ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPA079

SIMULATIONS OF RADIATION REACTION IN INVERSE COMPTON SCATTERING*

E. Breen†, E. Rogers, R. Shahan, E. Johnson, G. Krafft[1], B. Terzić, Old Dominion University, Norfolk, USA
G. Wilson, Regent Unviersity, Virginia Beach, USA
[1]also at Jefferson Lab, Newport News, USA

Abstract

The effect of radiation reaction is often negligible in inverse Compton scattering. However, in the nonlinear Compton regime, at high laser fields and high electron beam energies where electron recoil must be properly accounted for, there is experimental data which demonstrates the onset of radiation reaction [1]. We model the radiation reaction as a series of emissions from individual electrons with decreasing energy. This allows us to use the code we previously developed for simulating single-emission inverse Compton scattering events [2]. We use the new code to simulate the experiment reported in Cole et al. 2018, and to compare it to other models of radiation reaction.

INTRODUCTION

Commonly in experimental setups, the effects of radiation reaction are not large enough to be considered in calculations. As efforts continue in the development of high-intensity lasers and ultra-relativistic electron beams however, radiation reaction will likely become a larger issue in resultant spectra. Calculating radiation reaction exactly is computationally difficult, and there are several differing models. Here, we develop a calculation in order to include radiation reaction effects in a computed spectrum. By modeling the radiation reaction phenomenon as a series of discrete emission occurring at different calculated energies, we are able to use previously developed code [2] in order to generate spectra for each emission. We then combine all calculated emission spectra in order to create a total spectrum which includes radiation reaction effects.

CALCULATIONS

Our code models radiation reaction as a series of emissions occurring at decreasing energies. In our calculations an electron has some initial energy E_0 as it passes through the laser pulse. Due to conservation of energy, after emitting some radiation with energy E_{rad} the electron experiences some recoil, and now has an energy of $E_1 = E_0 - E_{rad}$. If the electron emits radiation once more, it will then emit radiation with its new lower energy, and as such the spectrum produced by a second emission will be red-shifted compared to the original spectrum. This process would continue for successive emissions, decreasing in energy each time.

The exponential falloff for a given spectrum was observed to follow a relationship related to a quantity ε_{crit} [1]. This behavior can be described by

$$\frac{dN}{dE} \propto E^{-2/3} e^{-E/\varepsilon_{crit}} \tag{1}$$

This relationship was observed in spectra where the presence of radiation reaction was expected, however this exponential falloff which is related to a value ε_{crit} is also found in spectra with no radiation reaction included. In these cases, the value of ε_{crit} is the analytic value for Thompson scattering from the value of the critical frequency [3]

$$\varepsilon_{crit} = 3\hbar\gamma^2 2\pi \frac{c}{\lambda} a_0 \tag{2}$$

In the code SENSE [2], the spectrum for each electron at a given energy is calculated. The relationship between spectra at different energies is known, thus for a single electron the spectrum calculated can be shifted to reflect the spectrum for an electron which has a different initial energy but otherwise has the same experimental parameters. In order to model radiation reaction then, we calculate the expected number of photon emissions for each electron and generate the spectrum for each individual emission. After each emission, the electron loses energy in the form of photons with an average value of $E_{rad} = \varepsilon_{crit}/3$ [1]. By using the analytic expression for ε_{crit} for each event, we are then able to sum the spectra together in order to create a total spectrum. This spectrum now includes both the original calculated spectrum and the additional effects due to radiation reaction. In order to calculate these radiation reaction effects, our code is only required to calculate a single spectrum from which all others in the system can be generated, thus we can calculated spectra with radiation reaction effects without greatly increasing the computational complexity.

In spectra where radiation reaction effects are present, the spectra follow the behavior described in Eq. (1), though in this case the value of ε_{crit} is no longer the analytic value calculated from the critical frequency of the spectrum. Instead, we must calculate a new value which includes behavior from additional emissions. For the total spectrum, we are able to calculate one total ε_{crit} by fitting a single spectrum to relationship described in Eq. (1) and using the ε_{crit} values of each individual emission:

$$e^{1/\varepsilon_{tot}} \propto \sum e^{1/\varepsilon_n} \tag{3}$$

Where ε_n are the values obtained from the critical frequency for each emission. This allows us to compare results from SENSE with experimental data obtained from [1] in order to verify our model's success at computing a spectrum which captures the effects of radiation reaction.

