STUDY OF CSR EFFECTS IN THE JEFFERSON LABORATORY FEL DRIVER*

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Abstract

In a recent experiment conducted on the Jefferson Laboratory IR FEL driver the effects of coherent synchrotron radiation (CSR) on beam quality were studied. The primary goal of this work was to explore CSR output and effect on the beam with variation of the bunch compression in the IR recirculator. This experiment also provides a valuable opportunity to benchmark existing CSR models in a system that may not be fully represented by a 1-D CSR model. Here we present results from this experiment and compare to initial simulations of CSR in the magnetic compression chicane of the machine. Finally, we touch upon the possibility for CSR induced microbunching gain in the magnetic compression chicane, and show that parameters in the machine are such that it should be thoroughly damped.

INTRODUCTION

The Jefferson Laboratory energy recovery linac (ERL) IR FEL Driver [1] consists of a superconducting radio frequency (SRF) linac, allowing for CW operation, and a recirculating transport system. This recirculation of the beam back to the linac, after it has passed through the wiggler, allows for recapture of the RF energy before the beam is dumped. The IR FEL can operate at a repetition rate of 75 MHz with a charge per bunch of up to 135 pC and a beam energy of 160 MeV. This gives a very high average power of as much as 14 kW in the 0.9 to 10.5 μm range, from the FEL. ERL operation allows for a much more efficient machine, in terms of RF power required, however, this mode of operation necessitates a layout that allows for the electron bunches to recirculate back to the linac (see Figure 1 for machine layout) raising many challenges with respect to maintaining necessary beam quality and suppressing instabilities. The primary concern of this paper is coherent synchrotron radiation (CSR) which can occur from the passage of very short electron bunches through bending magnets. This effect can cause losses in beam energy and an increase in energy spread from the coherent radiation emission as well as growth in the beam emittance in the bending plane. Understanding and controlling CSR's effect on the electron beam is an important facet to optimizing the performance of an FEL.

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OVERVIEW OF RELEVANT BEAM EFFECTS

While there are a number of important effects that must be taken into account for operation of the ERL FEL driver, here, we restrict ourselves to the examination of two that are often interrelated and may cause problems. CSR and microbunching are an important set of collective effects that have been the focus of much attention recently, particularly, in X-ray FELs. CSR is especially a concern in the operation of high average current machines. For the Jefferson Laboratory FEL the power output of CSR has been measured to be around 0.2% which gives about 200 W/mA of CSR; this can produce undesirable heating and cause a measurable rise in vacuum pressure [1]. The microbunching instability has been an important consideration in the design and operation of many recent FELs. However, for the Jefferson Laboratory FEL no signs of the microbunching instability have been observed in measurements. This lack of microbunching gain is supported by calculations shown later in this paper.

CSR

Like incoherent synchrotron radiation (ISR), CSR is produced when the beam experiences acceleration, such as in a bending magnet. When the radiation wavelength is on the order of the bunch length, though, the emission will be coherent. Coherent emission produces a power output that scales as N^2 where N is the number of electrons in the bunch, as opposed to linear scaling with N of ISR. Because of the desire for high peak currents for FEL operation magnetic compression chicanes are commonly employed to reduce bunch length. Because the bunch becomes very short within the chicane, while it is traversing several bending magnets, CSR is always a serious concern in chicanes. The other place where CSR may be a concern, and which is unique to the ERL, is in the two 180 arcs. The effect of CSR when it occurs is the production of a CSR wake that travels from tail to head along the bunch. This wake will cause different changes in energy within different slices along the bunch, increasing the slice energy spread. Because this occurs in a dispersive region this change in energy is coupled to position in the bending plane and may cause a rise in emittance. In addition, there is obviously a net loss in energy from the CSR radiation. In a high average current machine this power loss may be considerable

