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ANALYTICAL CALCULATIONS FOR THOMSON BACKSCATTERING BASED LIGHT SOURCES

P. Volz*, A. Meseck, Helmholtz-Zentrums Berlin für Materialien und Energie, Berlin, Germany

Abstract

There is a rising interest in Thomson-backscattering based light sources, as scattering intense laser radiation on MeV electrons produces high energy photons that would require GeV or even TeV electron beams when using conventional undulators or dipoles. Particularly, medium energy high brightness beams delivered by LINACs or Energy Recovery LINACs, such as bERLinPro being built at Helmholtz-Zentrum Berlin, seem suitable for these sources. In order to study the merit of Thomson-backscattering-based light sources, we are developing an analytical code to simulate the characteristics of the Thomson scattered radiation. The code calculates the distribution of scattered radiation depending on the incident angle and polarization of the laser radiation. Also the impact of the incident laser polarization and the full 6D bunch profile, including microbunching, are incorporated. The Status of the code and first results will be presented.

INTRODUCTION

Shortly after the invention of the LASER the idea of Thomsaon-backscattering light sources emerged [1]. Only in recent years however did lasers become powerful enough to make these sources viable due to the small Thomson scattering cross section. In the case of Thomson backscattering a relativistic electron beam interacts with a counter-propagating laser field. The backscattered photons travel in the direction of the electron beam in a small cone with an opening angle proportional to $1/\gamma$. The scattered laser photons experience a Doppler shift according to the energy of the electrons they are scattered on. This allows Thomson backscattering sources to produce very high energy photons, from relatively low energy electron beams, that would otherwise require GeV electron energies. Thomson scattering is the low energy limit of Compton scattering. The Thomson limit is accurate if the photon energy in the particle's rest frame is significantly lower than its rest mass.

Nowadays the demand for beam time at hard X-ray synchrotron facilities heavily outweighs supply. Such facilities however are very cost prohibitive to build and operate. Thomson-backscattering light sources provide an alternative to conventional sources at a cost that would be manageable for smaller laboratories and universities. Furthermore, in recent years there have been advances in the development of high brightness electron beam sources in both classical linac, and energy recovery linac (ERL) configuration. These sources provide electron beams with very low energy spread and emittance which results in less quality degradation of the backscattered light. This has opened up new possibilities for high performance ERL based Thomson backscattering light sources. The design and development of such a source requires a fast code that takes into account the relevant properties of the electron beam and laser pulse to calculate the critical properties of the backscattered radiation field. The development of such a code is the goal of the presented work.

First we will present a short description of our code, followed by some test cases to validate its results. Then we will present our first results in simulating the radiation of microbunched beams. Finishing off with an outlook of what improvements are planned.

CODE DESCRIPTION

The goal of our code is to calculate the spatial and spectral radiation distribution for different Thomson scattering events. It has to include the laser polarization, the incident angle between the laser and the electron beam, and the coherent effects resulting from the full 6D bunch profile of the beam. As of now emittance cannot be fully incorporated by the code because evaluation of transverse momentum distribution is not yet implemented. The laser is treated as a flat top pulse with no rise time or fringe effects. The 6D particle configuration can be imported from ascii files in ASTRA [2] output format. The underlying calculations are based on an Evaluation of Liénard-Wiechert potentials. The derivation of the formulas is shown in detail in [3] and [4]. The code does not use numerical integration. The essential calculations are based on complex Bessel functions.

Our code can calculate the spatial intensity distribution of the radiation produced by electrons interacting with a circularly or linearly polarized laser. The incident angle between the laser and the electron beam as well as the detector size and position can be chosen freely. The detector is modeled as grid of pixels. The number of pixels together with the size of the detector dictates the resolution. The backscattered radiation generated by individual particles are added up at each pixel. For multiple particles either the intensities or the amplitude of the radiation generated by the individual particles can be added. As will be explained in the following sections, the addition of amplitudes is necessary for the correct calculation of coherent effects.

A simulation run with 200 k particles and a detector resolution of 80×80 pixels takes around 2000 s on a current workstation CPU (single core load). The computation time scales linearly with the number of particles.

