STUDIES OF CSR IN THE JEFFERSON LAB FEL DRIVER WITH IMPLICATIONS FOR BUNCH COMPRESSION*

C. Tennant#, D. Douglas, R. Li
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
C.-Y. Tsai
Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, USA

Abstract

The Jefferson Laboratory IR FEL Driver provides an ideal test bed for studying a variety of beam dynamical effects. Recent studies focused on characterizing the impact of coherent synchrotron radiation (CSR) with the goal of benchmarking measurements with simulation. Following measurements to characterize the beam, we quantitatively characterized energy extraction via CSR by measuring beam position at a dispersed location (a direct measure of extracted energy) as a function of bunch compression. In addition to operating with the beam on the rising part of the linac RF waveform, measurements were also made while accelerating on the falling part. For each, the full compression point was moved along the backleg of the machine and the response of the beam (distribution, extracted energy) measured. Initial results of start-to-end simulations using a 1D CSR algorithm show remarkably good agreement with measurements. A subsequent experiment established lasing with the beam accelerated on the falling side of the RF waveform in conjunction with positive momentum compaction (R_{56}) to compress the bunch. The success of this experiment motivated the design of a modified CEBAF-style arc with control of CSR and microbunching effects.

BACKGROUND

Virtually all existing high energy linac-driven FELs compress bunch length through use of off-crest acceleration on the rising side of the RF waveform followed by transport through a magnetic chicane. Though effective to some degree, this approach has at least three flaws:

1) It is difficult to correct aberration effects, particularly phase space distortion due to RF curvature. Typically harmonic RF is invoked in response, at considerable expense and with the difficulties attendant to the use of high frequency resonant cavities.
2) Acceleration on the rising side of the RF waveform exacerbates some aspects of longitudinal space charge (LSC) induced degradation of beam quality, resulting in reduced peak current when interacting with coherent synchrotron radiation (CSR) effects.
3) Chicanes necessarily create a parasitic compression of the bunch during the final compression process and expose the (somewhat over-compressed) bunch to interaction with coherent transition radiation from the end of the penultimate dipole of the compressor.

It is possible to avoid all of these deficiencies by using acceleration on the falling side of the RF waveform and using a bunch compressor with $R_{56} > 0$ [1].

INTRODUCTION

Recent studies at the Jefferson Lab IR FEL Upgrade Driver focused on characterizing the impact of CSR with the goal of benchmarking measurements with simulation. The Driver is an energy recovery based linear accelerator used to condition an electron beam for high average power lasing in the infrared. Electrons are generated in a DC photocathode gun (135 pC), accelerated to 9 MeV and injected into the linac where they are further accelerated up to 130 MeV through three cryomodules. The spent electron beam is recirculated and phased in such a way that the beam is decelerated through the linac on the second pass. Nominal acceleration occurs off-crest at –10° to impart a phase-energy correlation across the bunch. The first- and second-order momentum compactions of the first Bates-style recirculation arc are set so that, in conjunction with the downstream chicane, the bunch is rotated upright at the wiggler and phase space curvature is eliminated. Following the undulator, the longitudinal phase space must be rotated back by 90° to energy compress the beam.

MEASURED EFFECT OF CSR

The experimental program consisted of characterizing the effects of CSR for two different longitudinal matches: accelerating on the rising (falling) side of RF waveform together with a negative (positive) momentum compaction for compression.

Accelerating 10° Before Crest

Measurements were made to quantify the effect of parasitic compressions on beam quality through the first Bates bend. With the nominal energy chirp the beam experiences 3 parasitic compressions. Quadrupole scans were performed at several locations around the machine and repeated with the linac cross-phased. Cross-phasing refers to switching the accelerating phase of only the middle cryomodule (which has the same gradient as the two outboard cryomodules combined) to the falling side of the RF waveform. Upon exiting the linac the energy

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#tennant@jlab.org

chirp is removed and the nearly mono-energetic distribution avoids parasitic compressions. Results of the measurements are summarized in Table 1. The small horizontal emittance growth through the machine for cross-phased measurements is not unexpected, while the effect of parasitic compressions is more dramatic. These measurements together with simulations suggest that while parasitic compressions in the Bates bend do not lead to copious CSR-induced energy loss, they do significantly degrade emittance in the bending plane.

Table 1: Normalized horizontal emittance and Twiss parameters at various locations in the machine. (0F corresponds to the injector, 2F to the exit of linac, 3F to the exit of first arc and 4F to the exit of the chicane).

