ULTRA-SHORT X-RAY PULSES GENERATION BY ELECTRON BEAM SLICING IN STORAGE RINGS*

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Abstract

We propose a new method to generate ultra-short x-ray pulses using focused short low energy (5-10MeV) electron bunches to create a short from the circulating electron bunches in a synchrotron radiation storage ring. When the low energy electron bunch crosses from top the high energy electron bunch, its coulomb force will kick a short slice from the core of the storage ring electron bunch. The separated slice, when passing through an undulator, will radiate ultra-short x-ray pulses at about 150 fs. We discuss the advantages and challenges and provide data which suggest the feasibility of this new method.

BASIC PRINCIPLES AND PARAMETERS

The community interested in science using sub-picsecond x-ray pulses is growing rapidly. Laser slicing is one of the approaches to generate ultra-short x-ray pulses [1-6]. Typically, the x-ray pulses are of order of 100 fs with repetition rate of order of 1 kHz and the number of photons per 0.1% bandwidth per pulse is of order of 1000. To generate ultra-short x-ray pulses with many orders of magnitude higher repetition rate, another method is proposed by Zholents [7] using a crab cavity which provides pulse lengths of order of a pic-second. It provides a continuous stream of x-ray pulses [8] with a much higher average flux.. A new source of ultra-short x-ray pulses is

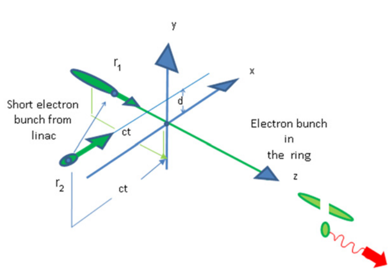

Figure 1: Illustration of electron beam slicing.

x-ray free electron laser, with the pulse energy many order of magnitudes higher than storage ring and pulse width of 100 fs or less [9]. However, compared with the storage ring sources, the intensity and wavelength fluctuation from a SASE FEL is large, and, the repetition rate is low. For example, the repetition rate of LCLS SASE FEL is 100 Hz. Hence, even though the single pulse energy is much lower than SASE FEL pulse, the high repetition rate and high pulse to pulse stability of storage ring sources continue to attract wide range of user interests.

In this paper we propose a different approach to generate ultra-short x-ray pulses of order of 100 fs pulse length by electron beam slicing. As shown in figure 1, when a short electron bunch from a low energy linac (for example, 5MeV, 50pC, 150fs) passes above a storage ring bunch (30 ps) at a right angle, it kicks a slice (200fs) of electron bunch vertically. The radiation from the short slice is separated from the core bunch. We find the following advantages of this method when it is compared with other schemes respectively:

1. When compared with crab cavity method, it needs much smaller space in storage ring for interaction point, and its pulse length (150fs) is much shorter.
2. When compared with laser slicing method, the flux per pulse may be increased significantly, by a factor of from 6 to 10, and the repetition rate can be much higher while the pulse length is comparable.
3. When compared with LCLS SASE x-ray free electron laser, its repetition rate can be 10^3~10^4 of orders of magnitude higher, and it is much more stable, even though the single shot pulse energy is many orders of magnitude lower.

Thus we expect the new method may provide a complimentary approach to other ultra-short x-ray pulse sources.

We explored the new method by calculating the angular kick received by a high energy electron which is generated by a point charge in the low energy linac electron bunch and integrated over the 3-D electron distribution of the low energy bunch. The result gives the angular kick as a function of the 3-D position of an electron in the storage ring bunch:

$$\theta = \frac{eq_2 Z_0 c}{2\pi E_1}\frac{\gamma_2}{\sqrt{\gamma_2^2+1}}\frac{1}{\sqrt{2}\sigma_y} f(\rho,\bar{u}_1,\bar{y}_1),$$

where f gives the profile as function of the position of the high energy electron:

$$f(\rho,\bar{u}_1,\bar{y}_1) = \int_0^\infty \mathrm{Re}[w(\bar{u}_1+\bar{y}_1)][e^{-(\rho y-\bar{y}_1)^2} - e^{-(\rho y+\bar{y}_1)^2}]dy$$

with

$$\rho = \sqrt{\frac{\gamma_2^2}{\gamma_2^2+1}\frac{\sigma_x^2+\sigma_z^2}{\sigma_y^2}},\quad \bar{y}_1 = \frac{d-y_1}{\sqrt{2}\sigma_y},\ \bar{u}_1 = \frac{x_1+z_1}{\sqrt{2(\sigma_x^2+\sigma_z^2)}}.$$

