

# Effects of CSR in Linear Collider Systems: A Progress Report

## Classification (subsystem)

Accelerator

## Personnel and Institution(s) requesting funding

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## Collaborators

Robert Warnock, SLAC

Collaborating personnel will work on CSR but are not requesting funding here.

## Project Leader

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## Guide for Reviewer

This is a progress report on a DOE/LCRD proposal which was funded in May 2004 for 3 years at \$36.8K/year. The award is in the form of a supplement to the project leaders DOE grant, DE-FG03-99ER41104 for “Investigations of Beam Dynamics Issues at Current and Future Accelerators” which is on the cycle April 1 - March 31. The supplementary award for 4/1/04-3/31/05 arrived at UNM in late August 2004.

In this report we have followed the Dugan format as much as possible. To make the progress report self-contained we have inserted the original four page proposal into the Project Overview Section (adding only several references that should have been there). Since this is a DOE progress report we have not included a “Broader Impact” section. The “Results of Prior Research” contains our progress report. The three year plan was contained in the initial proposal, however we make some additional remarks about activities for the second and third years in a section entitled: Project Activities and Deliverables for Years Two and Three. A reference section follows which contains the references from the original proposal as well as some new references related to the progress report.

## Project Overview

### I. Motivation

There are two points at which coherent synchrotron radiation (CSR) could be of concern in linear colliders. First, it may cause transverse  $x$ -emittance degradation in bunch compressors, since energy changes due to CSR get mapped into transverse coordinates through dispersion. Second, it might cause longitudinal bunch instabilities in the damping rings at high current, possibly leading to a quasi-periodic, sawtooth behavior of the bunch length. Damping ring designs contain many meters of wigglers (for instance 46 m at NLC and 432 at TESLA), to

reduce the damping time to a manageable value. The coupling impedance from CSR in the wigglers, combined with that from bending magnets, could induce the feared instability. For a review of microbunch instabilities due to CSR see [1].

## II. Bunch Compressors and Computation of CSR from Arbitrary Orbits

Preliminary estimates of emittance growth in bunch compressors have been made by Emma and Woodley [2]. They have done calculations for the Stage 1 and Stage 2 compressors (BC1 and BC2) of the NLC and for the Tesla bunch compressor (TBC) [3]. For BC1, BC2, and TBC their figures for emittance growth  $\Delta\epsilon_x/\epsilon_x$  due to CSR were 2.4%, 5.5%, and 1%, respectively. Although these values are regarded as reasonably small compared to other sources of emittance growth, they are based on a simplified model of the CSR field, and cannot be considered a definitive conclusion. The field calculation, as implemented in M. Borland's code ELEGANT [4], treats the source of the radiation as a line charge. In a macroparticle simulation the transverse charge distribution is projected onto a longitudinal line to produce an effective radiation source. Moreover, the formula for the field is for a source moving on a trajectory which is straight except for a single bend. Consequently there is no proper integration of single bends to make a true chicane orbit. Actually, there should be a residual field after a bend which does not decay completely before the next bend is reached.

There exist large codes to compute CSR from an arbitrary charge/current distribution on fairly general orbits (by Dohlus [5] at DESY and Rui Li at JLAB [6]), but these have proved to be cumbersome for actual design work and are not much used for that purpose. We have devoted considerable effort to finding a better calculational method, intended to be useful both for bunch compressors and rings, and perhaps also for wigglers.

## III. Ongoing and Proposed Work on Bunch Compressors and Computation of CSR from Arbitrary Orbits

### IIIA.

One approach that we have explored in recent months is to make a Fourier analysis of fields and sources in all spatial dimensions, with account of the large-wavelength shielding of CSR by the vacuum chamber (in a perfectly conducting parallel plate model). This avoids the tricky integrations over singularities of the Green function that make the usual approach in space-time quite difficult. The price to pay is in dealing with fast oscillations of the integrand in the inverse Fourier transform to compute the field. We hoped that this problem could be handled by the method of stationary phase, but it turns out that this method is only partially effective. Since it still might be used in combination with other procedures, we are currently writing a careful report on our experience.

### IIIB.

We have recently made what appears to be great progress by using a Fourier series only in the vertical coordinate  $y$ , perpendicular to the plane of the orbit. This makes it trivial to satisfy the field boundary conditions on the parallel plates that model the vacuum chamber. The resulting 2D wave equation has a "mass" term, the mass being the vertical wave number, and a remarkably simple Green function with a softer singularity than the usual Green function for the 3D wave equation. We think that this should provide an efficient and simple numerical method, and propose the implementation of such a method as a main item of research. We will first study a chicane bunch compressor with the charge/current source coming from a bunch with energy chirp, evolving only in response to the fields of the dipoles. Horizontal transverse spread of the charge distribution is fully accounted for, whereas the vertical distribution is arbitrary but constant in time. Later we hope to make the calculation self-consistent, allowing

the phase space distribution to be affected by CSR. This could be done in a macroparticle simulation, or preferably in a less noisy Vlasov treatment if that could be done in reasonable computation time.