CODE VALIDATION

To validate our code we simulated some simple scenarios for which we have a clear expectation of results.

* paul.volz@helmholtz-berlin.de

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Thomson Scattering on Single Electrons

The simplest case is the scattering of laser radiation on a single electron. For this case there are a number of simulations and analytical studies available, e.g. [3,4]. In particular, the spatial radiation distribution of scattering on a single electron for both circular and linear polarization of the incident laser has been derived in [3] and [4]. In [3], figure 2 shows the intensity distribution as a function of photon energy and polar angle to the detector. Our code can produce those plots as shown in Fig. 1. Our code also reproduces

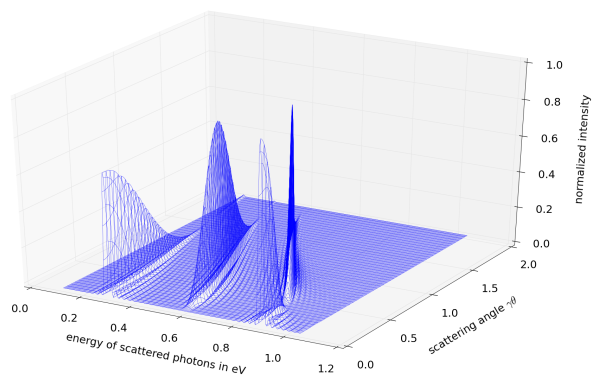

Figure 1: Normalized intensity as a function of scattered photon energy and scattering angle $\gamma\theta$ of the radiation scattered by a relativistic electron ($\gamma = 69.5$) from a counterpropagating linearly polarized laser pulse.

the results for both polarizations and for different incident angles shown in figures 3, 4, 6, 7, and 9 in [4]. Figure 2 shows the results for a linearly polarized laser pulse and Fig. 3 shows the circularly polarized case.

Coherent Addition

When looking at the radiation produced by more then one electron we need to make the distinction between coherent and incoherent addition. In the incoherent case the total intensity is just a superposition of intensities generated by scattering on single electrons. This case is examined for example by P. Tomassini et al. [5]. If we want to fully investigate the effects of the electron bunch structure we also have to take into account coherent addition. In this case we have to consider the complex amplitudes of the radiation produced by each electron. This allows us to take into account the phase of the propagating radiation and to calculate interference at the detector accordingly. In our code the phase is calculated by analyzing the path length to every detector pixel for the radiation field generated by each electron together with its frequency. The Thomson backscattering process can be compared to an electron traveling through an undulator. This way we can form some expectations based on what we know about coherent addition of electron spectra in undulators. There are however some key differences between an undulator field and the one produced by a laser pulse. The field of an undulator is constant in time. Two electrons passing through the undulator will witness the same field at a given point in space. The laser field on the other hand oscillates in both time and space as the pulse propagates. This introduces another phase factor that needs to be taken into account. As a proof of concept we simulated the case of two electrons at different longitudinal distances from each other.

For two electrons at the same position we expect a four-fold increase in intensity when adding coherently, compared to a two-fold increase for incoherent addition. Figure 4 shows the comparison between the intensities of radiation produced by a single electron and by two identical electrons treated coherently. As expected we see a four fold increase.

For two electrons half a wavelength apart the naive expectation considering an undulator field would be a phase difference of 180° and therefore zero intensity at the center of the detector. Away from the detector center the path length and therefore the phase difference changes so we would expect an interference pattern. Figure 5 shows the spectrum for the described case. In the center of the detector there is an intensity peak instead of a minimum. This is due to the additional phase factor of the laser field. If we omit this phase factor we get the expected result from an undulator case as shown in Fig. 6. The same test can be done for constructive interference with a phase difference of 360°. This means the two electrons are a full wave length apart. Figure 7 shows the coherent addition of scattered radiation including the laser phase factor and Fig. 8 shows the case where the laser phase has been omitted. This shows that the code produces the expected results for coherent addition of electron spectra and we can proceed to investigate microbunching effects.

