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From: Jim Ellison
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Effects of CSR in Linear Collider Systems

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1 Project Overview and Highlights

This is a progress report on our coherent synchrotron radiation (CSR) work which studies CSR from arbitrary planar orbits with ILC bunch compressors and damping rings in mind. This work has been partially supported by an ILC supplement to my DOE grant DE-FG02-99ER41104 and we request a continuation of this ILC supplement.

Excellent progress has been made. This is a collaboration between Gabriele Bassi (UNM and Cockcroft), Klaus Heinemann (UNM), Bob Warnock (SLAC) and me. Warnock continues to be a central figure; his CSR and numerical analysis expertise is invaluable. Bassi is finishing a PostDoc, he has been a prime mover in our work and is joining the group headed by Andy Wolsky in a joint position with the Cockcroft Institute and the University of Liverpool. Heinemann is an RA who is now deeply involved in several aspects of our CSR work. Marco Venturini (LBL) has been kind enough to interact with us on several aspects of his CSR and Vlasov work and we hope to work with him more in the future. Wolsky has been helpful in discussing with us his CSR work related to the ILC.

We complete this section by listing highlights of our work. Section 2 is our progress report. It gives an overview of our Vlasov-Maxwell approach to CSR from arbitrary planar orbits, and gives our results as applied to the important case of the Zeuthen benchmark which has been studied extensively. Section 3 outlines our work for the next year.

1. Our CSR work has been recognized by a PAC07 invited oral presentation [1].

2. We have a well developed unperturbed source (UPS) model and a polished UPS code. We have completed a study of the Zeuthen benchmark bunch compressor at 5 GeV [2].

3. We have made significant progress on a self-consistent Monte Carlo (SCMC) algorithm and we now have a working code. This is a major advance. See [3].

4. Both codes above have parallel versions which are being run at UNM's High Performance Computing Center. They scale with the number of nodes, which makes a study of various parameters feasible. Rob Ryne (LBL) will allow us to run at NERSC on his DOE SciDAC (Scientific Discovery through Advanced Computing) account.

5. We have several papers published, [2, 4, 5, 6], and two major papers in preparation, [7, 8], which will discuss in considerable detail our work to date. We have given several presentations (See Appendix). As a result of Bassi's presentation at the ERL workshop he was asked to be the lead person on an overview paper on CSR codes [9], including our own work; this took a lot of effort, but we learned a great deal about other peoples work on understanding CSR.

2 Progress Report

2.1 Overview of our Vlasov-Maxwell approach to CSR from arbitrary planar orbits

1. Vlasov-Maxwell system and our field formula
   Our basic system is the coupled Vlasov-Maxwell system which we formulate in 4D phase space. We solve the Maxwell equations in the lab frame, with the fields evolving in time, and the Vlasov/Lorentz equations in the beam frame, with the phase space density (PSD) evolving in arclength along a " design

orbit". A subtle point here is the lab to beam PSD transformation in which the time and arclength variables are interchanged. The derivation of the beam frame equations of motion (EOM) and our lab to beam PSD transformation will be submitted for publication shortly [7]. A novel feature is that we do not use a Hamiltonian framework, as in [10], to derive the beam frame EOM from the lab frame Lorentz equation.

We have developed a new formula for the field calculation, a double integral, with no singularity in the integrand, integrating over the history of the charge/current density. The main issue here is the determination of the support of the bunch which defines the region of integration. Our ultimate goal is to integrate the beam frame Vlasov equation using our method of local characteristics (PF method), which we developed in our work on the saw-tooth instability [11] (See also [12, 13]). We believe it is the best method to do the integration.

2. Unperturbed Source (UPS) Model
In the UPS model, the fields are calculated using the unperturbed source, i.e., the source evolves under the external fields only. This gives a Liouville equation to integrate. We numerically integrate the Liouville equation in the interaction picture (defined by no self-fields) using a Monte Carlo approach. We are able to obtain 2D densities (and thus moments) which we believe are quite accurate. Several subtle problems have been resolved including the controversial cancellation effects in the transverse force. This model is not self-consistent, nonetheless, it is a good testing ground for various numerical techniques and is quite useful as a guide to the self-consistent calculation. Furthermore, in certain cases it is in good agreement with a self-consistent calculation. Another important feature of the UPS is the decoupling of the Vlasov-Maxwell system. The field calculation can be done upfront allowing an efficient study of the Liouville equation.

