A COMBINED THz/X-RAY SOURCE BASED ON BRAKE-APPLIED VELOCITY BUNCHING AND MAGNETIC COMPRESSION *

Ruixuan Huang, Biaobin Li, Zhigang He†, Qika Jia, Weiwei Li, Lin Wang, Shancai Zhang
NSRL, University of Science and Technology of China, Hefei, Anhui, 230029, China

Abstract

Ultrashort electron beam can be realized by the process of velocity bunching and magnetic compression. Velocity bunching technique is able to compress the bunch at relatively low energy, which presents peculiar challenges when approaching a very high current and a low transverse emittance in photoinjectors. A brake-applied velocity bunching scheme was proposed, so that the transverse emittance of the beam could be almost compensated even if the compression factor was extremely high. By adding a magnetic compressor, one could obtain a shorter beam and achieve the coherent synchrotron radiation in THz range. Meanwhile, when making the final compressed beam collide with the laser, one could acquire high energy X-ray pulses. This opens the possibility for some interesting combinations of pump-and-probe experiments.

INTRODUCTION

A high brightness electron beam, which means a low transverse emittance and a high current with a sub-picosecond pulse length, has lots of applications in the accelerator community. The short wavelength free electron lasers [1], the inverse Compton scattering (ICS) sources for short X-ray pulses [2, 3], the plasma-based accelerators [4], the generation of coherent THz radiation [5] are in great demand for the high brightness beams.

On the one hand, short bunches could be achieved by the magnetic compression, which is usually applied at a relatively high energy [6]. On the other hand, a method termed velocity bunching is able to compress the beam at a relatively low energy in photoinjectors [7,8], which must be integrated into an emittance compensation process. It presents peculiar challenges when applied to obtain a beam with a very high current and a low transverse emittance. A scheme named "brake-applied" velocity bunching (BAVB) was proposed [9] and demonstrated by ASTRA [10] simulation. We will review the principle of BAVB and show the optimization result of a photoinjector.

In the BAVB process, an electron bunch is injected into the accelerator with a low gradient at a deceleration phase, like "a brake is applied", then it slips back to an acceleration phase since the velocity of the injected beam is slightly slower than the phase velocity of the rf wave. The principle of the scheme is schematically shown in Fig. 1. The 90° and 0° are defined as the crest and zero crossing of the electric field, respectively. The bunch is compressed during the slippage, and its time-energy correlation is maintained relatively linear.

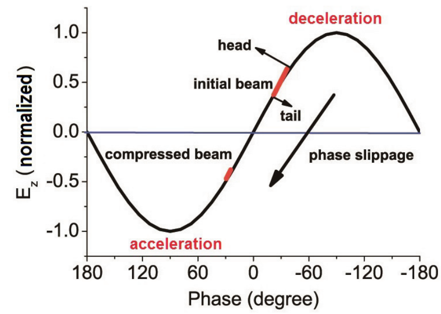

Figure 1: Principle of brake-applied velocity bunching.

To get the maximum compression factor, a reasonable deceleration phase is in demand due to the large phase slippage. Meanwhile, a linac with a low gradient should be applied to introduce a relatively linear energy chirp in the beam. We expect that, the velocity bunching behaves in the strong compression regime with a symmetric temporal beam distribution preserved. With a symmetric bunch compression, the transverse emittance could be compensated even if the compression factor is extremely high.

Based on the improved velocity bunching procedure, an ultrashort electron bunch with high charge and low emittance could be obtained. The coherent THz radiation can be produced by synchrotron radiation. Meanwhile, high energy X-ray pulse can be acquired by collision between laser and electron bunch. With a magnetic chicane, the electron beam would be further compressed, which could extend the THz radiation towards higher frequencies and shorten the X-ray pulse. This opens the possibility for some interesting combinations of pump-and-probe experiments.

TYPICAL RESULTS OF BAVB

To prove the effectiveness of BAVB, a photoinjector based on a 1.6 cell S-band rf gun operating at 80 MV/m peak field at the cathode is modeled. Three travelling wave linacs are applied, where one of the linacs is used as compressor while the other two are tuned for maximum output energy. Several solenoids wrapped around the first two linacs are designed to provide the ultimate compensation of the transverse beam emittance.

Various key aspects of BAVB setup have been studied and simulated in detail elsewhere [9], and the global optimization was carried out by a multi-objective genetic algorithm [11]. For a typical optimized result, the simulation showed that the beam was injected to the compressor at -15° phase and

* Work supported by Chinese Universities Scientific Fund under Contracts WK2310000063 and WK2310000047.
† hezhg@ustc.edu.cn

had a temporary energy decrease of 19.5% at the beginning of velocity bunching. The comparison between the uncompressed and compressed beams using ASTRA code is given in Fig. 2. The peak current increases from about 80 A to 1830 A for the charge of 800 pC, and the rms bunch length decreases from 1.05 mm to 0.056 mm (~200 fs). The projected emittance is 2.382 μm for the umcompressed beam, and 2.438 μm for the compressed one.