RESULTS

As a first test we simulate a circularly polarized laser pulse scattering head on with an electron bunch comprised of 200 k particles. The electron bunch and laser parameters are listed in Table 1. We compare three different electron beams, two

Table 1: Parameters Used in Simulations

Electron Bunch	
energy	35.5 MeV
γ	69.5
Laser Pulse	
λ	2.665 cm
number of periods in pulse	7
pulse duration	622 ps
a_0	2
intensity	7.79 GW/cm^2

microbunched beams with different energy spreads and a Gaussian beam with similar energy spread. To accentuate the effects of microbunching all three beams had no transverse momentum or spread. The electric field amplitudes of the radiation generated by the single particles were added to correctly incorporate coherent effects. This causes a lot of noise because most of the radiation gets canceled out by

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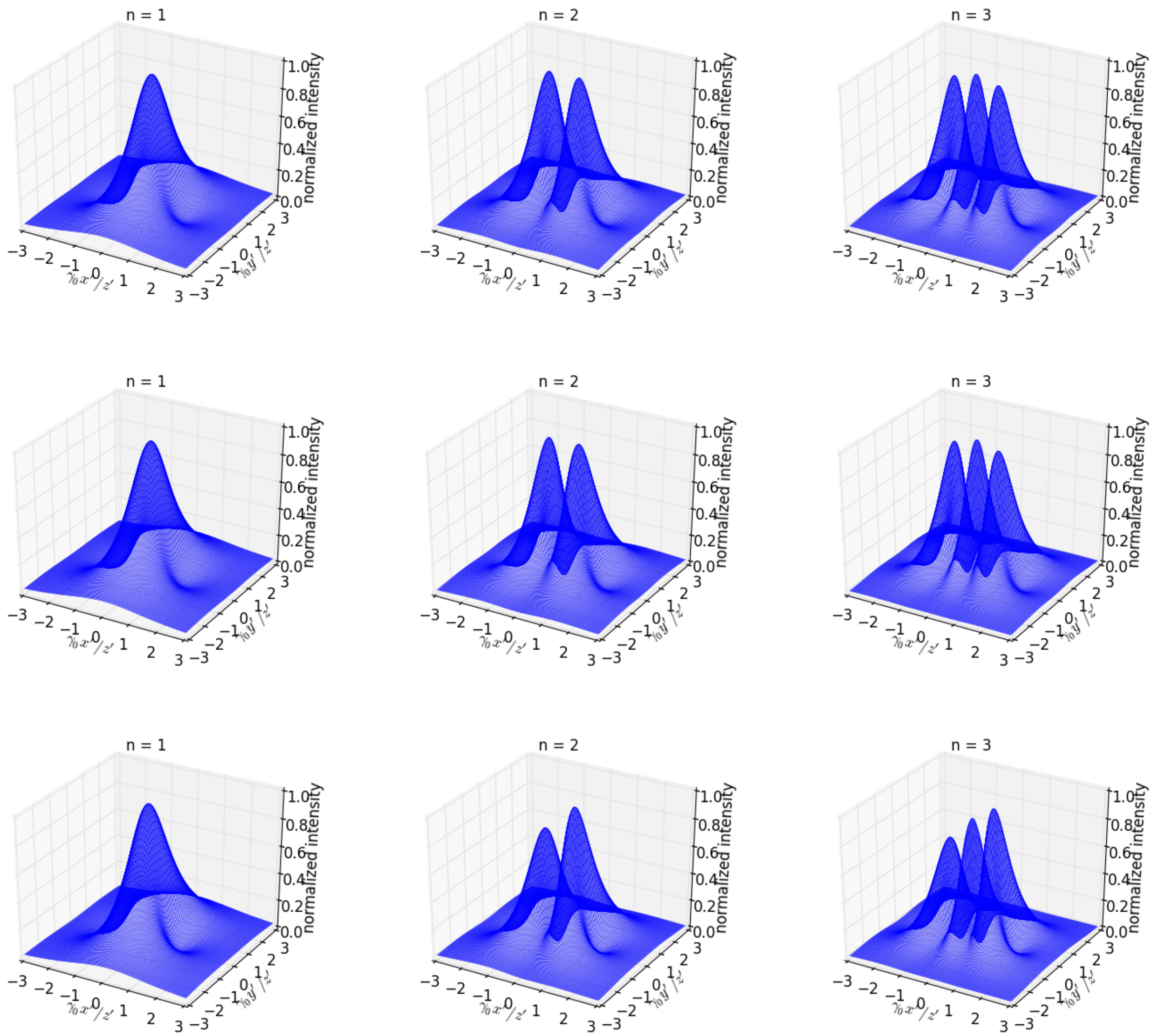

