SIMULATIONS OF X-RAY SLICING AND COMPRESSION USING CRAB CAVITIES IN THE ADVANCED PHOTON SOURCE*

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Abstract

Recently, Zholents et al. [1] proposed applying to the Advanced Photon Source an x-ray compression scheme based on a pair of crab cavities and asymmetric cut crystals. We have explored the feasibility and potential performance of this scheme through simulation. We used the code `elegant` to perform 6-D tracking, allowing us to understand the emittance growth and possible cures. We also explored tolerances on alignment, phase, and voltage of the cavities; lifetime effects; tradeoffs between cavity frequency and voltage; and performance with slicing alone instead of compression. Our conclusion is that subpicosecond rms x-ray pulse lengths should be feasible.

INTRODUCTION

This paper summarizes and updates simulation studies and analysis [2] of x-ray compression using transverse-deflecting rf cavities [1] ("crab cavities") in the Advanced Photon Source, a 7-GeV synchrotron radiation source. This is the most promising concept available now for producing high-flux short pulses from storage ring light sources.

In this concept, a crab cavity is used to impose a correlation between longitudinal position in the bunch and vertical momentum. A second cavity somewhere downstream is used to remove the correlation. Radiation-producing devices (undulators and bending magnets) between the two cavities will produce x-ray pulses with a correlation between vertical phase space and time. These correlations can be used to perform slicing or x-ray compression. The vertical plane is used because the effectiveness of compression depends on the amount of the chirp relative to the unchirped beam dimension. APS normally operates with 1% vertical coupling, the vertical beam size and divergence are much smaller than those in the horizontal.

TRACKING METHODS

We performed symplectic tracking with the 6-D code `elegant` [3]. Synchrotron radiation effects were modeled using a single `SREFFECTS` element, which applies quantum excitation and energy loss to the beam in a way that gives correct damping rates and equilibrium properties.

At the normal single-bunch current of about 4 mA, the rms bunch duration in APS is lengthened by potential well distortion from approximately 20 ps to approximately 40 ps [4]. To avoid time-intensive simulation of the longitudinal impedance, we simply lowered the simulated rf voltage from 9 MV to about 5.7 MV. This gives the correct single-particle synchrotron tune and the correct bunch length.

Deflecting rf cavities were simulated using `elegant`'s `RFTM110` element [2], which simulates a zero-length TM_{110} cavity using a sixth-order expansion of the fields.

The photon distribution was modeled using [5]

$$S(\theta) \approx \mathrm{sinc}^2 \left(\frac{nN\pi\gamma^2\theta^2}{1 + K^2/2} \right), \tag{1}$$

where n is the harmonic number, N the number of undulator periods, γ the relativistic factor for the beam, θ the polar angle, and K the undulator strength parameter. For estimates, we used the rms opening angle $\sigma_\theta = \sqrt{\lambda/2L}$.

LATTICE CHOICES AND CONSTRAINTS

An obvious requirement for the lattice is $m\pi$ vertical phase advance between the crab cavities, where m in an integer. Because of the small size of the APS beams and the functional form of the crab cavity fields, there is no particular phase advance constraint in the horizontal plane. The crab cavities must be placed in straight sections, meaning they compete with the undulators for space. Having the cavities many sectors apart is thus desirable, as this provides chirped pulses to many sectors. Putting the first (second) cavity in the upstream (downstream) half of its sector also provides chirped pulses to more users, at the cost of some manageable changes to the APS optics.

In this arrangement, the vertical phase advance between the first cavity and any insertion device is approximately an integer multiple of π. This means the cavity primarily imparts a chirp to the vertical slope. Hence, the compression depends on the relative magnitudes of the radiation opening angle σ_θ and the slice divergence of the electron beam $\sigma_{y',s}$. Assuming full compression, the minimum achievable bunch length is [2]

$$\sigma_{t,x} \approx \frac{E}{V 2\pi f_c} \sqrt{\sigma_{y',s}^2 + \sigma_\theta^2}, \tag{2}$$

where E is the beam energy, V the effective deflecting voltage, and $f_c = hf_m$, the crab rf frequency, which is at the $h = 8$ harmonic of the main ring rf frequency f_m. Good lifetime requires $V \leq 6$ MV [2].

EMITTANCE DEGRADING EFFECTS

Errors, nonlinearities, and other details can destroy the perfect cancellation by the second cavity of the chirp induced by the first cavity. In [2], we investigated many

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emittance-degrading effects. Effects for a machine without errors include sextupoles between the cavities, which result in x-y coupling, tune variation with amplitude, and phase space distortion; non-zero momentum compaction and energy spread, which leads to time-of-flight variation between the cavities; non-zero chromaticity and energy spread, which leads to phase advance variation; and quantum excitation in the longitudinal plane, which amplifies momentum compaction and chromaticity issues.