   Our work on the UPS model, with the Zeuthen parameters at 5 GeV, has been completed and results are presented briefly in [2], where it is called the LMA model. The UPS model and results will be presented in detail in [8].

3. Self-Consistent Monte Carlo (SCMC) algorithm for the Vlasov-Maxwell system
Roughly, the algorithm is as follows: Initially, we generate a large number of beam frame phase space points from a known PSD. Now assume that at arc length position s we know the phase space positions of the Monte Carlo points and the history of the charge/current density in the lab frame in a smooth representation. We then calculate the "forces" at arc length s using our field formula and move the Monte Carlo points to $s + \Delta s$ using the beam frame EOM. Finally, we calculate the new lab frame charge/current density from the Monte Carlo points using a Fourier representation calculated by a Monte Carlo integration (This is a standard statistical density estimation [14]). This proceedure is then iterated. The last step is key as we need a smooth charge/current density. It is meshless and differs from the usual PIC step in that it gives a smooth global representation without charge deposition.

   Our work on the SCMC algorithm has evolved into a working code. This is a major achievement and will be presented at PAC07 [3, 1]. Since many parts of the code also appear in the UPS code, there is a synergy between them, i.e., every improvement in one may lead to an improvement in the other. For example, parallelizing the UPS code taught us how to parallelize the SCMC code. In the UPS code the PSD is given analytically making it faster than the SCMC code. The SCMC code relies heavily on the UPS code and is able to accurately follow moments, marginal densities and the support of the PSD. In addition microbunching can be studied. We have a great deal of confidence in this code. It has gone through much testing, e.g., comparison with results from our UPS code for the Zeuthen parameters.

4. Paper detailing our CSR work to date
We are preparing a detailed and comprehensive paper, [8], for PRST-AB covering our CSR work. The sections are 1. Introduction, 2. Basic Vlasov-Maxwell model, 3. Derivation of our lab frame field formula, 4. Summary of the derivation of the beam frame EOM from [7], 5. Summary of our Lab-to-Beam density transformation from [7], 6. The UPS Model: Formulation, including analytical studies, 7. The UPS Model: Application to Zeuthen benchmark case and other systems, including cancellation effects, etc., 8. The SCMC algorithm and code, 9. The SCMC code applied to the Zeuthen benchmark parameters and other systems, 10. The support of the interaction picture PSD and preliminary thoughts on the PF method. This paper will be an expansion and extension of [2, 4, 5].

2.2 1D CSR models

Heinemann has outlined some general aspects of CSR in [6]. His emphasis is the comparison of the radiation power with the Schwinger power and with the power recently introduced by Saldin, Schneidmiller and Yurkov (SSY). The latter power formula applies to a one-dimensional bunch of particles moving on the same spatial curve hence a line charge treatment is possible. The Schwinger power and the SSY power are closely related since both are defined in terms of mechanical work per unit time. Originating from the Lorentz-Dirac theory, the Schwinger power is the negative mechanical work per unit time done by half the retarded minus half the advanced electromagnetic field. One can view the SSY power as a modified Schwinger power which involves an electric field tailored to cope with one-dimensional bunches. A merit of the SSY power is that it does not involve the advanced field while a merit of the Schwinger power is that it even can be applied to bunches which are not one-dimensional. Nevertheless one-dimensional bunch models are important since they are used in various CSR codes and since they serve to some extent as role models for higher-dimensional models.

2.3 CSR in bunch compressors

Our basic model is a magnetic chicane with 4 dipole magnets as in the Zeuthen benchmark. In [2] we presented the UPS moments and reduced distribution densities at 5 GeV, in the free space case, both with and without transverse force, and including shielding. The relevant results are: (1) the beam frame transverse force has a small effect on the mean energy loss and its variance, but a large effect on x-emittance and (2) the shielding had a large effect on all three moments. A preliminary calculation at 500 MeV shows that the charge density support is roughly the same as that for the unperturbed source and that the change in the moments is considerably larger than at 5 GeV. In addition, we did a study of the support of the PSD in the interaction picture; this showed the necessity of a moving grid for our PF-Vlasov approach (See Section 3.3).

