COHERENT SYNCHROTRON RADIATION IN ENERGY RECOVERY LINACS

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Abstract

Collective beam effects, including coherent synchrotron radiation (CSR), have been studied on free-electron lasers (FELs). Here we will discuss a particular case of the CSR effects, that in energy-recovery linacs (ERLs). Special consideration is given to these machines because of their high average beam power and the architecture of the machine for energy recovery forces extreme bends. A recent study conducted on the JLab IR FEL looked at how CSR impacts both average energy and the energy spectrum of the beam. Such studies are important, both broadly, to the understanding of CSR and more specifically for a number of proposed ERL projects. A few proposed examples include the MEIC bunched beam cooler ERL design and ERL FELs for potential lithography purposes that would operate in the EUV range.

INTRODUCTION

The damaging effects of coherent synchrotron radiation (CSR) have been an area of intense research for free-electron lasers (FELs). For the very short bunches required in many FELs the very intense CSR can cause a host of problems, such as, increasing emittance and the slice energy spread, as well as, giving rise to the microbunching instability [1–4]. For energy recovery linacs (ERLs) CSR can be especially troubling due to the design of these machines. In order to recover the stored power in the beam it must be brought back through the linac. This necessitates the use of arcs composed of many dipole magnets where there is the potential for a great deal of CSR generation. ERLs could also face additional issues [5] due to very high currents that are often used in such machines, from 10 mA up to 100 mA in proposed machines. CSR remains a difficult computational problem to model due to the scaling with number of particles N as N^2 [6]. To model CSR in most accelerator simulations a 1-D model is employed that projects the transverse bunch distribution onto a line [7]. Thus far this model has shown great success in comparison with experiments [8, 9]. Since the 1-D CSR model has been so effective there is still some question as to at what point it becomes unreliable. Various 2-D and 3-D models of CSR have been developed, but to date analysis of most experiments with the 1-D model has been sufficient [10–12]. As CSR continues to be a topic of ongoing interest within the FEL community it is important to continue to perform machine studies to help better characterize its affects and to improve theory and simulation. In the first part of this paper we give an overview of a recent experiment performed on the Jefferson Lab ERL FEL driver studying CSR [13] and describe some of the key lessons learned. The second part reviews some ongoing accelerator projects for which CSR and other collective effects instabilities may be a key concern.

JLAB EXPERIMENT DESCRIPTION

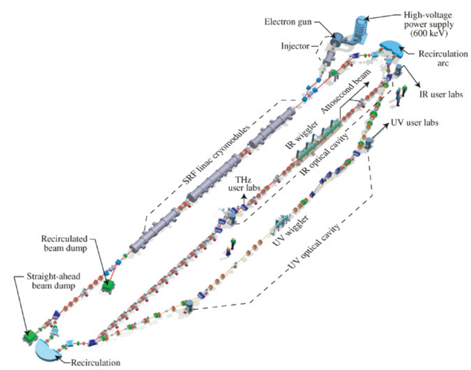

Figure 1: Layout of the JLab FEL. The IR wiggler line was used in the experiment described here.

The JLab ERL IR FEL driver [14] (Fig. 1) consists of an SRF linac that was used to accelerate the 9-MeV beam from the injector up to 135 MeV. The beam passes through the first recirculation arc which is used to provide first and second order longitudinal phase space control through the use of quadrupole and sextupole magnets placed in dispersive regions of the arc. By tuning the quadrupoles it is possible to easily manipulate the total momentum compaction (R_{56}) of the machine. Final compression of the bunch is normally performed in a standard four-dipole chicane immediately before the wiggler. This chicane also provides separation between the FEL optical components and electron beam. After passage through the wiggler (not active during the experiment) the beam passes through a THz suppression chicane [15] which serves to decompress the bunch slightly before it reaches the second recirculation arc. This decompression helps to alleviate heating on the downstream FEL optics due to CSR production in the leading dipole of the second arc. In the second arc the beam again undergoes more

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conditioning in the longitudinal phase space, this time in preparation for energy recovery when it passes back through the linac [16].

In this experiment the impact of CSR on average energy was studied by manipulating the previously mentioned quadrupoles in the first arc to change the point of maximum compression. In addition, a synchrotron light monitor was used in a dispersive section of the second arc, where horizontal position will be closely matched to energy, to capture the energy spectrum of the bunch while the compression point was being moved.