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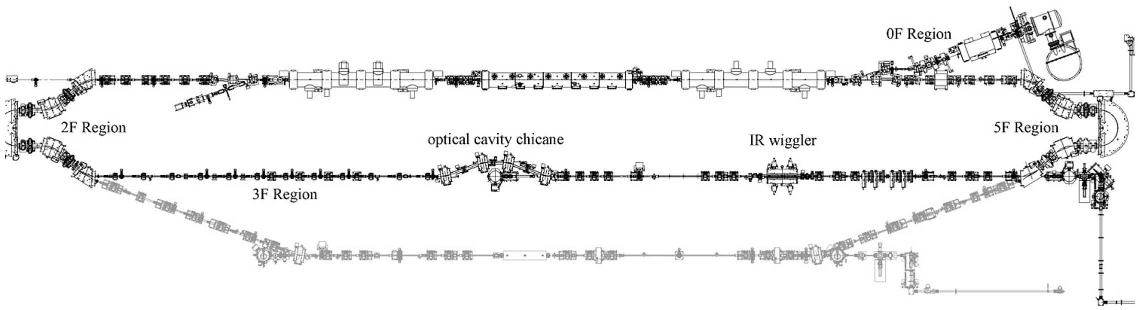

Figure 1: Layout of the IR FEL at Jefferson Laboratory.

and careful planning may be required to intercept and mitigate the impact of the radiation.

Microbunching

CSR also comes into play as a cause of the microbunching instability [2, 3]. Density modulation of the beam current may develop from the action of longitudinal space charge on shot-noise in a bunch, while the beam is at low energy, creating micro bunches within the macro bunch. These bunches may also radiate coherently, further exacerbating the problem of CSR. Even worse, this can have a further amplifying effect on the microbunching already present, greatly increasing its intensity. This may cause significant increases in the slice energy spread and emittance, both of which degrade FEL performance. Due to beam parameters, in particular, the relatively large transverse emittance $\epsilon_{n,x} \approx 9\ \mu m$ microbunching should not appear in the Jefferson Lab ERL. In the last section of this paper show calculations demonstrating that CSR microbunching will be damped out in the chicane.

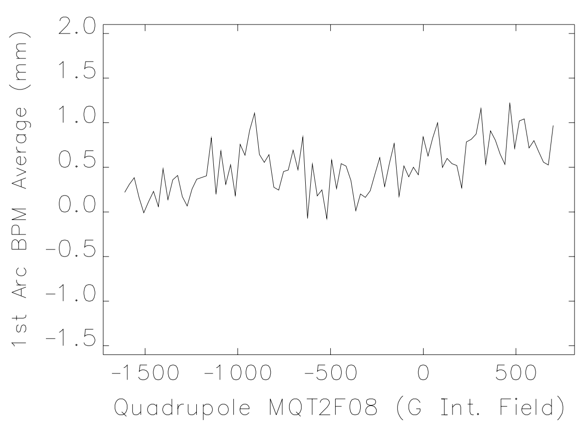

Figure 2: Average horizontal beam position as measured in the first arc. This measurement is used to remove any beam jitter present.

EXPERIMENTAL SETUP

While the 180 degree arcs contribute to CSR based effects on the beam they also provide an excellent system to measure CSR in the accelerator as a function of beam compression. The arcs, which are Bates type bends, contain two sets of two quadrupoles on either side of the 180 degree bend. By changing the strengths of the quadrupole sets while maintaining a fixed ratio between the strength of the first and second quadrupole of each set one may control the sign and magnitude of the R_{56} value in the Bates bend and thus vary the total R_{56} from the Bates bend and

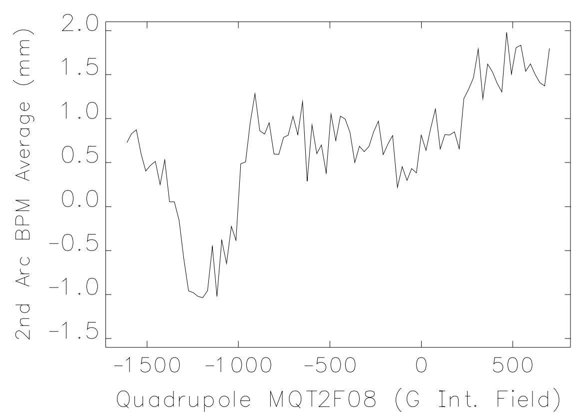

Figure 3: Average horizontal position as measured in the second arc. Because the measurement is taken in a dispersive section the horizontal position correlates to beam energy lost to CSR.

