EXPLORING BENEFITS OF USING RF DEFLECTION FOR SHORT X-RAY PULSE GENERATION FOR AN ENERGY-RECOVERY LINAC UPGRADE TO THE ADVANCED PHOTON SOURCE*

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Abstract

One option for the Advanced Photon Source (APS) upgrade is an energy-recovery linac (ERL). In its main operating mode, the ERL rms bunch length would be two picoseconds. Even though this bunch length is already a factor of 20 shorter than the present APS bunch length, some experiments might benefit from even shorter x-ray pulses. For the APS storage ring, we plan to use an rf deflection technique [1] to generate one-picosecond-long x-ray pulses. In this approach, an rf cavity is used to deliver a longitudinally dependent vertical kick to the electron beam and then a pair of slits is used to slice the vertically streaked x-ray beam (see Figure 1). Here, we investigate the possibility and benefits of utilizing this technique to generate shorter x-ray pulses in an ERL.

ANALYSIS

Let's consider the beam motion after the first cavity, which provides time dependent vertical kick:

$$y_0'(t) = \frac{V}{E}\sin(\omega t) \approx \frac{V}{E}\omega t\,,$$

where V is the deflecting cavity voltage, ω is the deflecting cavity frequency, E is the beam energy, and we have assumed that the beam is short enough to stay within the linear part of the rf waveform. At the location of the undulator, the beam will have the following coordinates [2]:

$$y_{ID}(t) = \frac{V\omega t}{E}\sqrt{\beta_{RF}\beta_{ID}}\,\sin(\psi)\,,$$

$$y_{ID}'(t) = \frac{V\omega t}{E}\sqrt{\frac{\beta_{RF}}{\beta_{ID}}}\left(\cos(\psi) - \alpha_{ID}\sin(\psi)\right),$$

where β and α are Twiss functions, and ψ is the betatron phase advance. These equations describe the vertical position and angle of the beam slice located at longitudinal position t. Each beam slice has beam size σ_y and divergence $\sigma_{y'}$. Considering the undulator radiation divergence σ_θ, the photon beam position and its vertical size a distance L down the beamline are

$$y_L(t) = y_{ID}(t) + y_{ID}'(t)\cdot L =$$

$$= \frac{V\omega t}{E}\left(\sqrt{\beta_{RF}\beta_{ID}}\,\sin(\psi) + L\cdot\sqrt{\frac{\beta_{RF}}{\beta_{ID}}}\left(\cos(\psi) - \alpha_{ID}\sin(\psi)\right)\right),$$

$$\sigma_L^{\,2} = \sigma_y^{\,2} + L^2\left(\sigma_{y'}^{\,2} + \sigma_\theta^{\,2}\right).$$

At this point, an asymmetrically cut crystal can be used to compress the photon pulse as shown in Figure 2. Such a crystal performs horizontal sheering as shown by the red arrows, and the resulting minimum pulse length after the crystal is $\sigma_s = \sigma_y / \tan(\vartheta)$. The same length can be achieved by using slits instead of the crystal to slice the beam along the horizontal axis. The minimum achievable pulse length is

$$\sigma_t = \frac{\sigma_L}{dy_L(t)/dt} =$$

$$= \frac{\frac{E}{V\omega}\sqrt{\sigma_y^{\,2} + L^2\left(\sigma_{y'}^{\,2} + \sigma_\theta^{\,2}\right)}}{\left(\sqrt{\beta_{RF}\beta_{ID}}\,\sin(\psi) + L\cdot\sqrt{\frac{\beta_{RF}}{\beta_{ID}}}\left(\cos(\psi) - \alpha_{ID}\sin(\psi)\right)\right)}\,.$$

There are two phase-advance values between the cavity and the undulator that simplify the expression above by zeroing the sine or cosine term. One can see that having *sin(ψ)* equal zero rather than *cos(ψ)* allows for achieving shorter pulses assuming reasonable values for beta functions and distance to the beamline optics. The expression can be simplified for this case as follows:

$$\Delta t = \frac{E}{V\omega}\sqrt{\frac{\beta_{ID}}{\beta_{RF}}}\sqrt{\sigma_{y'}^{\,2} + \sigma_\theta^{\,2}}\,. \qquad (1)$$

This expression is the same as obtained in Ref. [3] with the addition of a beta function ratio. Looking at this equation, one can see what steps are necessary to achieve as short a pulse as possible: higher rf voltage and frequency, smaller ratio of beta functions, and smaller electron beam size divergence and undulator radiation divergence.

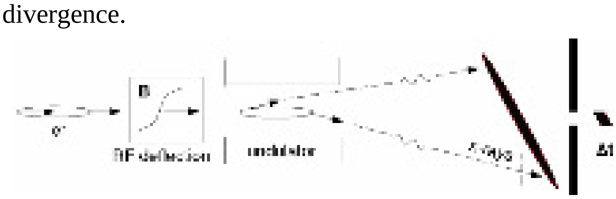

Figure 1: Schematic of the rf deflection approach to producing a short pulse.