Figure 2: Normalized Intensity of radiation scattered by a relativistic electron ($\gamma = 10$) from a high intensity ($a_0 = 2$) linearly polarized laser pulse, viewed in plane of the detector. The detector is located at z' and centered on the electron beam axis. Distances in x', y' are measured in units $\gamma_0(x'/z'), \gamma_0(y'/z') \propto \gamma_0\theta$. Head-on scattering on top, transverse scattering with the electron moving perpendicular to the laser's plane of polarization in the middle, transverse scattering with the electron moving in the laser's plane of polarization on the bottom. The first three harmonics are shown.

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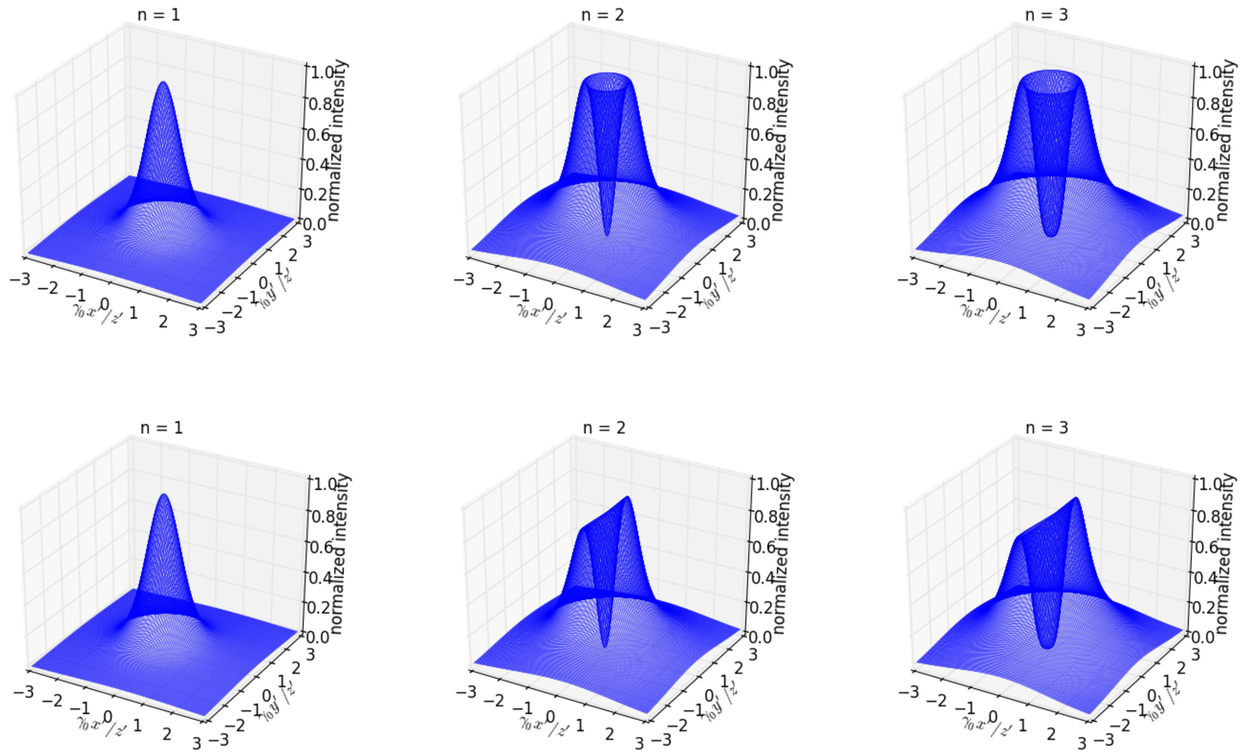

