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A BUNCH COMPRESSION METHOD FOR FREE ELECTRON LASERS THAT AVOIDS PARASITIC COMPRESSIONS *

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Abstract

Virtually all existing high energy (>few MeV) linac-driven FELs compress the electron bunch length through the use of off-crest acceleration on the rising side of the RF waveform followed by transport through a magnetic chicane. This approach has at least three flaws: 1) it is difficult to correct aberrations- particularly RF curvature, 2) rising side acceleration exacerbates space charge-induced distortion of the longitudinal phase space, and 3) all achromatic "negative compaction" compressors create parasitic compression during the final compression process, increasing the CSR-induced emittance growth.

One can avoid these deficiencies by using acceleration on the falling side of the RF waveform and a compressor with M_{56}>0. This approach offers multiple advantages: 1) It is readily achieved in beam lines supporting simple schemes for aberration compensation, 2) Longitudinal space charge (LSC)-induced phase space distortion tends, on the falling side of the RF waveform, to enhance the chirp, and 3) Compressors with M_{56}>0 can be configured to avoid spurious over-compression.

We will discuss this bunch compression scheme in detail and give results of a successful beam test in April 2012 using the JLab UV Demo FEL.

INTRODUCTION

To preserve electron beam brightness in a linac based accelerator used as an FEL driver it is necessary to produce a long, low peak current bunch in the injector, accelerate off crest in the accelerator, and then bunch in a bunch compressor. Brightness preservation is difficult due to the effects of LSC, coherent synchrotron radiation (CSR), and RF curvature. The canonical method for compression is to accelerate on the rising side of crest and compress in a chicane, which requires use of negative momentum compaction. It is possible however to reverse this and accelerate on the falling side of crest and compress in a bend with positive momentum compaction. When used in an energy recovering linac (ERL), this option has many advantages.

COMPRESSION OPTIONS

We describe here a low-energy compression method, which is a parallel-to-point longitudinal map. At higher beam energies, one usually wants to have a two-stage compression. Though this example describes the low energy procedure, the same ideas described below may still apply to the final compression of a high-energy system.

Negative Momentum Compaction Compressor

In most linear accelerators the simplest method of achieving a non-zero momentum compaction is to use a magnetic chicane. This is illustrated in Fig. 1. The beam is accelerated on the rising portion of the RF waveform, leading to the higher energy electrons being in the rear of the bunch. A transport system with negative momentum compaction then compresses the bunch. Note that the second order momentum compaction (T_{566}) is non-zero positive in a chicane, and is thus the wrong sign to correct for the RF curvature in the electron bunch. RF curvature is generally handled using harmonic RF, which is used to create a nearly linear voltage versus time and to additionally compensate for the T_{566} of the chicane.

Longitudinal space charge tends to accelerate the head of the bunch and decelerate the tail. This reduces the energy spread of the bunch, which is helpful in matching the energy spread to the acceptance of the FEL. In some cases however, it can produce second or third order curvature in the distribution, which decreases the peak current after the compressor unless it can be compensated using the harmonic RF and transport settings.

Similarly, CSR can produce curvature that can cancel part of the RF curvature on the bunch. If too large, however, it can produce a monoenergetic segment in the longitudinal phase space. This part of the bunch cannot be compressed due to the lack of any time-energy correlation. This is shown schematically in Fig. 2.

The emittance growth due to CSR can be large in a negative momentum compaction bending system because the compaction in a single dipole is always positive. This means that the momentum compaction of the transport upstream of the last dipole must be more negative than is required to simply bunch the beam. The beam is, for example, over-bunched in the earlier magnets of a chicane, and then slightly debunched to the optimum length in the last dipole. There is thus a parasitic compression that is inherent in a chicane compressor.

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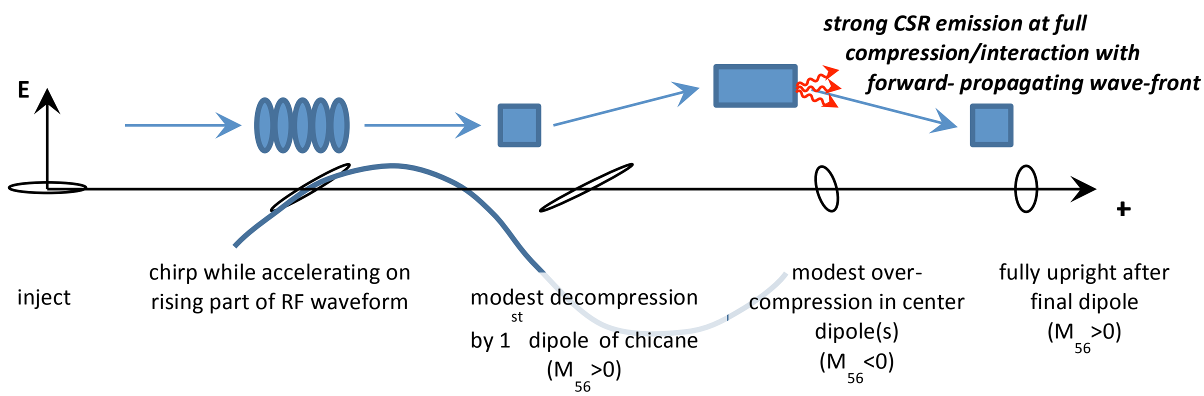


Figure 1: Canonical bunch compression in a free-electron laser using negative momentum compaction. Higher energy machines typically use a two-stage compressor, which still uses chicanes to compress the beam.