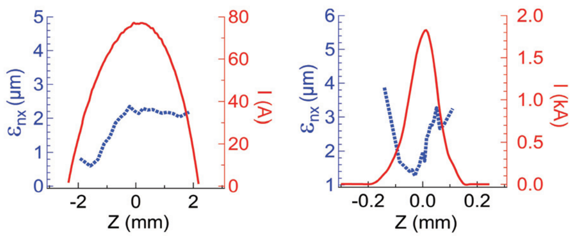

Figure 2: Slice emittance (blue) and current (red) profiles for the uncompressed (left) and compressed (right) beams.

A compression factor of 19 with an effective emittance compensation has been demonstrated. By investigating the longitudinal phase spaces, one can find that the electron beam has a linear dominated energy chirp during the entire bunching process, which guarantees a symmetric bunch compression and possible emittance compensation.

HIGH BRIGHTNESS BEAM FOR THZ/X-RAY SOURCES

Pump-probe Sources Design

Previously, it was testified that a high brightness beam could be generated by the brake-applied velocity bunching. The high quality beam allows to develop several radiation sources and serve different users stations. The coherent THz radiation could be obtained by synchrotron radiation from bending magnets [12]. And an X-ray source could be realized via ICS.

This work is under consideration and we briefly mention the main idea illustrated in Fig. 3. A high brightness electron beam is compressed in BAVB down to a few hundred fs, then accelerated to 110 MeV by two linacs. A magnetic chicane is added to further compress the beam, and produces the broadband THz pulse in the dipoles. Downstream the compressor, the electron beam is collided with the drive laser pulse, consequently the X-ray pulse is generated.

Generation of Radiation by BAVB Beam

The power spectrum of the radiation from a bunch with N particles is given by [13]:

$$\frac{dP_{\text{total}}}{d\omega} = \frac{dP_0}{d\omega} N[1 + (N-1)g(\omega)], \tag{1}$$

where $dP_0/d\omega$ is the single particle power spectrum. The first term represents the incoherent radiation, while the second term represents the coherent enhancement which is proportional to N^2. g is the bunching factor describing the Fourier transform of the normalized longitudinal distribution in the bunch, which is

$$g(\omega) = \left| \int_{-\infty}^{\infty} e^{i\omega \mathbf{n}\cdot z/c} S(z) dz \right|^2, \tag{2}$$

where $S(z)$ is the distribution function in the bunch. To extend the radiation spectrum towards higher frequencies, the bunch must be shortened.

In principle, THz radiation could be extracted immediately before the magnetic compressor. The bunching factor

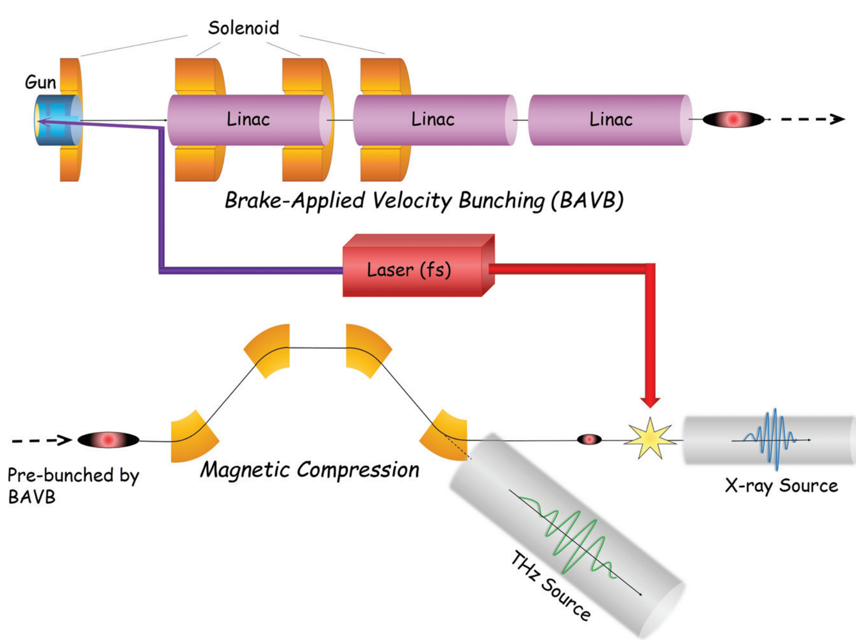

Figure 3: Design of THz/X-ray sources for pump-probe experiments.

ISBN 978-3-95450-182-3

of the BAVB compressed beam is shown in Fig. 4. The considerable radiation covers the region of 0 to 2 THz.

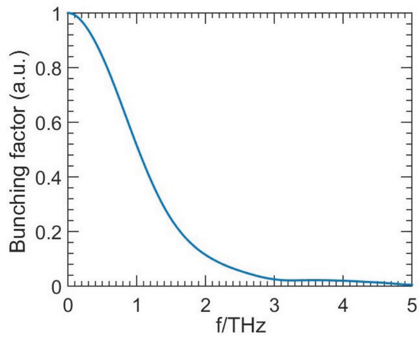

Figure 4: The beam bunching factor after BAVB.