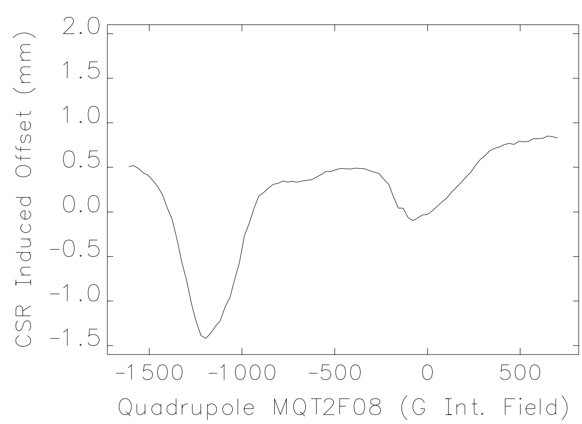

Figure 4: The difference between the measurement in arc two and arc one showing beam energy loss from CSR as a function of the maximum compression point.

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chicane, the chicane having a fixed R_{56} of -50 cm. In this way the compression point may be controlled, allowing for the study of beam energy losses and emittance growth as a function of the compression. For the measurement shown in this paper the bunch was accelerated with an RF phase 10 degrees after the crest, that is, on the falling side of the RF wave. This imparts a correlation between longitudinal position and energy, or chirp, with a sign $h < 0$. This requires that the total R_{56} of the accelerator be positive to compress the bunch.

To find the energy loss from CSR we may monitor the beams position in the dispersive regions of the first and second Bates bends using BPMs located immediately before and after the 180 degree bend in each arc. Measuring the average position from the two BPMs gives a measure of the beam energy variation while canceling out any residual betatron offset. This is due to the point-to-point imaging of the 180 degree bend with magnification of -1. Making such a measurement in each Bates bend and then subtracting the measurement in the first Bates bend (Figure 2) from the beam position measure in the second arc (Figure 3) allows for the removal of any common beam jitter. This result, showing just CSR impact on the beam as a function of maximum compression position is shown in Figure 4. This plot shows two dips in beam energy. The first of these occurs around the point of full compression at the end of the chicane, when the beam is very short in the 3rd and 4th dipoles of the chicane. The second occurs when the beam is fully compressed at the end of the Bates bend before it reaches the chicane.

SIMULATION OF CSR IN THE CHICANE

The code ELEGANT [4] was used for simulation of the effect of CSR on the beam in the magnetic compression chicane. For these simulations only the chicane was modeled and CSR was included in bends and drifts within the chicane. Shown in Figure 5 is a plot of the average energy deviation of the beam $< \delta >$ at the end of the chicane as a function of the Twiss parameter α_z before the chicane, which directly correlates to the beam chirp. The first large drop in energy occurs at the point of maximum compression, where the beam will be very short in the third and fourth dipoles as seen in Figure 6, which shows the RMS bunch length change σ_t along the length of the chicane. The second dip occurs when the chirp is such that the beam will over-compress in the chicane. In-between the second and third dipoles, in this case, the bunch becomes very short and gives off a large amount of CSR, see Figure 7, which shows the variation of $< \delta >$ along the length of the chicane. This second dip is much smaller and appears to have not been well resolved by the measurement that was taken (Figure 4). It should be noted that at maximum compression if the beam has an average current of 10 mA this equates to a power output of around 1000 W from CSR, according to this simulation. This CSR induced power loss will be high concentrated in the 3rd and 4th dipoles, as seen in Figure 7.

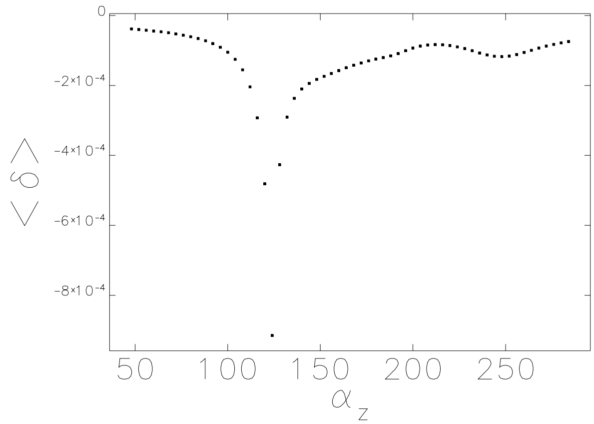

Figure 5: Simulation of energy lost in just the chicane as a function of the bunch's intial α_z which may be directly related to the beam chirp.