We found previously [2] that interior sextupole nonlinearity was a serious issue, resulting in large emittance growth in both planes. This motivated turning off the interior sextupoles. However, this results in significant emittance growth due to the uncorrected chromaticity. Looking at a few hundred turns after turning on the cavities, the sextupoles-off case appears much better. However, in the long term, the advantage is greatly reduced because of randomization of particle energy offsets by quantum excitation. These considerations would limit us to 4-MV deflecting voltage. Fortunately, it is possible to determine a special tuning of the interior sextupoles that greatly reduces the emittance degradation and allows using higher voltage.

SEXTUPOLE TUNING FOR EMITTANCE PRESERVATION

The field expansion for a sextupole is

$$\begin{aligned} B_y &= \frac{1}{2}S(x^2 - y^2) \\ B_x &= Sxy, \end{aligned} \tag{3}$$

where S is the sextupole strength and x (y) the horizontal (vertical) coordinate. In the first sextupole after the first cavity, a particle with a large y amplitude receives a horizontal kick from the $B_y y^2/2$ term. This turns into an x displacement at downstream sextupoles, leading to kicks in the y plane that are dependent on the initial vertical amplitude. Particles arriving at the second cavity have vertical phase advance dependent on their initial vertical amplitude, which leads to non-cancellation of the initial cavity's kicks and thus emittance growth. Horizontal emittance growth will occur as well, since there is nothing to cancel the $B_y y^2/2$ kicks.

We performed direct minimization of a single-pass emittance increase by varying all interior sextupoles. Similar work was reported in [2], but with fewer constraints leading to an unworkable solution. To minimize the effect on the dynamic aperture, the sextupoles were varied symmetrically around the center of the deflecting system. The optimization was performed using `elegant`, which has a powerful built-in optimization engine. We used single-pass tracking through the deflecting system with $V = 6$ MV and $h = 8$ for one hundred particles with a 6-D Gaussian distribution. The optimization requirements were to minimize the vertical emittance increase and give zero chromaticity between the cavity for both planes.

Note that while the nominal vertical chromaticity for the entire APS ring is +6, we compensated the chromaticity for the deflecting section to zero to minimize the effect of tune spread due to natural beam energy spread. The sextupoles outside of the deflecting section were used to obtain the nominal total chromaticities.

After optimization, 500 particles were tracked 1000 turns to compare new sextupoles with the old ones and with the case of sextupoles turned off. Figure 1 shows vertical emittance after 1000 turns for all three cases as a function of deflecting voltage. These results do not include synchrotron radiation effects, which will make the sextupoles-off case much worse, as discussed above.

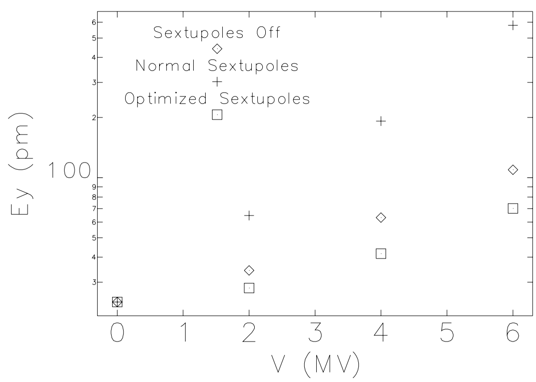

Figure 1: Vertical emittance as a function of deflecting voltage for different sets of sextupoles.

Previously [2], it was found that sextupole nonlinearities or uncorrected chromaticity would limit the number of sectors between cavities to no more than two, which limits the number of beamlines that can benefit from chirped pulses. We repeated our sextupole optimization for three and four sectors between the cavities, obtaining the results listed in Table 1. The number of sectors between cavities is no longer limited by the vertical emittance increase. Indeed, because there are more sextupoles available for adjustment, the results are better with more sectors included. The new limiting factor will be the dynamic aperture decrease due to sextupole distibution symmetry breaking. We plan to repeat the optimization including dynamic aperture as an additional constraint.

Table 1: Resulting Vertical Emittance for Deflecting Voltage of 6 MV for Different Number of Sectors between Cavities

Number of Sectors	Vertical Emittance
2	70
3	59
4	41

COMPRESSION RESULTS

To model compression, we first tracked 1000 particles for 10,000 turns including synchrotron radiation. We com-

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bined the phase space from the last 100 turns to create a beam with 100,000 particles, which gives good statistics for subsequent work. We tracked this beam for 10 turns, saving the phase space from each turn.

