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 slice 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 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

\[
\theta = \frac{qfZ_0c}{2\pi E_1}\gamma_2 \frac{1}{\sqrt{\gamma_2^2 + 1}} \sqrt{2\sigma_z} \mathcal{f}(\rho, \pi_1, \gamma_1),
\]

where \(\mathcal{f}\) gives the profile as function of the position of the high energy electron:

\[
\mathcal{f}(\rho, \pi_1, \gamma_1) = \int_0^\infty \text{Re}[w(\pi_1 + \gamma_1)][e^{-i(\rho_0 \gamma_1 \pi_1)} - e^{-i(\rho_0 \gamma_1 \pi_1)}]d\gamma_1
\]

with

\[
\rho = \sqrt{\gamma_2^2 + \sigma_\gamma^2}, \quad \pi_1 = \frac{d - v_1}{\sqrt{2}\sigma_\gamma}, \quad \gamma_1 = \frac{x_1 + z_1}{\sqrt{2(\sigma_x^2 + \sigma_z^2)}}.
\]

E1 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, \(\sigma_x, \sigma_y, \sigma_z\) are the RMS beam size of the low energy bunch. \(q_2\) is the charge of low energy bunch, \(\gamma_2\) is its dimensionless energy. Z0=377\(\Omega\) is the vacuum impedance. w is the error function: \(w(u) = e^{-u^2}erfc(-i \cdot u)\). 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 \( \beta_y = 25 \text{m} \), the RMS beam divergence is 0.6 \( \mu \text{rad} \). To separate from the core we need the angular kick more than 5 times larger, i.e. 3 \( \mu \text{rad} \). Assuming a charge of 50 pC, we find that if the low energy bunch beam size is focused to 35 \( \mu \text{m} \) and a bunch length compressed to 100 fs, then the above formula gives that the optimized position for the angular kick is at \( d = 50 \mu \text{m} \) vertical distance from the core of the storage ring bunch. Under this condition, the factor before the function \( f \) is 6 \( \mu \text{rad} \) and the peak value of \( f \) is 0.54. Thus the maximum kick is 3.2 \( \mu \text{rad} \), 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 5 MeV 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 100 MV/m at the cathode and we fix the laser spot size at a radius of 2 mm. 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 5 MeV with 50 pC charge and a 5 m compressor chicane, the optimization leads to 166 fs RMS bunch length at the focal point with 28 \( \mu \text{m} \), and 31 \( \mu \text{m} \) 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 \( \mu \text{m} \). The centre of the slice is deflected by 3.3 \( \mu \text{rad} \), i.e., slightly larger than 5 times the RMS divergence of the high energy beam with \( \beta_y = 25 \text{m} \). If the vertical betatron phase advance is near 180 degree, and if \( \beta_y = 1 \text{m} \) at the radiator, then the deflection would be about 16 \( \mu \text{rad} \) 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 a 20 mm period in-vacuum-undulator of NSLSII as the radiator, the photon flux for 8 keV x-rays is \( 5 \times 10^{15} \) photons/\( \text{sec} \)/0.1\%BW for a beam current 500 mA. With about 1000 bunches, bunch current is 0.5 mA. As an estimate, for a slice of 0.3 ps out the 30 ps core bunch length (for NSLSII, RMS bunch length is 15 ps) the slice fraction is 0.3 ps/30 ps = 1%. Since revolution time is about 2.6 \( \mu \text{s} \), the single pulse photon flux is \( 10^{15} \times 0.3 \text{ps}/30 \text{ps} \times 2.6 \mu\text{s}/1000 = 2.6 \times 10^9 \) photons/\( \text{sec} \)/0.1\%BW. For camshaft current of 3 mA, the flux is \( 16 \times 10^9 \) photons/\( \text{sec} \)/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 \( 5 \sigma_y \) with a slice of 300 fs in a 30 ps bunch increases \( \epsilon_y \) by 0.3 ps/30 ps \( \times 5^2/1/2\epsilon_y = 12\% \epsilon_y \). With a repetition rate of 100 Hz for a single bunch, and damping time of 10 ms, the emittance increase is 12\% \( \epsilon_y \times 100 \text{Hz} \times 10 \text{ms} = 12\% \epsilon_y \). 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 \( 2.6 \times 10^9 \) photons/\( \text{sec} \)/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 100 kHz to 1 MHz 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.](image)

If after a betatron phase advance of \( \pi \) or a multiple integer of \( \pi \), another low energy electron bunch, synchronizes 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 -10 MHz. These options present a number of challenges yet to be studied.

### Table 1: Performance of Compressor

<table>
<thead>
<tr>
<th>Case</th>
<th>Energy [MeV]</th>
<th>Charge [pC]</th>
<th>Bunch length [fs]</th>
<th>Rms Beam Size (H) [( \mu \text{m} )]</th>
<th>Rms Beam Size (V) [( \mu \text{m} )]</th>
</tr>
</thead>
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<tr>
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<td>50</td>
<td>166</td>
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<tr>
<td>2</td>
<td>12</td>
<td>100</td>
<td>110</td>
<td>34</td>
<td>31</td>
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<td>3</td>
<td>12</td>
<td>150</td>
<td>122</td>
<td>32</td>
<td>22</td>
</tr>
</tbody>
</table>

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 5 MeV as a basis to study 12 MeV cases by adding an accelerator section and gradually increasing the RF amplitude during the optimi-
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 separation of the slice from the core, we should 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.

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 Figure 3. Since \( \beta_x \approx 8.3m \), the horizontal beam size is about 25 µm. The vertical emittance of the slice increases from 9.5µm of the core to 34 pm.

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 9.5µm of the core to 34 pm.

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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 9.5µm of the core to 34 pm.

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Figure 5: Illustration of angled crossing.

REFERENCES


Figure 3: Left: NSLSII lattice. Right: phase space \( y', y \) versus \( z \) 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 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 9.5µm of the core to 34 pm.