AN EXTENSION OF CORNELL'S ENERGY RECOVERY LINAC FOR COMPRESSED HIGH-CHARGE BUNCHES

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Abstract

The proposed Cornell Energy Recovery Linac (ERL) is designed for bunches of 77pC and 100mA whose energy is recovered. However, the ERL linac can also be used for larger bunch charges of reduced average current whose energy does not have to be recovered. The proposed Cornell ERL light source currently uses a split linac arrangement connected by a turnaround arc. In order to avoid the detrimental effects of Coherent Synchrotron Radiation (CSR) in this arc, a high charge (1nC) bunch must remain relatively long (2ps), and be compressed at high energy (5GeV). An appropriate bunch compressor must take second order effects into account, which adds complications for the large energy spread associated with compression to 100fs or less. We have therefore designed a very simple four dipole bunch compressor at high energy, which uses second order time of flight terms in the turnaround arc rather than in the bunch compressor. This design is tested using particle tracking simulations incorporating CSR.

INTRODUCTION

When probing samples with hard X-rays generated in a synchrotron radiation source, often to do this on increasingly smaller time scales, it is instrumental to use X-ray pulses that are as short as possible. To generate short X-ray pulses in a synchrotron radiation source, electron bunches must be compressed using a dedicated bunch-compressing lattice.

The proposed Cornell Energy Recovery Linac light source uses two linacs for acceleration connected by a turnaround arc. Due to Coherent Synchrotron Radiation (CSR) effects in the dispersive turnaround arc, the small bunches desired will be difficult to maintain in this section. Instead, to minimize the influence of CSR, a relatively large bunch is steered through the turnaround with compression done following the second linac at $5\,\mathrm{GeV}$. A simple four dipole chicane compressor is used to compress to first order, while additional second order terms are zeroed with sextupoles in the heavily dispersive turnaround section. This second order compression scheme achieves bunches of $100\,\mathrm{fs}$ or less in length.

In the presented, we study this lattice design using Bmad, a particle tracking simulator with additional functionality for CSR damage [1]. The influence CSR has on the bunch's emittance growth, RMS length, and phase space cross section are observed. An analysis is also conducted to determine the smallest size bunch that may be steered through the turnaround and still compressed despite increased CSR damage.

THEORY

For off crest acceleration, a correlation between the longitudinal position and energy spread is introduced in dispersive sections where we have

$$z_f = z_i + R_{56}\delta + T_{566}\delta^2 + \ldots. \qquad (1)$$

For a second order compression scheme, assuming the final beam energy is much larger than the initial, we may approximate the energy spread by

$$\delta \approx \frac{\cos(\phi - kz_0)}{\cos\phi} - 1, \qquad (2)$$

where z_0 is the initial z position, k the RF wave number, ϕ the RF phase shift [2]. Plugging this into Eq. (1),

$$z_2 \approx z_1 + R_{56}\left[\frac{-\cos(\phi - kz_0)}{\cos\phi} - 1\right] \\ + T_{566}\left[\frac{-\cos(\phi - kz_0)}{\cos\phi} - 1\right]^2 + \ldots, \qquad (3)$$

where z_1 is the longitudinal position at some initial time, and z_2 is the longitudinal position at some later time. Assuming the initial distribution of the beam is a Gaussian in the longitudinal direction, we can compute the variance in z_2 from the expansion in Eq. (1). We zero the first and second order terms in this expansion by setting $R_{56} = -\frac{1}{k}\cot\phi$ and $T_{566} = -\frac{1}{2k}\cot^3\phi$, resulting in a bunch compressed to second order with RMS length given by

$$\sigma_{z_2} = k^2\sigma_{z_0}^3\sqrt{15}\left|\frac{1}{6} + \frac{1}{2}\cot^2\phi + k\,U_{5666}\tan^3\phi\right| + O(\sigma_{z_0}^4) \qquad (4)$$

Further third and higher order compression is unnecessary considering limitations CSR poses on the minimum compressed bunch size.

Now, assuming only motion in the $x - z$ plane, the path length of a trajectory is given by:

$$|dr| = \sqrt{(1 + \kappa x)^2 + x'^2}\,ds, \qquad (5)$$

where κ is the magnetic dipole strength [3]. The difference in the longitudinal position can then be expressed as

$$\triangle z = \int_0^L 1 - \sqrt{(1 + \kappa x)^2 + x'^2}\,\mathrm{d}s. \qquad (6)$$

Substituting the nonlinear equation of motion for x, $x(s) = x(s)_{\delta=0} + R_{16}\delta + T_{166}\delta^2 + \ldots$ and $\triangle z = R_{56}\delta + T_{566}\delta^2 +$
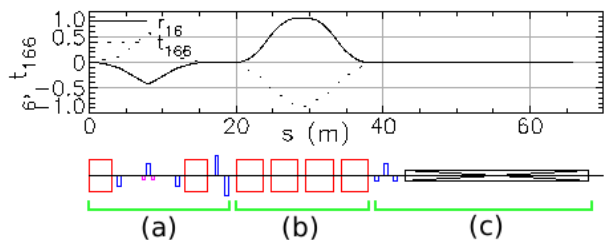
Figure 1: (a) Demerger section, (b) Chicane compressor section, (c) Undulator section. Dipoles are marked in red, quadrupoles in blue, and sextupoles in violet. The height and width of the rectangles represents their strength and length respectively. Above the lattice, a plot of the first order R_{16} dispersion (solid line) and second order T_{166} (dotted line) is shown on the same axes.