Most recently, as discussed above, we have developed a parallel SCMC code. Our preliminary self-consistent results are: (1) the 5 GeV results are close to the UPS results and (2) the 500 MeV results clearly show that CSR has a bigger effect and the results appear to be close to the UPS results, but this needs further study. For example, at 5 GeV the x-emittance increases by a factor of 1.5 whereas it appears that at 500 MeV the factor is 5. There is some indication of microbunching in the 4th magnet which we are pursuing.

2.4 CSR in damping rings

We have studied the evolution of the longitudinal dynamics in damping rings with a Vlasov/Vlasov-Fokker-Planck solver. This resulted in a Master's thesis [15]. Salas studied the collective effects from machine and CSR wakes at the SLAC damping ring and the VUV storage ring at BNL. He used a Vlasov-Fokker-Planck solver to calculate the onset of instabilities and did preliminary studies on microbunching. His work helped us understand the need for improvements in the numerical integration of the Vlasov-Fokker-Planck equation. Secondly, we were involved in [13, 16].

3 Final Year Project Activities and Deliverables

1. SCMC Method: Code refinement and perturbation studies
   The most expensive parts of the code are the charge/current density calculations and the double integral field calculation. As explained above, we construct a smooth density from the Monte Carlo data as in [14]. In [3], we will compare this with the standard PIC plus smoothing. We believe there may be better approaches and we will look at more state of the art methods using e.g., the quasi-MonteCarlo method of [17] (low discrepancy sequences), radial basis functions [18] and least squares moving averages [19].

   We do not yet understand how to view the UPS as the first term in a systematic perturbation expansion of the self-consistent dynamics. It is important to understand this, as there is a range of parameters for which it is a good approximation and in these cases the calculations could be done much faster with the UPS.

2. SCMC code bunch compressor parameter studies
   Our previous studies were for a Gaussian initial PSD (thus linear chirp). Here, we will (1) vary the initial density to look at an initial parabolic density in bunch length and a nonlinear chirp (as suggested by Paul Emma), (2) vary the energy, (3) vary the charge (to study the N^2 effect as suggested by Wolsky) (4) study other bunch compressors (e.g., ILC magnetic chicanes, CLIC and FERMI@Elettra) and (5) study the of support of the PSD which will be important for our PF approach below. See also [3].

3. PF for Vlasov-Maxwell
   A major effort now is the creation of a Vlasov code using the PF algorithm, [11, 13], to accurately follow the PSD. We will build on the SCMC approach and this will involve a refinement of our Vlasov algorithm [4, 11, 12, 13]. We will study the interaction picture moving grid in the context of the simpler 2D model of [12] and study a bunch compressor case where the uncorrelated energy spread is large enough so that a moving grid may not be necessary. We believe the latter is the case for the CLIC study in [20] and possibly for FERMI@Elettra as discussed in [12]. A major issue here is an accurate determination of the support of the PSD. Our work will include the development of a code using modern methods of numerical and high performance computing.

4. 1D CSR Models
   Warnock is working on a very promising 1D model which we will be studying (see the Warnock abstract on the PAC07 web site).

   The Heinemann 1D work discussed above will be continued: We will (1) compute the radiation power (as defined in Jackson) for simple geometries (e.g. arc, piecewise linear curve) and compare it with the Schwinger and SSY power, (2) compute and compare the corresponding radiated energies, and (3) compare these results with the 1D Warnock theory.

5. Damping Rings
   If time, we will refine and extend the numerical Vlasov work in [12, 13, 15] as it relates to damping rings.

A Presentations

Aspects of our work have been presented at (1) the Energy Recovery Linac Workshop, Thomas Jefferson Lab, Newport News, March 2005 (Bassi), (2) PAC05 (Bassi), (3) the 27th International Free Electron Laser Conference, Stanford, August 2005 (Bassi), (4) COULOMB05: High Intensity Beam Dynamics Workshop, Senigalla, Italy, September 2005 (Warnock), (5) the annual Los Alamos/Arizona/New Mexico Days workshop in nonlinear science, CNLS, Los Alamos, January, 2006 (Heinemann), (6) the New Mexico Tech Graduate Student Association Conference, "Standing at a Crossroad: Making the Transition from Student to Professional through Research and Publishing", February 2006, Socorro, New Mexico (Salas), (7) EPAC06 (Bassi), (8) EPAC06 (Heinemann), (9) two Cockcroft Institute seminars, July 06 and March 07(Bassi) and (10) a presentation at the John Adams Institute, January 07 (Bassi).

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