A sketch map of the chicane is shown in Fig. 3. It is confirmed by simulation that the energy chirp from BAVB is negative due to the space charge effect, indicating the head particle has higher energy. To compress such a bunch, a chicane with a positive R_{56} must be used. Between the dipoles, we set several quadruples (which are not displayed in the layout) to flip the particle trajectory so that higher energy particle has a longer path length than the lower's. After magnetic compression, the electron beam would be further compressed by about 3 times with a peak current over 8 kA. The ultimate compressed beam has the distribution of bunching factor of Fig. 5. The considerable radiation covers the whole THz region. Because of the short electron bunch and high bunch charge, the THz radiation has a high pulse energy and high peak current with a broadband in frequency spectrum.

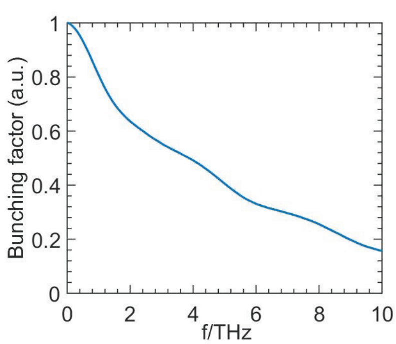

Figure 5: The beam bunching factor after chicane.

In ICS, the scattered photon energy E_x is given by [14]:

$$E_x = \frac{E_p\left(1-\beta\cos\theta_1\right)}{\left(1-\beta\cos\theta_2\right)+E_p\left(1-\cos\left(\theta_2-\theta_1\right)\right)/E_e}, \quad (3)$$

where E_p is the energy of the drive laser photon, E_e is the electron energy, β is the ratio of the electron speed to the speed of light c, θ_1 is the collision angle, and θ_2 is the scattering angle.

The scattered photon energy depends on the collision angle, the drive laser energy, and the energy of the electron beam, which gives several options for creating a broadly tunable light source. If a head-on collision is considered, the scattered photon has a maximal energy of $E_x = 4\gamma^2 E_p$, where γ is the relativistic factor. For example, an IR laser with a wavelength of 1 μm head-on collides with a 110-MeV electron beam. It produces a 0.05 (or 232-keV) X-ray with a pulse duration of ~100 fs. Theoretically, a continuously tunable X-ray source could be realized by adjusting the collision angle or the electron energy. Since an electron beam with a moderate energy allows having high energy X-rays, the facility is more compact and costs less money than the free electron lasers.

It is notable that both the coherent THz radiation and the X-ray pulse have the femtosecond time scale and are produced via the same drive laser, as Fig. 3 shows. One can expect a good synchronization between the two light sources. The ultra-short X-ray pulse can be used as a probe while the THz radiation as a pump for low-energy excitations in matter such as phase transition, molecular rotations and spin waves etc. The proposed THz/X-ray source would allow several possible modes of pump-probe experiments.

SUMMARY

The brake-applied velocity bunching scheme was proposed and proved in simulation. With proper design and optimization, the transverse emittance of the beam could be almost compensated even if the compression factor was extremely high. A combined THz/X-ray source was proposed based on the high brightness electron beam. The broad-band THz radiation and high energy X-ray pulse both in femtosecond time scale could be obtained synchronously. It will open the possibility for some interesting combinations of pump-and-probe experiments.

REFERENCES

[1] H. Tanaka *et al.*, Nature photonics **6**, 540, 2012.

[2] P. Sprangle *et al.*, Journal of applied physics **72**, 5032, 1992.

[3] S. Chen *et al.*, Phys. Rev. Lett. **110**, 155003, 2013.

[4] R. Pompili *et al.*, NIM-A **829**, 1, 2016.

[5] A. M. Cook *et al.*, Phys. Rev. Lett. **103**, 095003, 2009.

[6] R. Akre *et al.*, PRST-AB **11**, 030703, 2008.

[7] L. Serafini and M. Ferrario, AIP Conf. Proc. 581, 87, 2001.

[8] M. Ferrario *et al.*, Phys. Rev. Lett. **104**, 054801, 2010.

[9] R. Huang *et al.*, submitted to NIM-A.

[10] K. Flottman, ASTRA: A space charge tracking algorithm, `http://www.desy.de/~mpyflo/`

[11] K. Deb *et al.*, IEEE Trans. Evol. 435 Comput. 6, 182, 2002.

[12] F. C. Michel *et al.*, Phys. Rev. Lett. **48**, 580, 1982.

[13] C. Hirschmugl *et al.*, Phys. Rev. A **44**, 1316, 1991.

[14] Workshop on Compact Light Sources, 11-12 May 2010, Rockville, USA.

ISBN 978-3-95450-182-3