... and keeping only terms to the second order, the relationship between the x and z dispersion becomes clear [4]

$$R_{56} = -\int_0^L \kappa R_{16}\, \mathrm{d}s, \tag{7}$$

$$T_{566} \approx -\int_0^L \kappa T_{166}\, \mathrm{d}s. \tag{8}$$

Therefore we can adjust R_{56} and T_{566} to the appropriate values for bunching by optimizing over the first and second order dispersion in a standard chicane compressor with higher order corrections.

As an alternative to this usual approach, it is possible to take advantage of the dispersive turnaround section and use pre-existing sextupoles in this flexible lattice to set the correct second order dispersion needed for bunching. The bunch compressor needs only then optimize over the associated first order dispersion for bunching using only linear structures, thus waiving the need for sextupoles in the compressor.

DESIGN AND RESULTS

The compressor lattice consists of three parts: an achromat demerger section, the chicane compressor, followed finally by an undulator (see Fig. 1).

Since energy is not recovered in compression, the beam must be extracted from the main line. Extraction is done by kicking, then demerging the beam with two bending magnets, bending the beam $2.5°$ each from the main line. Between these two magnets, a quadrupole triplet with strengths of about $10\,\mathrm{T/m}$ is optimized to cancel the dispersion introduced by the bends. On each side of the middle quadrupole, sextupoles with strengths about $-70\,\mathrm{T/m}^2$ each are optimized to zero the higher order T_{166} and T_{266} terms (see Fig. 1). Naturally, the nonzero dispersion in the demerger section influences the R_{56} and T_{566} time of flight terms and must be considered. Fortunately, this contribution introduced is very little and no compensation was required from the turnaround section.
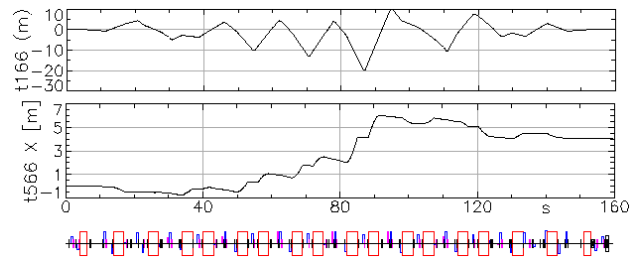

Figure 2: Dispersion over the turnaround and the T_{566} contribution from this section are plotted above the turnaround lattice structure.

Following the demerger, a quadrupole doublet is placed to control the beta function entering the compressor and undulator. The compressor itself is a simple chicane achromat consisting of four equal and opposite dipoles (field strength $0.834\,\mathrm{T}$) each bending the $5\,\mathrm{GeV}$ beam $10.5°$.

The demerger lattice is very close to the main line it bends away from, so to avoid overlapping elements, the position of the magnets in this section is limited to the open spaces between the structures in the main line. As a result, the optics in the demerger section are fixed and cannot be used to help optimize for bunching R_{56} and T_{566} values. We are free however to adjust the chicane compressor dipole strengths, and the turnaround sextupole strengths to achieve a compressing R_{56} and T_{566} pair. Smaller time of flight terms are often more practical, so for our $100\,\mathrm{fs}$ target, the R_{56} value from the compressor was chosen to keep the analogous T_{566} contribution needed from the turnaround section low [2]. The contribution to R_{56} and T_{566} from each section is summarized in Table 1.

Table 1: Time of Flight Term Contributions

	Turn Around	Demerger	Chicane
R_{56} (m)	1.76×10^{-9}	-1.60×10^{-3}	0.237
T_{566} (m)	4.02	-2.62×10^{-2}	-0.356

The dispersion over the turnaround lattice is plotted in Fig. 2 along with the T_{566} contribution from this section.

Observing the transverse emittance growth over the compressor, Table 2 details the emittance values at the beginning and end of the section for multiple initial conditions. With CSR calculations omitted, we observe little emittance growth. In comparison, with CSR being considered for a $1\,\mathrm{nC}$ bunch, the y-emittance is again contained, though the x-emittance grows very significantly. Reducing the bunch charge to $77\,\mathrm{pC}$ to reduce the influence of CSR effects, the x-emittance growth is reduced, though still a factor of three.