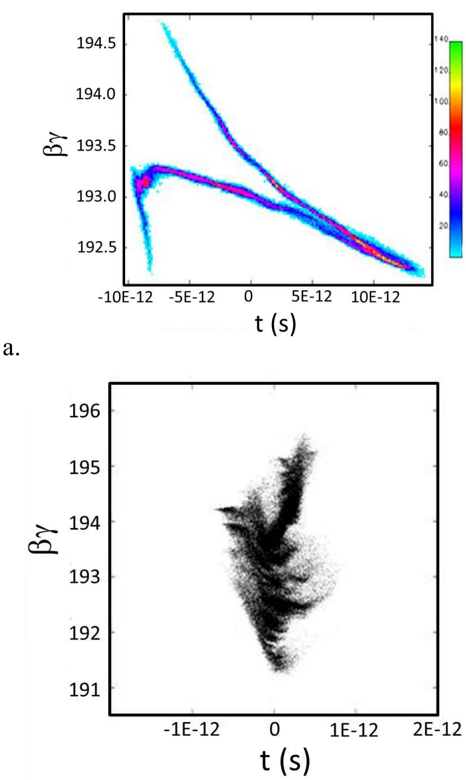
Positive Momentum Compaction Compressor

In an ERL the beam generally must be bent around at least 180 degrees before going into the FEL. The natural momentum compaction of a 180-degree bend is positive so it makes sense to accelerate on the falling side of the RF waveform, and bunch with the positive momentum compaction. The sign of the compressor momentum compaction also matches to the final dipole so that the bunch need not reach the shortest length until it reaches the end of the compressor. The bunch compresses in an adiabatic fashion as one goes around the final arc of the ERL.

The T_{566} of the arc can be adjusted to compensate the RF curvature. This is routinely done at the Jefferson Lab ERL. By adjusting sextupoles one may even cancel part of the curvature induced by CSR. By using a self-cancelling design for the compressor, it is possible to cancel most of the CSR effects in such a compressor [1].

POSITIVE COMPACTION EXPERIMENT

The Jefferson Lab UV Demo FEL uses Bates bends to supply the 180 degree bends at either end of the ERL [2]. These bends are quite flexible and can be adjusted to provide a net positive or negative momentum compaction for the bend. The sextupoles can also be optimized to correct for the RF curvature from the accelerator. The accelerator was commissioned with a negative momentum compaction and showed excellent performance. The gain at 400 nm was over 280% and the efficiency exceeded 0.8%, both greater than expected. We changed out our wiggler for a slightly longer version and started to recommission this device. The gap mechanism failed however and left the undulator resonant at 800 nm. This is actually outside of the bandwidth of the mirrors. There is a side peak at 760 nm however with a reflectivity of 50% and the laser lased there (see Figure 3). When the ERL was moved to the other side of crest and the M_{56} and T_{566} of the Bates bends readjusted and optimized, the laser lased as well or better than with the negative momentum compaction setup. The cavity length detuning curve was up to 11 microns in length and the laser turned on in less than 10 μsec (47 passes). This indicates a net gain of over 50% with losses of over 50%, indicating an electronic gain of over 150%. Note that very little time was spent in optimizing this configuration so the fact that the performance was comparable to that of the nominal configuration is very promising.



a.

b.

Figure 2: Compression in a system with negative momentum compaction (a) with strong CSR can lead to an incompressible longitudinal distribution, while compression in a system with positive momentum compaction (b) leads to a more compact phase space.

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The rms bunch length, as measured using a Martin-Puplett interferometer, was similar for the two cases, about 140 fsec. Again, this result was achieved with very little optimization.

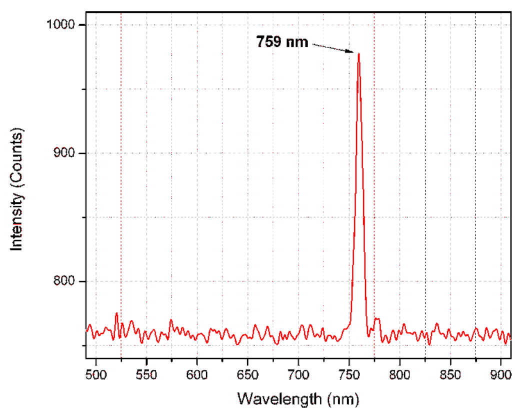

Figure 3: Lasing spectrum with the ERL operating with a positive momentum compaction. The losses for the 800 nm resonant wavelength were huge so the laser lased at a shorter wavelength where the losses were about 50% per pass.

CONCLUSION

The use of a positive momentum compaction with operation on the rising side of crest has several advantages over the usual method of bunch compression. We have demonstrated energy recovery with this arrangement and found that, even with minimal optimization time, the performance was comparable to or better than the configuration with negative momentum compaction.

ACKNOWLEDGMENT

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REFERENCES

[1] D. Douglas *et al*., "Control of Coherent Synchrotron Radiation and Micro-Bunching Effects During Transport of High Brightness Electron Beams", JLAB-ACP-14-1751, 1 March 2014; http://arxiv.org/abs/1403.2318

[2] D. Douglas *et al*., "High Average Power UV Free Electron Laser Experiments At JLab", IPAC'12, New Orleans, May 2012, p. 2111 (2012); http://www.JACoW.org/.