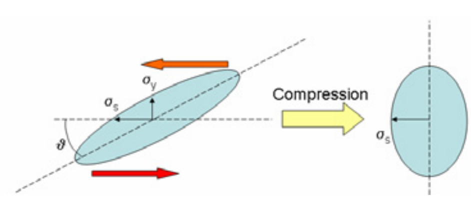

Figure 2: Illustration of pulse compression and minimum achievable pulse length.

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Extensive optimization of all parameters for achieving short pulses was performed for the APS storage ring [4]. Simulations rather than analysis of Eq. (1) were used for a number of reasons: the bunch length of the APS (70 ps rms) was comparable to the rf wavelength, making the rf kick strength nonlinear with the particle position in the bunch; vertical beam emittance was dependent on the deflecting rf voltage due to nonlinear coupling in the sextupoles; and second harmonic radiation in undulator affected the achievable pulse length.

For the ERL beam, the electron bunch duration (2 ps rms) is much shorter than the rf period, which keeps the entire beam in the linear region of the rf waveform. Sextupoles can be safely removed from the lattice between the cavities, thus removing beam emittance dependence on the rf voltage. For a longer undulator, the effect of the second-harmonic radiation also becomes less important. For the APS ring, having initial large vertical beam size presents difficulties for pulse compression using asymmetrically cut crystals [5], which is much less of an issue for the ERL since the beam size and divergence at the crystal will be smaller. Therefore, we will first analyze Eq. (1) and then perform simulations for cases of interest.

First, we will write Eq. (1) using expressions for the electron beam divergence and photon beam divergence:

$$\Delta t = \frac{E}{V\omega}\sqrt{\frac{\beta_{ID}}{\beta_{RF}}}\sqrt{\frac{\varepsilon_y}{\beta_{ID}}+\frac{\lambda}{2L_U}},$$

where λ and L_U are radiation wavelength and undulator length respectively, and we assumed that the beta function slope is zero in the middle of the undulator. According to this equation, the minimum pulse length depends on seven different parameters (we don't consider beam energy E as a parameter – it is always 7 GeV).

For our analysis here we assume the following fixed parameters: β_{ID}=2 m, β_{RF}=20 m, ε_y=10 pm. The beta function choice is somewhat arbitrary (but reasonable). The emittance value was given by ERL gun simulations [6]. To analyze the effect of the undulator length on the achievable pulse duration, we further assume the following values for rf and radiation wavelength: V=6 MV, ω=2π·2.8 GHz, and λ =1.2 Å (photon energy 10 keV). Figure 3 shows the dependence of the pulse length on the undulator length. One can see that there is definitely a benefit in increasing undulator length from 2.4 m (standard APS undulator length) to at least 5 m. Considering also that longer undulators provide more photons, for our further analysis we chose an undulator length of 10 m. Figure 4 shows the dependence of the pulse length on the photon energy for three different rf settings: 4 MV and 1.4 GHz, 6 MV and 2.4 GHz, and 8 MV and 5.6 GHz. One can see that pulse length shows little change after about 10 keV, but different rf settings (different curves on the plot) affect pulse length significantly. For the most extreme rf values of 8 MV and 5.6 GHz, an rms pulse duration of about 25 fs could be achieved. Figure 5 shows pulse length as a function of rf voltage and frequency for 10-keV photon energy to demonstrate possible trade-offs between rf voltage and frequency.

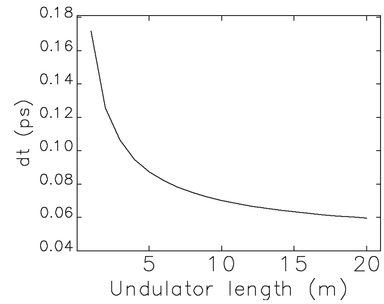

Figure 3: Minimum pulse length dependence on the undulator length for V=6 MV, ω=2π·2.8 GHz, and λ =1.2 Å.

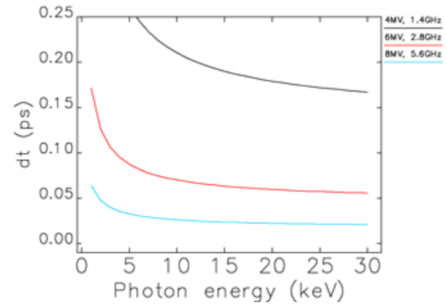

Figure 4: Minimum pulse length dependence on the photon energy for different rf voltages and frequencies.