#### IV. Damping Ring Instabilities

A representation of the impedance for CSR in wigglers has been proposed by Wu, Raubenheimer, and Stupakov (WRS)[7]. Wu, Stupakov, Raubenheimer and Huang (WSRH) [8] have combined this impedance with the usual impedance for CSR in dipoles to discuss the longitudinal instability threshold in damping ring designs for NLC and TESLA, and for the existing prototype damping ring at the KEK ATF. The instability study is done with coasting beam theory for a line-charge beam, and without shielding of CSR. The conclusion is that the instability is indeed worrisome. The threshold is close to the nominal current for NLC and ATF. On the other hand, the dipole and wiggler impedances scale differently with frequency, and that leads to a possibility of optimizing the damping ring design to raise the threshold, perhaps by a factor of 4.

#### V. Proposed Work on Damping Ring Instabilities

Although the work of WSRH is a valuable first survey of the problem, it involves some serious assumptions that one would like to avoid. We propose to pursue the following improvements:

1. Avoid coasting beam theory by applying our program for numerical integration of the nonlinear Vlasov-Fokker-Planck (VFP) equation [9, 10]. We would begin with the Haïssinski equilibrium distribution, and see whether it becomes unstable under time evolution by the VFP integrator. As the authors WSRH point out, the coasting beam theory is doubtful in this instance, because the Boussard criterion does not apply: the bunch length is not much larger than the unstable wave lengths.
2. Study possible saturation of any instability, again using the VFP code. That code has proved to be very useful for long term simulations, giving plausible results over several damping times.
3. Include shielding of CSR, which will be necessary in studying dynamics of unstable cases, and may have some effect on thresholds as well. We are not yet sure how to describe shielding for the wiggler radiation, and there is the complication that the vacuum chamber has different sizes in bends and wigglers. Some innovative approximations will certainly be necessary.
4. Criticize the mathematics and physics of the model of the wiggler impedance in WRS. This is for an infinite wiggler, and takes as its starting point results of Saldin *et al.* [11]. As far as we know the complicated Saldin analysis has not been verified by other authors, and in any case there are some puzzling singularities in the result that we would like to understand. After becoming familiar with the problem, perhaps we can treat the case of a wiggler of finite length, which of course would be more relevant for the prediction of thresholds.
5. Try to include non-zero transverse extent of the bunch. This would relate to work on the 2D Green function mentioned above.

#### VI. Budget and Personnel

Warnock is a retired SLAC physicist with several years experience in CSR, see, for example,[10]. The proposal is based on his recent work, our joint progress over the last few months, and

discussions with other experts at SLAC. Ellison has some modest experience with radiation by moving charges from his work on channeling radiation at CERN and Aarhus in the late eighties and is now deeply involved in the basic issues of CSR from particle bunches on more or less arbitrary orbits. Bassi has been hired as a PostDoc, as of mid June 2003, after completing a Ph.D. at DESY and the University of Bologna. He is making a substantial contribution to our CSR work.

Warnock is not asking for financial support; he finds it sufficient to get theoretical and numerical collaboration from Ellison and Bassi. Ellison is not asking for financial support either as CSR is one item in the research of his current DOE grant - DE-FG03-99ER41104 for "Investigations of Beam Dynamics Issues at Current and Future Accelerators". In addition, Ellison has funds in his DOE grant to partially support the CSR work of Bassi. We are requesting \$36.8K/year for the 3 year period June 1, 2004 to May 31, 2007 to fill out the support of Bassi's CSR work and to partially support a graduate research assistant. The \$36.8K includes salary, fringe benefits, tuition, health insurance and the 50% indirect cost rate. Our current LCRD/DOE funding arrived too late to support a graduate student in the fall, however we have just hired a student who will begin work in January.

The proposal outlines an ambitious program that we find quite challenging.

## **Results of Prior Research: Progress Report on DOE/LCRD Award**

### **A. Bunch Compressor and Computation of CSR from Arbitrary Planar Orbits**

Considerable progress has been made on the computation of CSR from arbitrary planar orbits as proposed in IIIA above.