Figure 3: Normalized Intensity of radiation scattered by a relativistic electron ($\gamma = 10$) from a high intensity ($a_0 = 2$) circularly polarized laser pulse, viewed in plane of the detector. The detector is located at z' and centered on the electron beam axis. Distances in x', y' are measured in units $\gamma_0(x'/z'), \gamma_0(y'/z') \propto \gamma_0\theta$. Head-on scattering on top, transverse scattering on the bottom. The first three harmonics are shown.

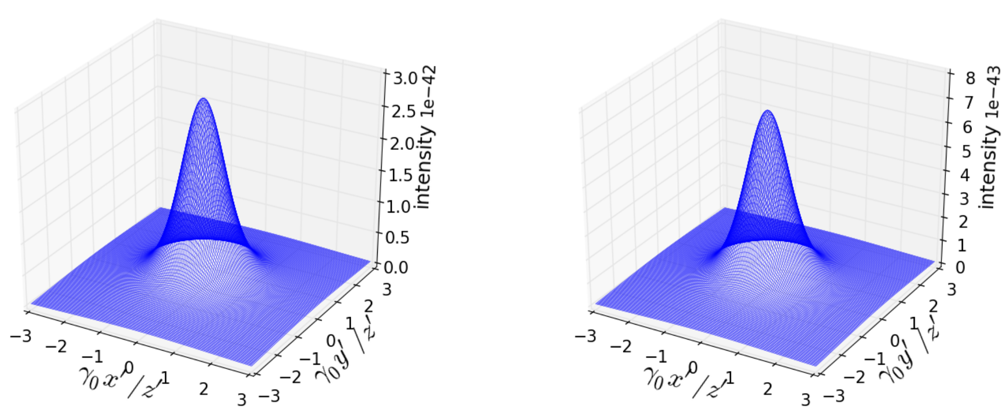

Figure 4: Intensity of radiation in arbitrary units produced by a single electron on the right and by two identical electrons treated coherently on the left. The coherent addition of radiation increases the intensity four-fold.

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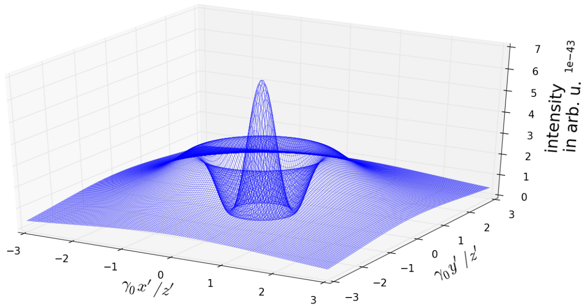

Figure 5: Two electrons with a longitudinal distance of half a wavelength. Laser wavelength of 500 nm and $\gamma = 10$.

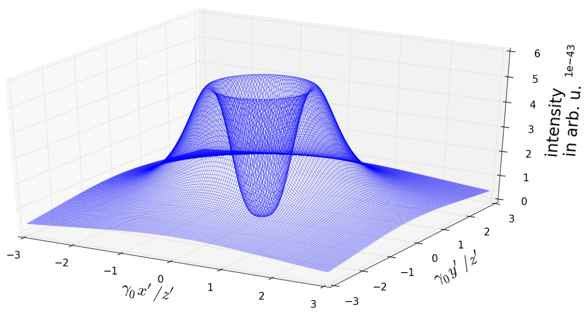

Figure 6: Two electrons with a longitudinal distance of half a wavelength. Laser wavelength of 500 nm and $\gamma = 10$. The laser phase factor has been omitted.

phase difference to radiation generated by other particles in the bunch thus fewer particles effectively contribute to the spectrum. This noise is amplified by the pseudo-random noise reduction algorithms that most particle tracking codes use to generate their electron bunches. In this case the bunch was generated with ASTRA, which uses Hammersley sets. Figure 9 shows the spacial intensity distribution of the radiation generated by a Gaussian electron bunch when the field amplitudes are summed up. As a comparison Fig. 10 shows the incoherent intensity generated by the same bunch.