* WORK SUPPORTED BY OLD DOMINION UNIVERSITY AND JEFFERSON LAB
† ebree001@odu.edu

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPA079

MODEL COMPARISON

Using the analytic ε_{crit} value for each individual emission, the SENSE code was modified to include radiation reaction effects and the calculation of a total ε_{crit} value for the composite spectrum. Calculations presented in Cole et al. 2018 were performed for a range of initial electron beam energies $E_{initial} = 550 \pm 20$MeV, and normalized laser amplitudes $4 \leq a_0 \leq 20$ to produce a range of calculations for comparison to experimental values. Over this spread of initial energies and a_0 values, SENSE calculated the total electron energy loss and ε_{crit} value of each spectrum. The range of ε_{crit} values varies with a_0 according to Fig. 1, and the range of ε_{crit} values compared to final energies is graphed alongside the experimental data extracted from the paper by Cole et al. 2018 in Fig. 2.

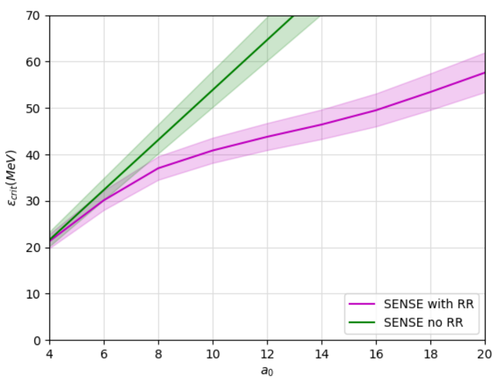

Figure 1: Calculated ε_{crit} over a range of a_0 values.

In SENSE calculations which do not include radiation reaction effects, the value of ε_{crit} is the analytic value from Eq. (2) which is directly proportional to a_0. For calculations with radiation reaction effects included, the value of ε_{crit} diverges from the no radiation reaction case as a_0 increases, with the effects of radiation reaction becoming stronger with larger a_0 values.

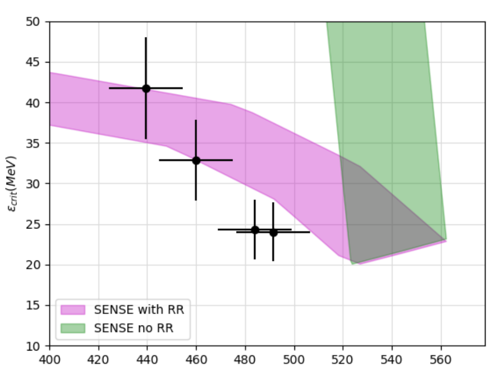

Figure 2: Calculated ε_{crit} versus final electron energy for SENSE calculations with data points extracted from Cole et al. 2018.

As shown in Fig. 2, the SENSE results where no radiation reaction effects are included appear to greatly underestimate the electron beam energy loss as these calculations assume single emissions. Meanwhile, in calculations with radiation reaction effects included the SENSE calculated ε_{crit} and final energies for spectra over the range presented in Cole et al. 2018 show a strong correlation to experimental data points.

CONCLUSION

Calculating spectra which include radiation reaction effects can be computationally difficult, but by modelling radiation reaction as a series of photon emissions SENSE has produced promising results compared to experimental data. Results from SENSE with the new radiation reaction model lie between predictions from reference [1]'s classical and quantum models, demonstrating this model's success in computing radiation reaction effects compared to other methods. This demonstrates that with the new method for the inclusion of radiation reaction effects SENSE may be able to more accurately calculate spectra in regimes where radiation reaction produces a measurable effect on the spectral output.

REFERENCES

[1] J. M. Cole, K. T. Behm, E. Gerstmayr, T. G. Blackburn, J. C. Wood, C. D. Baird, M. J. Duff, C. Harvey, A. Ilderton, A. S. Joglekar, K. Krushelnick, S. Kuschel, M. Marklund, P. McKenna, C. D. Murphy, K. Poder, C. P. Ridgers, G. M. Samarin, G. Sarri, D. R. Symes, A. G. R. Thomas, J. Warwick, M. Zepf, Z. Najmudin, and S. P. D. Mangles. Phys. Rev. X, **8**:011020, 2 (2018).

[2] B. Terzić, A. Brown, I. Drebot, T. Hagerman, E. Johnson, G. Krafft, C. Maroli, V. Petrillo, and M. Ruijter. EPL (Europhysics Letters), **126**(1):12003, (2019).

[3] J. Jackson. *Classical Electrodynamics* 3rd ed. (John Wiley & Sons, Inc., U.S.A.,1999).