Observing how CSR affects the final bunch length, it is found that with CSR calculations omitted for a $1\,\mathrm{nC}$ bunch, the final bunch length is about $100\,\mathrm{fs}$; as expected since theoretical optimizations were made particularly for this final value. With CSR considered for a $77\,\mathrm{pC}$ bunch, the com-
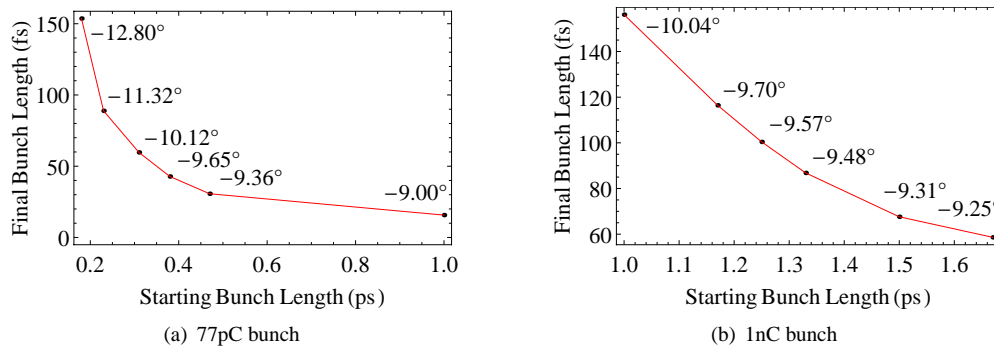
(a) 77pC bunch

(b) 1nC bunch

Figure 4: Each point is labeled with its associated phase shift that produces the smallest final bunch. From this, we may interpolate a smallest possible starting bunch size that may be compressed to 100 fs with only phase shift compensation.

(a) 77pC bunch, $\sigma_z/c \simeq 100\,fs$
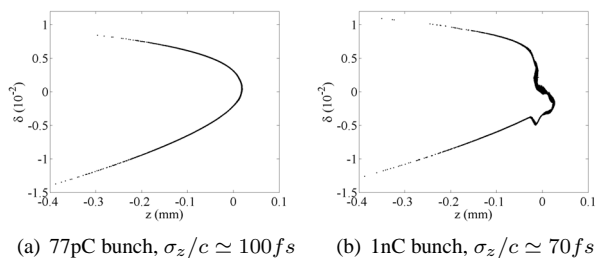

(b) 1nC bunch, $\sigma_z/c \simeq 70\,fs$

Figure 3: Longitudinal phase space after compression for 0C, 77pC and 1nC bunches.

pressed length is not changed much and the beam shape appears undistorted (see Fig. 3.a). With CSR considered for a 1 nC bunch, the CSR effects are much more significant, and the length shrinks to about 70 fs at the end of compression (see Fig. 3.b). This decrease in length is most likely due to aberrations shifting the would-be head of the bunch backwards after compression. In all cases, the shape is of a rotated quadratic rather than an expected cubic for second order compression because we are under-compressing to a target 100 fs rather than to the minimum size possible, so some second order residual remains. See Table 2 for a summary of the RMS bunch lengths for multiple initial conditions.

Finally, to study the limitations CSR effects pose on the bunch size in the turnaround, the injected beam size was decreased and simulated through the compressor until compression to 100 fs became impractical. When changing the starting bunch size, to optimize back to the desired 100 fs final RMS length, adjusting the lattice design for new time of flight terms is difficult. Instead, compensation is done by changing the RF phase shift, ϕ (see Eq. (4) for the dependence of the final bunch length on ϕ). To find the optimal compensating phase shift, simulations were run for a spectrum of phases from -3 to -15 degrees and a local minimum of the final bunch size was interpolated from the data obtained. Fig. 4 summarizes the results for 77 pC and 1 nC bunches. The minimum starting bunch length that may be compensated with only phase offset fixing is found

Table 2: Bunch properties at the beginning and end of the compressor for multiple bunch charges. Bunches are accelerated at 1.3 GHz with a $-9°$ phase shift and 2 ps starting RMS-length Gaussian particle distribution.

	Bunch Charge		
	0 C	77 pC	1 nC
Initial			
$\epsilon_x\,(\,\mathrm{pm})$	32.6	32.3	55.0
$\epsilon_y\,(\,\mathrm{pm})$	33.6	33.6	33.6
$\sigma_z/c\,(\,\mathrm{fs})$	2024	2023	2019
Final			
$\epsilon_x\,(\,\mathrm{pm})$	32.7	114	2680
$\epsilon_y\,(\,\mathrm{pm})$	38.0	37.7	37.7
$\sigma_z/c\,(\,\mathrm{fs})$	100.5	95.2	71.0

to be about 0.25 ps for a 77 pC bunch and 1.25 ps for a 1 nC bunch. Keeping below these limiting cases, a 2 ps starting bunch more than meets our desired 100 fs target compressed size for both considered bunch charges without compromising the beam structure too much.

ACKNOWLEDGEMENTS

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