	Cross-Phased			Nominal		
	ε_x (mm-mrad)	β_x (m)	α_x	ε_x (mm-mrad)	β_x (m)	α_x
0F	15.2	11.2	–0.1	15.2	11.2	–0.1
2F	17.5	11.8	6.3	17.9	12.9	6.6
3F	20.8	3.7	–1.0	30.5	3.1	–0.7
4F	21.3	11.8	–5.5	41.8	16.8	–8.0

Accelerating 10° After Crest

Nominally the R_{56} and T_{566} in the Bates bend are selected (using trim quadrupoles and sextupoles) such that together with a downstream chicane, the bunch is rotated upright at the wiggler. However, it is possible vary the trim quadrupoles to produce a range of linear momentum compactions from –0.5 m to +1.0 m. After moving the acceleration to the falling side of the RF waveform, data was recorded of the energy extracted via CSR (measuring BPMs in the dispersive region in the π-bend of the second Bates bend) as function of bunch compression. This is illustrated in Fig. 1. Most energy is extracted when full compression occurs at the optical cavity chicane (left dip) rather than at the end of the arc (right dip). While the R_{56} was varied in the arc, T_{566} was fixed such that the native T_{566} of the chicane corrects the curvature, generating high peak current and exacerbating the effects of CSR [2].

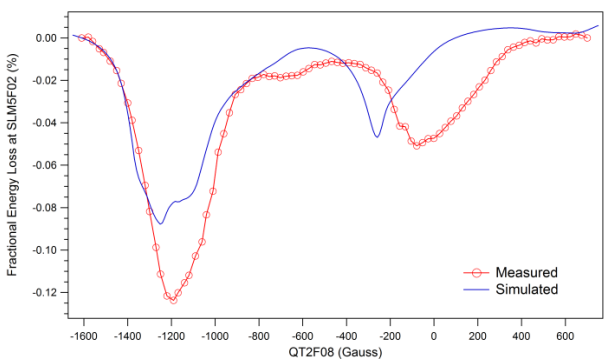

Figure 1: Measured and simulated CSR-induced energy loss as a function of compression state after acceleration on the falling part of the RF waveform.

In addition to measuring the CSR-induced energy loss, images from a synchrotron radiation monitor were recorded to capture details of the bunch momentum distribution while the compression state was varied (the synchrotron light monitor is located at a dispersive location where the horizontal beta function is small, effectively mapping the momentum distribution onto the horizontal axis of the viewer). An animation of the beam response to variable compression is available at [3]. Preliminary start-to-end simulation results show good agreement with measurement, even to the point of replicating observed filamentation on the momentum distribution (see Fig. 2).

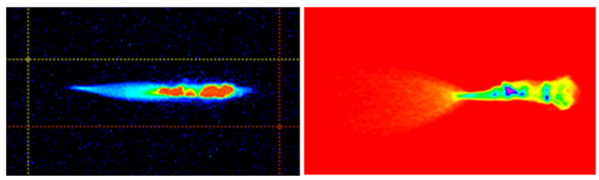

Figure 2: Observed beam momentum distribution modulation (left) compared with simulated results (right).

Figure 3 illustrates changes to the momentum distribution as measured in the second arc (projections plotted along momentum axis) as a function of the compression state (characterized by the strength of one of the quadrupoles varied in the first Bates bend). Two distinct troughs running through the surface plot are clearly discerned. As previously noted, a curved bunch in longitudinal phase space (e.g. when second-order compactions are not properly set) will limit the minimum compressed bunch length and generate one or more localized current spikes. It has been shown that a local concentration of charge can produce stronger CSR wakes than compared to a Gaussian distribution of the same rms length [4]. The strong CSR wake and its effect – namely the redistribution of energy within the distribution – is localized to the region of the current spike which itself moves temporally through the bunch as the compression state is changed. Note that the regions of depletion correspond to the measured maximum energy loss (compare to Fig. 1).

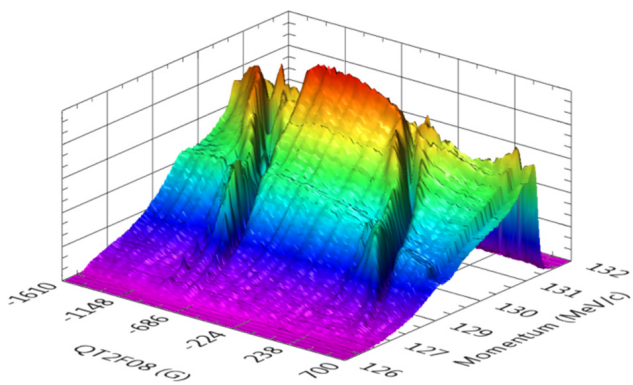

Figure 3: Surface plot illustrating the effects of CSR on the momentum distribution as a function of compression state.