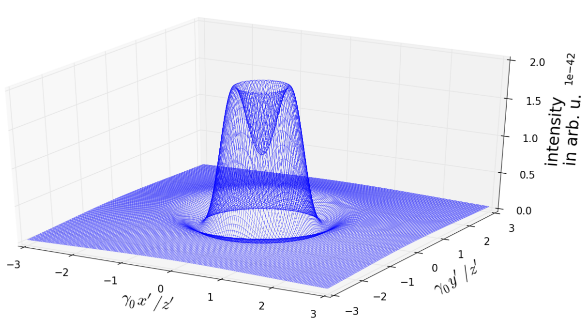

Figure 7: Two electrons with a longitudinal distance of a full wavelength. Laser wavelength of 500 nm and $\gamma = 10$.

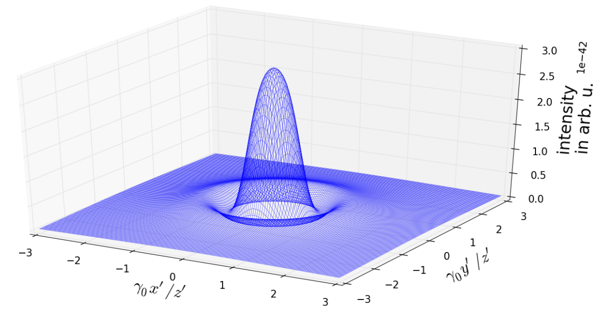

Figure 8: Two electrons with a longitudinal distance of a full wavelength. Laser wavelength of 500 nm and $\gamma = 10$. The laser phase factor has been omitted.

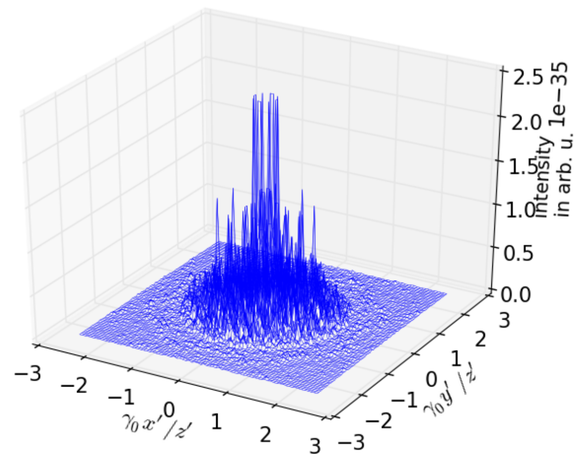

Figure 9: Coherent addition of radiation generated by electrons from a bunch with a Gaussian longitudinal distribution and energy spread.

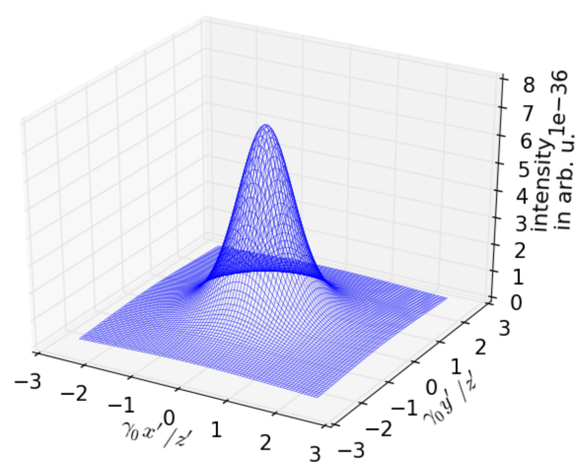

Figure 10: Incoherent addition of radiation generated by electrons from a bunch with a Gaussian longitudinal distribution and energy spread.