E_1 the energy of the high energy beam in MeV, while d is the vertical distance between the centres of the low energy beam and the high energy beam. x_1, y_1, z_1 are the coordinates of the high energy electron, σ_x, σ_y, σ_z are the RMS beam size of the low energy bunch. q_2 is the charge of low energy bunch, γ_2 is its dimensionless energy, Z_0=377Ω is the vacuum impedance. w is the error function: $w(u) = e^{-u^2}erfc(-i\,u)$. This result gives a profile of the slice of the high energy bunch, and is used to determine the pulse width of the slice. At a position in the ring where β_y=25m, the RMS beam divergence is 0.6 μrad. To separate from the core we need the angular kick more than 5 times larger, i.e. 3 μrad. Assuming a charge of 50 pC, we find that if the low energy bunch beam size is focused to 35 μm and a bunch length compressed to 100 fs, then the above formula gives that the optimized position for the angular kick is at d=50 μm vertical distance from the core of the storage ring bunch. Under this condition, the factor before the function f is 6 μrad and the peak value of f is 0.54. Thus the maximum kick is 3.2 μrad, the FWHM of the kicked slice is 300 fs. To minimize cost, the linac beam energy should be as low as possible. We investigated slicing with a 5 MeV beam, directly from a photocathode RF gun. For 5MeV the final focus is in the space charge dominated regime which represents a challenge for the design of an electron gun and magnetic chicane system for the compression. While our result shows that we achieve our goal quite closely, an increase of the energy and the charge of the low energy electron bunch would further reduce the length of the x-ray pulses and increase the angular kick. This analysis provides a reference for the future design of an electron beam slicing system.

BUNCH COMPRESSOR SIMULATION

We carried out a simulation study to design a system consisting of only a BNL photo-cathode RF-gun, and a compressor chicane with a matching section. We assume the field gradient is 100MV/m at the cathode and we fix the laser spot size at a radius of 2mm. The simulation code used is PARMELA. We carried out a multi-objective optimization procedure using the genetic algorithm [10], allowing the laser pulse length, the laser phase relative to the RF phase, the field strengths of quads and dipole in the chicane to vary with the two target functions set as the sum of transverse RMS beam sizes, and the bunch length respectively. At 5MeV with 50pC charge and a 5 m compressor chicane, the optimization leads to 166 fs RMS bunch length at the focal point with 28 μm, and 31 μm for horizontal and vertical RMS beam size respectively. A more detailed description is to be found in ref [11]. Using the formula for the angular kick, we can estimate the profile of the slice generated. The optimized vertical distance from the high energy core bunch is 40 μm. The centre of the slice is deflected by 3.3 μrad, i.e., slightly larger than 5 times the RMS divergence of the high energy beam with β_y=25m. If the vertical betatron phase advance is near 180 degree, and if β_y=1m at the radiator, then the deflection would be about 16 μrad in the radiator. The FWHM of the deflection function is 370 fs, this gives an estimate for the FWHM of the slice pulse length.

In an 20mm period in-vacuum-undulator of NSLSII as the radiator, the photon flux for 8keV x-rays is S=10^{15} photons/sec/0.1%BW for a beam current 500mA. With about 1000 bunches, bunch current is 0.5mA. As an estimate, for a slice of 0.3 ps out the 30 ps core bunch length (for NSLSII, RMS bunch length is 15ps) the slice fraction is 0.3ps/30ps=1%. Since revolution time is about 2.6 μs, the single pulse photon flux is 10^{15}×0.3ps/30ps ×2.6 μs/1000 = 2.6 ×10^4 photons/sec/0.1%BW. For camshaft current of 3mA, the flux is 16 ×10^4 photons/sec/0.1%BW.

The emittance increase sets the limitation on the repetition rate. For a single bunch, the emittance increase due to angular kicks is equal to the emittance increase rate times the damping time. One angular kick of 5 σ_θ with a slice of 300 fs in a 30 ps bunch increases ε_y by 0.3ps/30ps ×5^2×1/2ε_y=12% ε_y. With a repetition rate of 100Hz for a single bunch, and damping time of 10ms, the emittance increase is 12% ε_y ×100Hz×10ms=12% ε_y. If we distribute the kicks uniformly over all 1000 bunches, the repetition rate would be 100 kHz. For 100 kHz repetition rate, the photon flux is 2.6 ×10^9 photons/sec/0.1%BW for the example above.

For most synchrotron light source users, the requirement on vertical emittance is not very stringent. Thus depending on the tolerance of the vertical emittance increase, the repetition rate limit can be 100kH to 1MHz on the expense of a slightly reduced separation for the same kick.

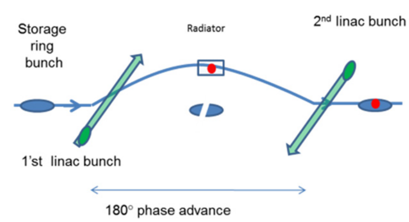

Figure 2: Two linacs bunches to form a local bump for the kicked electrons in storage ring.

If after a betatron phase advance of π or a multiple integer of π, another low energy electron bunch, synchronized with and identical to the first one but precisely time delayed and positioned, will kick the sliced electron bunch back into the separated core bunch, as shown in figure 2. This second low energy electron bunch allows the storage ring high energy electron bunch slice to pass through a local bump and recover its distribution after the radiation, thus minimizing the perturbation to the storage ring so that it is possible to increase the repetition rate significantly. If the time jitter is 10% of the pulse width, the repetition rate will increase to 1 -10MHz. These options present a number of challenges yet to be studied.