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LASING WITH $R_{56} > 0$ COMPRESSION

The FEL itself serves as the best beam diagnostic. Leveraging the flexibility of the Driver to completely change the longitudinal match, a test was performed of lasing with compression using $R_{56} > 0$. Acceleration occurred on the falling side of the RF waveform and signs of the compactions were switched. Lasing was challenged by fact that wiggler gap control software was unavailable, keeping the wavelength "stuck" at value for which optical cavity mirrors performed poorly (over 50% losses). Additionally, the "high" reflector had higher transmission than the outcoupler requiring greater than 200% gain just to lase. Despite these issues, the system lased well. After optimization the wavelength was 762 nm with a (10-11) mm detuning curve and a (9.5-10) msec turn-on time (both typical values for the nominally configured system).

IMPLICATIONS FOR COMPRESSION

Accelerating on the falling side of the RF waveform and using a compressor with positive momentum compaction has important implications:

1) Positive compaction is the natural result of bending and is readily achieved in simple beamline configurations (e.g. a FODO arc) supporting simple and effective schemes for aberration compensation, rendering harmonic RF unnecessary.
2) LSC-induced phase space distortion, on the falling side of the RF waveform, increases the phase-energy correlation on the beam. Thus, LSC enhances the chirp, rather than suppressing it (as occurs on the rising side of the RF waveform), where the suppression can result in a potentially incompressible region of phase space.
3) Compressors can be configured to avoid any spurious over-compression; the final compression occurs in the back end of the final compressor dipole.

The idea of using a compressor arc leads one to contemplate recirculated linac driven light sources. The cost saving benefits of recirculating linacs are well known [5], but concerns about beam degradation, especially due to CSR, through 360° of bending presents a challenge. Progress on an emittance preserving, low microbunching instability (μBI) gain, isochronous arc is discussed below.

ISOCHRONOUS ARC DESIGN

We apply the compensation analysis of Reference [6] – as previously used by Borland [7] – to the design of transport systems for use with low emittance beams, and find that appropriately configured second order achromats will suppress transverse emittance growth due to CSR and appear to limit μBI gain [8]. A second-order achromat composed of superperiods that are individually linearly achromatic and isochronous meet all the requirements for the suppression of CSR effects. In this case, any CSR-induced momentum shift will be paired to a matching shift at a downstream location with the same lattice parameters and the same bunch length. The transverse phase space configuration is "inverted" by the (modulo) half-betatron wavelength phase separation. The impact of the second transverse momentum shift therefore completely cancels (to linear order) that of the first. Of considerable interest is the additional observation that these beam line designs also manifest little or no evidence of microbunching.

One such design is for a 1.3 GeV arc based on a modified CEBAF design. Simulation of transport with CSR was performed with elegant [9]. For an initial transverse normalized emittance of 0.25 mm-mrad and assuming an initially upright bunch of length of 3 psec and momentum spread 11.67 keV, the emittance is well-preserved over a broad range of bunch charges and initial (rms) bunch lengths. Though wake distortion is evident on the longitudinal distributions, there is no visible microbunching until the bunch charge approaches 1 nC. The modulation of the (linear) momentum compaction through the system is extremely small (maximum and minimum values are at the millimeter level) which analysis shows has very low microbunching gain (see Fig. 4) [10].

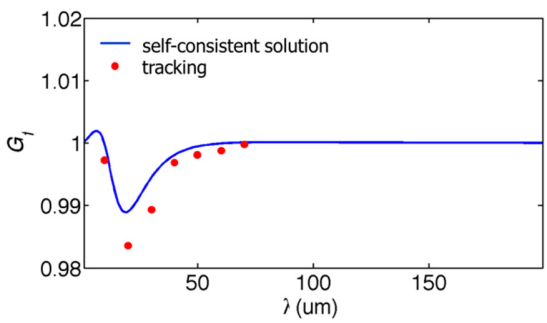

Figure 4: Microbunching gain spectrum as a function of modulation wavelength.

SUMMARY AND OUTLOOK

Using the native positive compaction of an arc for bunch compression leads one to consider the possibilities of recirculated-linac driven light sources. Design of a high energy isochronous arc which provides excellent suppression of CSR-induced emittance growth and limits the gain of the microbunching instability has been presented. Work on a compressor arc is in progress.

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