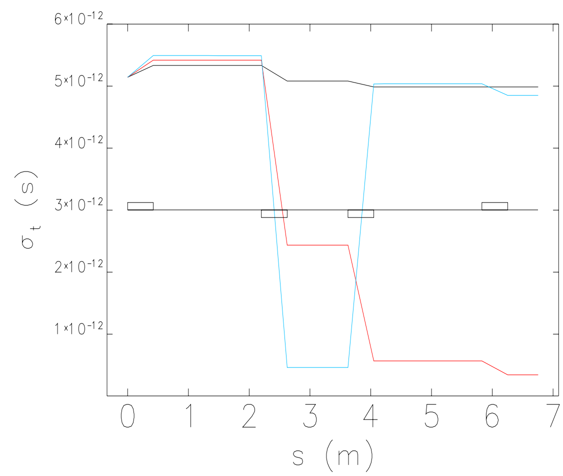

Figure 6: Simulation of the energy lost along the chicane for a beam with α_z=4, 132, and 240 in black, red, and blue respectively. Representing under-compression, near maximum compression, and over-compression.

Validity of the 1-D CSR Model

ELEGANT employs a 1-D model of CSR [5] that assumes the horizontal spread of the bunch is much smaller than the bunch length. This requirement may be expressed [6] as $\kappa = \sigma_\perp (\frac{1}{R\sigma_{||}^2})^{\frac{1}{3}} \ll 1$ sometimes called the Derbenev criterion. Here $\sigma_{||}$ is the bunch length, $\sigma_\perp$ is the bunch size in the bending plane, and R is the dipole bend radius. This corresponds to the assumption in the 1-D model that propagation of the CSR wake is well modeled by projecting the longitudinal profile of the beam onto a line tangent to the bend. However, if there is large transverse separation particles that appear to be able to see the CSR wake from a certain point in the beam in the 1-D model may in fact have too large a transverse separation for this to hold in an accurate 3-D description. Because of the comparatively large emittances for this machine the Derbenev parameter can reach $\kappa > 0.85$ for regions inside of dipoles where dispersion will be present and where the beam is being compressed.

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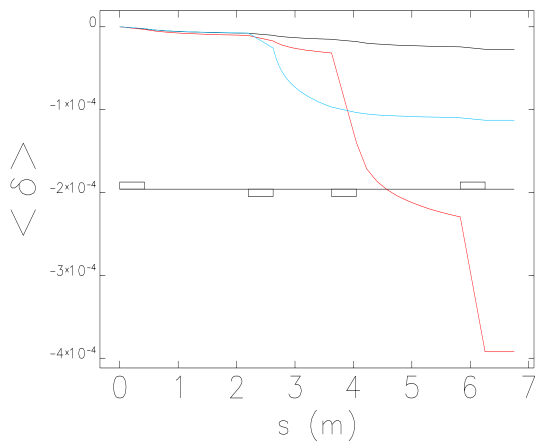

Figure 7: Simulation of the bunch length along the chicane for a beam with α_z=4, 132, and 240 in black, red, and blue respectively. Representing under-compression, near maximum compression, and over-compression.

The fact that this key assumption of the 1-D model is being so badly violated certainly necessitates further study with a code that employs a full 3-D CSR model, such as CSR-Track [7]. However, the current work does, so far, show a surprising degree of qualitative agreement with the experimental results.

CALCULATIONS OF CSR INDUCED MICROBUNCHING

During this experiment some filamentation of the energy spectrum of the beam was observed in measurements at the 2nd Bates bend as bunch compression was varied. Microbunching is one possible explanation for this observation. At 135 MeV the beam is too relativistic to pick up additional density modulation in drifts after acceleration. If there is large gain in density modulation within the chicane, however, this could cause increased energy modulation downstream. The degree of amplification of an initial density modulation in a chicane from CSR, though, decays exponentially based on the chicane R_{56} and the uncorrelated energy spread σ_δ of the beam.