A detailed report [12] on the approach based on the full Fourier method has been written as promised in IIIA. Our conclusion is that the method of stationary phase, applied to reduce the number of integrations and the field calculation time, is not a good approximation in a large enough region of Fourier space and thus the computation time is too long for practical use. Although a negative result, we gained a great deal of understanding and it was helpful in the implementation of the method based on the 2D wave equation of IIIB. Nevertheless, the method of stationary phase may be useful in combination with other procedures and might be effective in a third variant of the Fourier method (1D wave equation after a Fourier transform in  $x$ ).

In IIIB we proposed work on a new approach based on a 2D wave equation. To date, we have focused primarily on the important task of the field calculation and we have reported on our results in [13]. The fields exited by the bunch are computed in the laboratory frame from a new formula that leads to much simpler computations than the usual retarded or Lienard-Wiechert potentials. This computation is much faster than the full Fourier method above. Work has begun on the fully self-consistent calculation in which the Vlasov equation will be integrated in the beam frame interaction picture as discussed in [13]. Important to this is the transformation from lab to beam frame. This is somewhat complicated and we have a draft of a paper on this [14]. Our progress on the fully self-consistent calculation will be presented at PAC 2005.

In addition, we have studied low order moments using particle simulation in a first order perturbation theory, i.e., the field is calculated from the distribution evolving in response to the fields of the dipole magnets only. We have compared our results for the mean energy loss with results of Emma and Kabel (see figures in [13]). Our semi self-consistent results are in

reasonable agreement with [15] which gives us confidence in our field calculation. The next step will be to compare our fully self-consistent calculation with the Zeuthen benchmark.

### **B. Damping Ring Instabilities**

The work on damping ring instabilities as proposed in IV and V above is in its initial stages. As mentioned, the award didn't arrive at UNM until late August 2004 and so we weren't able to hire an RA for the fall. However, we have now hired a research assistant, Klaus Heinemann, and he is focusing his attention on the wiggler problem and the Saldin approximations. He has a good background in beam dynamics and some experience with renormalization, which should be helpful in understanding and improving upon the Saldin approximations. Prior to the current LCRD award we had a \$20K award. A significant part of this was used to support an RA for the spring semester of 2004. His task was to work through the Saldin papers however it took considerable time to get the proper background which didn't leave much time for understanding Saldin. However he did come to some useful insights on which Heinemann is building.

### **Facilities, Equipment and Other Resources**

Our only needs are office space and computing facilities. We have good work stations from DOE money and UNM has a high performance computing laboratory which we can access. At some point we might like access to NERSC.

### **Project Activities and Deliverables for Years Two and Three**

#### **A. Bunch Compressor and Computation of CSR from Arbitrary Planar Orbits**

We will continue our work on CSR from arbitrary planar orbits. As mentioned above considerable progress has been made in the context of the Bunch Compressor. Now, our main focus is on the implementation and testing of the fully self-consistent algorithm outlined in [13]. The algorithm is based on a standard technique of numerical analysis, namely spline approximation [16], to represent charge and current densities and the phase space distribution function. Splines are extremely convenient and have well understood convergence properties. As far as we know, other investigators have not used general methods of numerical analysis, instead preferring special techniques such as a representation of the bunch as a superposition of small Gaussian macro-particles [5]. We will focus on the construction of a good serial code, afterwhich we will look for ways to take advantage of parallel platforms. The code will be applied first to study CSR effects in a bunch compressor and carefully compared with the Zeuthen benchmark case. We will then take steps to study the nonlinear chirp and non-Gaussian case both in a semi and self-consistent approach. Next we will apply the code in the context of the ILC.

#### **B. Damping Ring Instabilities**

Because the money for the first year arrived late, the work on wigglers and undulators is just beginning. Here we will do as discussed in part V of the proposal. As mentioned above, Heinemann has been hired and his initial charge is to study the Saldin and Stupakov papers, to give more insight into the line charge models mentioned above. In addition once the code of A is developed, we will consider modifications needed to apply it to the wiggler/undulator problem as mentioned in part V5 of the proposal.

The bunch compressor work was partially supported by Ellison's DOE grant DE-FG03-99ER41104 for "Investigations of Beam Dynamics Issues at Current and Future Accelerators", which was awarded at \$145K per year for the period April 1, 2002 to March 31, 2005.

The grant topics are Vlasov dynamics, nonlinear collective effects, collective and weak-strong beam-beam and spin dynamics in addition to CSR.

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**Budget justification:**

The budget justification is included in the original proposal. See VI above.

**Three-year budget**

The three year budget is as in the original proposal, see VI above. It is \$36.8K/year for partial support of Bassi's CSR work and for Heinemann.