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Microbunching

Microbunching refers to a density modulation within an electron bunch. This allows for a coherent emission of photons at distinct frequencies and therefore greatly increased intensity. To test the feasibility of microbunching in Thomson backscattering sources, we simulated two microbunched beams with different energy spreads. The energy spread and longitudinal particle distribution of one case is shown in Fig. 11. The corresponding spatial intensity distribution of the coherent radiation is shown in Fig. 12. Figure 13 shows the case with higher energy spread. A higher energy spread seems to be detrimental to the intensity. However, compared to Fig. 9 the differences aren't immediately obvious.

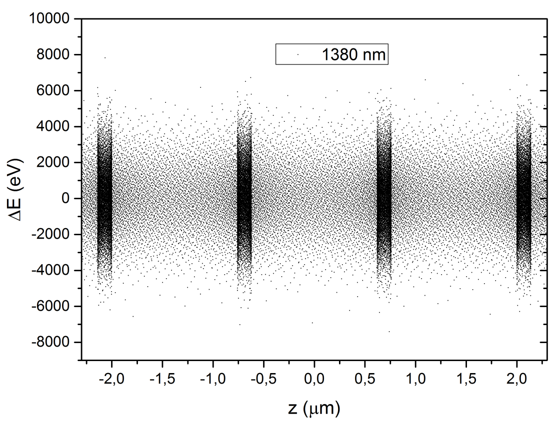

Figure 11: Energy spread and longitudinal electron distribution of the simulated bunch.

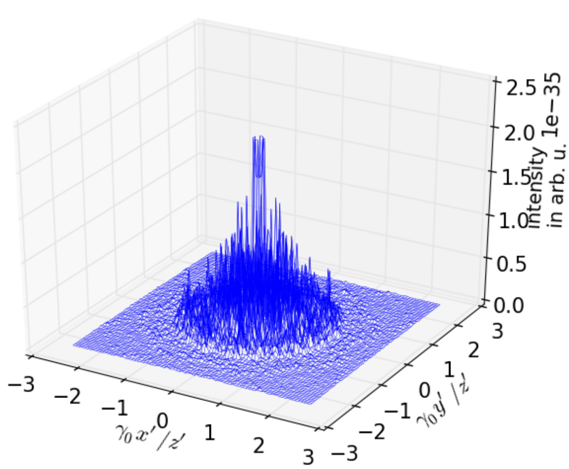

Figure 12: Coherent addition of radiation generated by electrons from a microbunched beam and a relatively small energy spread.

CONCLUSION AND OUTLOOK

A fast analytical code has been developed to simulate coherent radiation interactions in Thomson backscattering

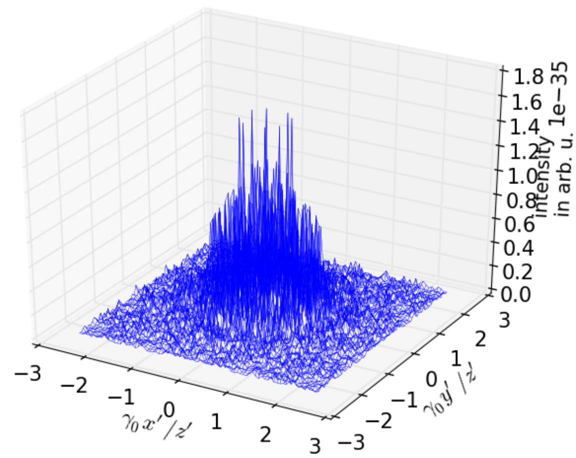

Figure 13: Coherent addition of radiation generated by electrons from a microbunched beam and a relatively large energy spread.

events. From simple tests we can conclude that our code is able to correctly calculate the coherent interaction of radiation produced by different particles as well as the incoherent superposition of Intensity. The simulated bunches have very strong microbunching of 60 %. It is possible that the resonance is not exactly hit by the laser or that most of the radiation cancels out due to the aforementioned pseudo-random methods of bunch generation. The next step is to fully implement emittance of electron bunches. The noise level for coherent treatment of many particles needs to be improved as well before first design studies utilizing our code can start.

ACKNOWLEDGEMENTS

We would like to thank Michael Scheer for the fruitful discussions about coherent addition of synchrotron radiation.

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