Table 1: Performance of Compressor

Case	Energy	Charge	Bunch length	Rms Beam Size (H)	Rms Beam Size (V)
	[MeV]	[pC]	[fs]	[μm]	[μm]
1	5	50	166	31	28
2	12	100	110	34	31
3	12	150	122	32	22

To further reduce the slice pulse length and to increase the kick angle for a better separation of the slice from the core, we used the simulation result for 5MeV as a basis to study 12 MeV cases by adding an accelerator section and gradually increasing the RF amplitude during the optimi-

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zation. The increase of beam energy allows the increase of charge while maintain the required small beam size and bunch length at the focal point. The result is given in Table 1.

A SPECIFIC EXAMPLE OF SLICE PROFILE

We use the case of 12MeV beam with 150 pC for the low energy bunch as an example to calculate the slice profile. The formula for angular kick gives the optimum vertical distance from the linac beam to the storage ring beam as 31 μm. Since the maximum angular kick is determined by these parameters already, to improve angular

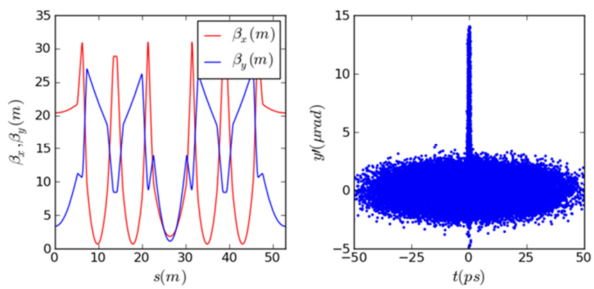

Figure 3: Left: NSLSII lattice. Right: phase space y', y

separation of the slice from the core, we should choose the crossing point in the storage ring with maximum β_y to minimize the core vertical divergence. In the meantime, since the longer crossing time increases the slice pulse length, we need to minimize β_x so horizontal beam size is small. This criterion led us to choose the slicing point at the position of either about 8.3m or 19.3m in left side of Figure 3. These two positions are both located next to the dipoles. They have vertical betatron phase advances from the radiator U20 at position 26m of about 125 and 88 degrees respectively. Use the parameters in Table 1, we can calculate the angular kick received by particles in the storage ring bunch after the crossing and plot the phase space distribution. In right side of Figure 3 we show the phase space for y' versus z. And in Figure 4, we show y' versus y at the crossing point at 8.3m, and y' versus y at the radiator at 26 m.

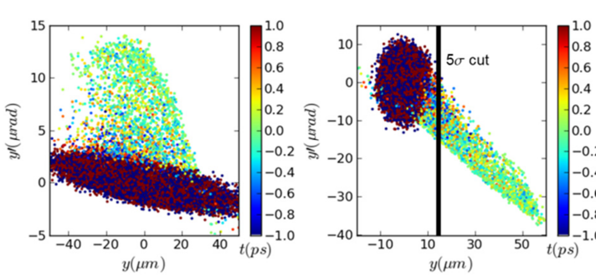

Figure 4: Phase space of y', y at crossing point and radiator respectively.

The right of Figure 3 shows a thin slice is kicked up right after the crossing, while left side of Figure 4 shows how the slice is separated from the core in y', y phase space. The right of Figure 4 shows the same phase space after a 125 degree phase advance at the radiator. The phase space rotation is such that the slice can be separated from the core both angularly and spatially. To understand the separation from the core, we draw a vertical line at about 15 μm from the core indicating the 5σ separation boundary and calculate the properties of the slice. We find in this case the centre of the slice is 37μm from the core, while the RMS size of the core size is 3.2 μm. Thus the spatial separation is more than 10 times the core size. In addition there is a mixture of angular separation of about 25 μrad to further improve the separation. We find the fraction of the slice separated is 1.7% in this case. The slice size is 11 μm, larger than the core size of 3.2 μm. The vertical emittance of the slice increases from 9.5pm of the core to 34 pm.

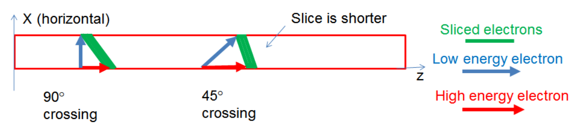

Figure 5: Illustration of angled crossing.

The RMS bunch length in this case is 270 fs, much larger than the linac bunch length of 122 fs. This is because the horizontal crossing time at the interaction point at 8.3 m in Figure 3. Since β_x=3.8m at this point, for horizontal emittance of 1 nm, the RMS beam size here is 61 μm corresponding to about 200 fs crossing time. It is possible to reduce the crossing time by reducing the crossing angle, for example from 90 degree to 45 degree between the forward direction of the linac beam and the storage ring beam. This is illustrated in Figure 5 showing at 45 degree the linac bunch has a velocity component parallel to the storage ring bunch making the slice shorter. The simulation shows the bunch length is reduced to 150fs at the expense of only a small reduction of spatial separation from 37 μm to 29 μm. A more detailed description of angled crossing will be given in a separate paper[12]. Thus we confirmed the feasibility of electron beam slicing approach.

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