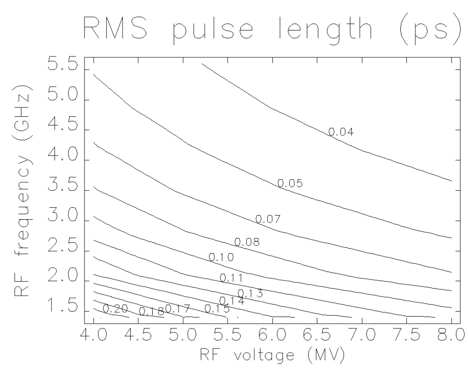

Figure 5: Minimum pulse length as a function of rf frequency and voltage.

SIMULATIONS

We performed detailed simulations for the particular set of parameters shown in Table 1.

Table 1: Parameters Used in Simulations

Beam energy	7 GeV
RF voltage	6 MV
RF frequency	2.8 GHz
ID beta function	2 m
RF beta function	20 m
Vertical emittance	10 pm
Undulator length	10 m
Photon energy	10 keV

A description of the ERL lattice can be found in [7]. The insertion with deflecting cavities was placed at the end of the turn-around arc (TAA). For simplicity, we used TAA sectors for insertion but removed the dipoles and sextupoles. Deflecting cavities and the undulator were located in successive ID straight sections. The full insertion consists of four sectors with the symmetry point in the middle. The first sector brings the vertical beta function to 20 m at the first deflecting cavity, a second sector brings the beta functions to 2 m at the undulator, and the rest is reflectively symmetric. The vertical phase advance of each sector was tuned to 0.5 and the natural chromaticity was also minimized. The accelerator code `elegant` [8] was used for lattice matching and particle tracking.

For the initial particle distribution we used the results of a gun simulation with 0.1-micron normalized emittance [6]. The bunch was then tracked through the entire linac and TAA. At the insertion entrance, the vertical beam emittance was close to 11 pm·rad. At the undulator location, the photon distribution was generated by combining the electron distribution and the single-electron radiation pattern. The photon distribution was then propagated 30 m to a point where either an asymmetrically cut crystal can be used to compress the pulse or a slit can be used to slice it. Figure 6 shows the pulse shape before and after compression. The resulting rms pulse duration after compression was 62 fs. If calculated using Eq. (1), the pulse duration would be 70 fs.

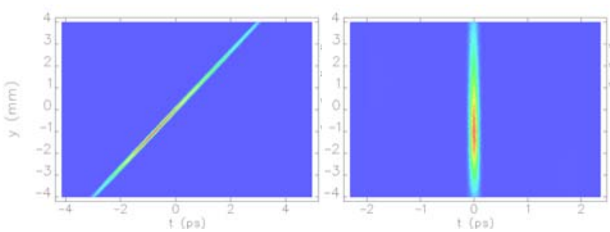

Figure 6: Photon pulse shapes before (left) and after (right) compression.

Figure 7 shows the pulse profile. One can see small peaks at around ±2 ps. These are produced by the second-harmonic undulator radiation. The intensity of the peaks is about 0.3% of the main peak intensity.

From our previous analysis of the rf deflection for the APS storage ring [3], we know that the vertical kick can increase the vertical beam emittance due to magnet nonlinearities and chromaticity between the cavities. Figure 8 shows the emittance at the exit of the insertion after the second cavity, as a function of rf frequency for two different rf voltages. A diamond symbol represents the point corresponding to the parameters in Table 1. The increase in this case is 6%, which can be tolerated. However, if one considers increasing the voltage and frequency, then the emittance increase might present a challenge and might require special study to mitigate the problem.

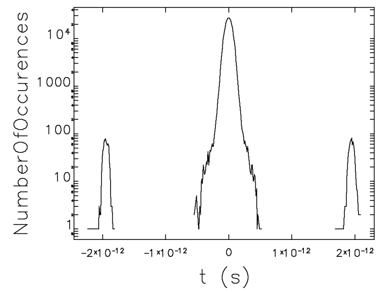

Figure 7: Photon pulse profile. The rms pulse length is 62 fs. Small peaks at around ±2 ps are produced by the second-harmonic radiation.

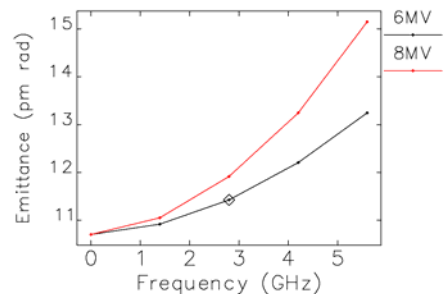

Figure 8: Vertical beam emittance after the second deflecting cavity for different rf frequencies and voltages. A diamond symbol shows the point corresponding to the parameters in Table 1.

CONCLUSION

We have studied the application of an rf deflection scheme for achieving short pulses at an APS ERL. We have found that an rms pulse duration of 62 fs can be achieved with the beam and rf parameters shown in Table 1, which are very similar to those considered for the APS storage ring. We confirmed through tracking that vertical emittance of the beam does not increase significantly after the second cavity. We also have found that for some extreme rf parameters (8 MV and 5.6 GHz), the rms pulse length can be decreased to 25 fs.

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