reference particle.

### *Limits of Ballistic Bunching*

Naturally, there is always a random initial velocity spread that limits the bunch duration. In order to account for this effect, it is convenient to imagine the bunch as a set of ensembles, each of which has the same velocity fluctuation. Then, we can apply the results of the previous subsection to each such ensemble and we will find that all ensembles form almost identical longitudinal phase-space distributions but the distributions slip with respect to each other because of the different mean energies, which are dependant on a specific velocity fluctuation attributed to that ensemble. In other words, we can say that the energy spread results in spreading of the centres of the considered ensembles having the same magnitude of velocity fluctuation. Let $\sigma_{\gamma 0}$ be the rms energy spread in units of the rest mass, then the minimum bunch duration at distance $L$ reads as

$$\sigma_t=\sqrt{2}\,\frac{L}{c}\frac{\sigma_{\gamma_0}}{\langle\beta_0\rangle^3\langle\gamma_0\rangle^3}\,, \qquad (5)$$

where the brackets $\langle\ldots\rangle$ mean averaging over the bunch electrons. The effect of the energy spread is negligible for $\sigma_{\gamma 0}$ less than 100 eV.

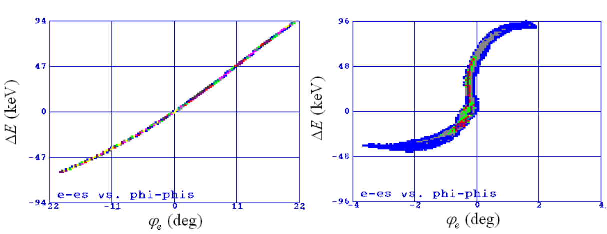

Figure 3: Phase-energy distributions simulated with PARMELA. The left plot shows the initial quasi-hyperbolic energy chirp along the bunch and the right one is calculated at the position of the maximum compression.

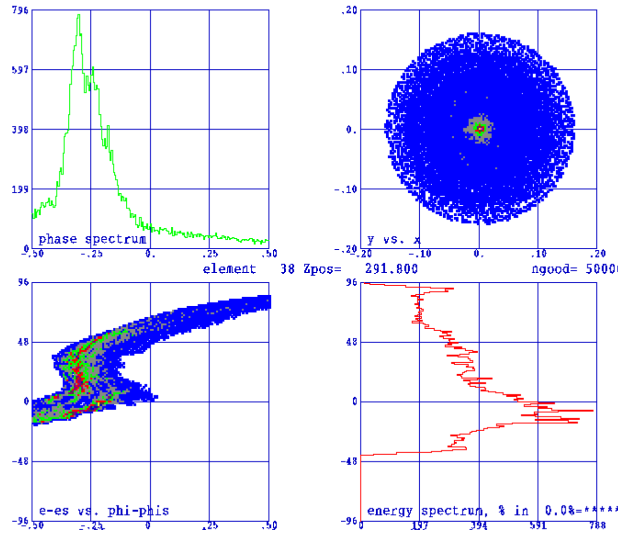

Figure 4: Beam parameters after ballistic bunching.

## CONCLUSION

We found that in order to compensate the non-linear dependence of the electrons transit time on their position in a bunch, one should use the hyperbolic profile of velocity modulation. Even by using only the fundamental and the third harmonics, one can substantially improve the bunching. The preliminary calculation shows that the ballistic bunching in conjunction with the emittance compensation method allows compressing a 1 ns, 0.63 nC bunch down to 6 ps FWHM with the 1.9 mm·mrad normalized rms emittance.

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