We next created a photon distribution from this output by adding random slope changes distributed according to Eq. (2). This distribution was fed back into `elegant` to model the compression, which consists of a 30-m drift (typical of undulator-to-monochromatic distances at APS), vertical slits, and a matrix representing the compression optics. The compression was modeled simply as a linear variation in time of flight with vertical position $\Delta t = k\Delta y$. Using `elegant` for this photon simulation allowed us to easily optime k to minimize the pulse length for a series of slit sizes. Rather than minimize the rms, which can be misleading due to tails, we minimized the duration of the central 70% of the particles.

Figure 2 shows the optimum x-ray pulse durations as a function of slit size for several rf harmonics. For wide slit spacing, the lower harmonics are advantageous as the chirp is more linear, allowing better compression. As the slit spacing is decreased and the nonlinear part of the chirp is removed, the higher harmonics show a clear advantage. Since the vertical emittance increase is linear in the harmonics, this result is not a foregone conclusion. Fortunately, the emittance increase is small enough that the slice photon distribution is still dominated by the undulator radiation opening angle.

Figure 3 shows the fraction of the photons left after the slits as a function of the x-ray pulse duration. X-ray optics losses are not included, but are expected to be modest for x-ray energies in the region of 10 keV [6]. We thus expect that subpicosecond x-ray pulses can be achieved while still retaining about 50% of the original intensity.

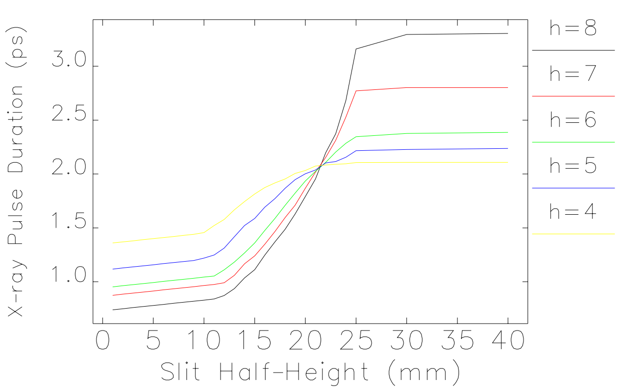

Figure 2: Duration of the central 70% of the x-ray pulse as a function of slit half-height for various rf harmonics, using 6 MV.

EFFECT OF ERRORS

Using the optimized sextupole configuration, we examined the effect of various errors: lattice errors, leading to phase advance and beta function errors; roll of one or both cavities about the longitudinal axis; lattice coupling between the cavities due to rolled or skew elements; and rf phase and voltage errors. Space does not permit a detailed discussion of the methods or results (see [2]).

The most challenging tolerances are those related to the rf phase. In particular, phase errors between the cavities can result not only in emittance growth, but also in beam centroid motion outside the region between the cavities. To keep this under 10% of the vertical beam size, we must control the cavity-to-cavity phase error to less than 0.04 degrees. Voltage errors are less difficult. A 0.25% tolerance on the voltage difference between the cavities should ensure less than 10% additional vertical emittance growth.

CONCLUSION

We have performed extensive studies of x-ray compression using an electron beam chirped by transverse rf cavities. We improved on previous results by finding an optimized sextupole configuration that greatly reduces emittance blow-up. Subpicosecond pulses are possible while retaining 50% of the x-ray photons.

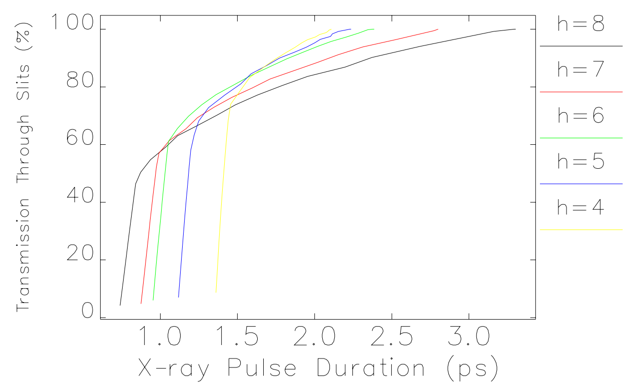

Figure 3: Fraction of photons passing through the slits vs duration of the central 70% of the x-ray pulse. X-ray optics losses are not included.

REFERENCES

[1] A. Zholents et al., NIM A 425 (1999) 385-389.

[2] M. Borland, submitted to Phys. Rev. STAB.

[3] M. Borland, Advanced Photon Source LS-287, September 2000.

[4] Y.-C. Chae et al., Proc. 2001 PAC, 1491 (2001).

[5] K.-J. Kim, AIP Conference Proceedings 184, 565 (1989).

[6] S. Shastri, private communication.