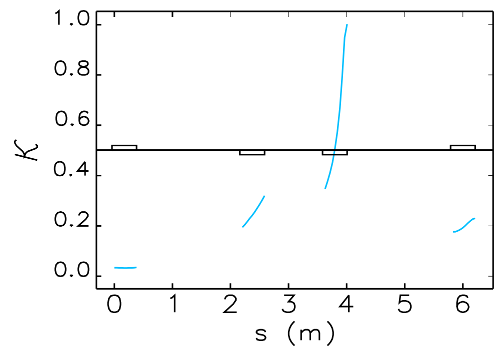

Figure 2: The Derbenev parameter, κ, plotted within the dipoles of the optical cavity chicane of the JLab FEL.

KEY LESSONS

CSR in Drifts

While CSR is produced inside bending magnets the CSR wake may continue to propagate out of the dipole for some distance. Over this period the electron bunch and CSR may continue to interact leading to an impact on the energy of the electron bunch. Due to the fact that the CSR wake has a spatial dependence based upon the longitudinal electron bunch structure this will lead to a heavily position dependent change in energy along the bunch. This interaction will manifest itself then as a 'fragmentation' in the energy spectrum which has been noted in several experiments at various facilities [17, 18].

Sextupole Curvature Correction

It is standard for many FELs to make use of a higher-order harmonic cavity placed before the chicane to correct for second-order curvature effects that will appear after compression in a chicane. The JLab FEL, however, uses sextupoles in the first recirculation arc to fulfill this need instead. It is interesting to note that simulations suggest that the proper tuning of these sextupoles can be used to help alleviate energy fragmentation, while still fulfilling their intended purpose of linearize the beam.

2-D CSR Effects

As noted CSR is normally simulated using a projected 1-D model. This model assumes the bunch will be much larger longitudinally than transversely. This is normally quantified using the Derbenev parameter [19]. Which is given by $\kappa = \sigma_{\perp}(\frac{1}{R\sigma_{\parallel}^2})^{\frac{1}{3}} \ll 1$. Where $\sigma_{\perp}$ is bunch size in the bending plane and $\sigma_{\parallel}$ is the bunch length. However, this criterion is not well satisfied in the JLab FEL chicane as shown in a plot of κ within the dipoles of the chicane in Fig. 2. This illustrates the point that better understanding of 2-D and 3-D CSR effects may be important for understanding how to mitigate CSR effects in future high-power accelerators.

FUTURE HIGH-POWER MACHINES

With the success of such facilities as the JLab FEL [20], Novosibirsk ERL [21], and ALICE [22] the successful operation of ERL facilities has been demonstrated. There is now considerable interest for ERLs, both to drive light-sources, and for use in high-energy and nuclear physics. Examples of ongoing projects include: the operational Compact ERL test facility at KEK [23], the proprosed Cornell ERL lightsource [24], and the Large Hadron Electron Collider (LHeC) [25]. The proposed design for the Medium Energy Electron-Ion Collider (MEIC) would employ an ERL driven electron cooling ring to increase brightness [26]. The proposed electron cooler design would require bunches with 2 nC of charge at a repetition rate of 750 MHz and energy of 55 MeV [27]. With such high bunch charges even a very long bunch may experience significant degradation due to CSR induced microbunching [28]. While recent design studies suggest that careful design of the ring lattice may allow for suppression of the microbunching instability [29] this operating regime remain less explored than that of VUV/X-ray FELs. There is also growing interest in the use of ERLs to power an EUV FEL for use in lithography [30, 31]. Such a system would require 0.5 - 1.5 kW average power at 6.7/13.5 nm and a pulse repetition rate of several hundred kHz. In order to maintain requirements on emittance and energy spread [32], around $\epsilon_x < 1 - 2\ \mu m$ and $\sigma_\delta = 2x10^{-4}$, for FEL operation the ERL design will need to be optimized to reduce CSR effects.

CONCLUSION

Energy recovery linacs hold a great deal of promise for high-power applications. However, as machines progress to higher powers and tighter limits on beam quality it becomes more essential to understand the role that CSR plays in beam dynamics. As shown in recent work on the JLab ERL FEL simulations using the 1-D CSR model show good agreement to measurements of CSR's impact on the beam. The work also provided a number of interesting insights into both operation and correct modeling of ERLs with regard to CSR. This reinforces the need to continue such experiments at other facilities. This is especially true given the growing interest demonstrated in using ERLs for a variety of applications.

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