This is because the chicane will shift the longitudinal position of off-energy particles by $\delta z = R_{56}\sigma_\delta$ washing out short wavelength modulation. To show this more quantitatively, gain curves may also be calculated from an analytic integral approximation [8]. The density modulation gain as a function of the initial modulation wavelength is plotted in Figure 8 for several different values of the beam chirp upstream of the chicane. Starting from no compression when the initial chirp, h, is zero to near full compression at $h = 2$. This calculation uses the parameters from Table 1. The initial current is calculated assuming a 135 pC bunch with a length of 5 ps before the chicane. As can be seen the density modulation gain is strongly suppressed until one reaches extremely large modulation wavelengths, on the order of the bunch size. This would suggest the microbunching gain induced from CSR in the chicane should not be a factor, and may actually damp down any previously collected modulation.

Table 1: IR Chicane and Beam Parameters

Parameter	Value
Energy	135 MeV
$I_{initial}$	27 A
$\gamma\epsilon_0$	9.77 μm
σ_δ	1.4×10^{-4}
R_{56}	-50 cm
ρ_0	1.2 m
L_b	0.424 m
ΔL	1.78 m

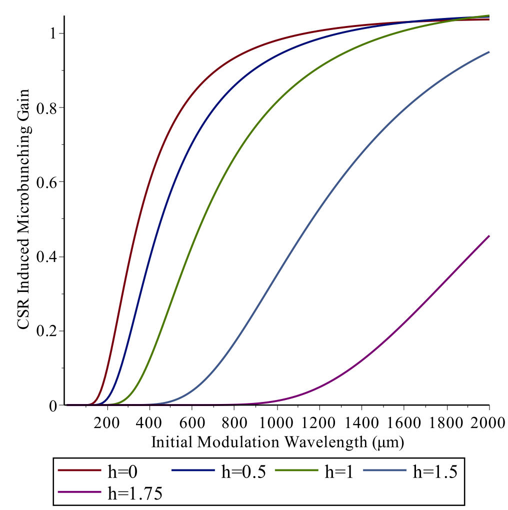

Figure 8: Gain curves as a function of initial modulation wavelength for the IR chicane. Gain remains extremely low in all cases and for high values of h, the beam chirp, the scale must be extended to wavelength on the order of the bunch size.

CONCLUSION

We have shown experimental measurements of the impact of CSR in the Jefferson Laboratory IR FEL driver. Initial simulations of CSR induced energy loss in the IR chicane show very promising qualitative agreement with the experiment. Because the normal beam parameters in the chicane violate the assumptions of the 1-D CSR model further simulation with a fully 3-D code is ongoing; however, surprisingly, the 1-D model seems to provide very good qualitative agreement with measurements. Finally, no signs of the microbunching instability have been experimentally observed. Calculations of microbunching gain from CSR support this and show that in almost all cases microbunching would be damped out in the chicane.

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REFERENCES

[1] S. Benson et al., “High Power Operation of The JLAB IR FEL Driver Accelerator”, Proceedings of PAC07, Albuquerque, New Mexico, USA., p.79.

[2] M. Borland, Y.-C. Chae, S. Milton, R. Soliday, V. Bharadwaj, P. Emma, P. Krejcik, C. Limborg, H.-D. Nuhn, M. Woodley, “Start-to-end jitter simulations of the linac coherent light source”, Proceedings of the PAC 2001, Chicago, IL, p. 2707.

[3] S. Heifets, G. Stupakov, “Beam instability and microbunching due to CSR”, Proceedings of the PAC 2001, Chicago.

[4] M. Borland, “elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation”, Advanced Photon Source LS-287, September 2000.

[5] M. Borland, “Simple method for particle tracking with coherent synchrotron radiation”, Phys. Rev. ST Accel. Beams 4, 070701 (2001)

[6] Ya. S. Derbenev, J. Rossbach, E. L. Saldin, V. D. Shiltsev, “Microbunch Radiative Tail-Head Interaction”, September 1995, TESLA-FEL 95-05.

[7] M. Dohlus, T. Limberg, “CSRtrack: Faster Calculation of 3-D CSR Effects”, Proceedings of the 2004 FEL Conference, 18-21

[8] Zhirong Huang and Kwang-Je Kim, “Formulas for coherent synchrotron radiation microbunching in a bunch compressor chicane”, Phys. Rev. ST Accel. Beams 5, 074401 (2002)

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