PROJECT DESCRIPTION

Study of Space Charge Effects in the International Linear Collider Damping Rings

Personnel and Institution requesting funding

Samuel Danagoulian, Department of Physics, North Carolina A&T State University
Sekazi Mtingwa, Consultant

Collaborators

Andrzej Wolski, Lawrence Berkeley National Laboratory
Marco Venturini, Lawrence Berkeley National Laboratory

Project Leader

Sekazi Mtingwa
mtingwas@ncat.edu
(617) 493-2859

Project Overview

Indispensable subsystems of the International Linear Collider (ILC) will be the damping rings, which will shrink the emittances of the electron and positron beams. This idea was first proposed by Amaldi [1]. Once the beams enter their respective main linacs, the ultra low emittances should already have been achieved in the damping rings, where the equilibrium emittances are determined by the balancing of a variety of effects, including radiation damping, quantum excitations, intrabeam scattering, gas ions in the electron ring, electron clouds in the positron ring, and of particular interest for this project, space charge. Recently, there have been alternatives proposed for the damping rings baseline configuration that were derived from a number of studies of seven reference lattices covering a range of beam parameter options, with circumferences ranging from roughly 3 to 17 km and energies from 3.74 to 5.066 GeV [2]. Thus, a major task continues to be to compare the impact of as many effects as possible on the various reference lattices.

Space charge effects should be important only toward the end of the damping cycle, when the vertical beam size is quite small (See Table I). However, it could cause a degradation of the vertical emittance specified at extaction by enlarging the width of existing lattice resonances, or even driving new resonances, both of which have been observed during simulation studies [2].

In a recent study that considered the importance of a variety of factors on a baseline configuration decision for the damping rings, space charge was given a rating of "A," signifying that it is one of the most critical effects that impacts a final damping ring design [3]. To date, the baseline configuration favors a 6 km damping ring, in which space charge ought not to be a problem. However, severe ion and electron cloud effects may force the baseline recommendation to switch to the TESLA-style 17 km design. If that happens, space charge effects definitely will become a critical issue.

	Electron beam	Positron beam
Numbers of bunches	2820	2820
Number of particles per bunch	2×10^{10}	2×10^{10}
Bunch separation in main linac	337 nsec	337 nsec
Normalized horizontal emittance	8 μm-rad	8 μm-rad
Normalized vertical emittance	0.02 μm-rad	0.02 μm-rad
Natural energy spread	$< 0.15\%$	$< 0.15\%$
Natural bunch length	6 mm	6 mm
Polarization	$> 80\%$	0

TABLE I. Nominal beam parameters at extraction from the damping rings.

In previous space charge studies for the TESLA dogbone design, there was a proposal to couple the beam locally in the long straight sections in order to reduce the impact of space charge via reducing the charge density [4]. Local coupling could be achieved by using a pair of skew quadrupole triplets, so that inside the coupled region, the vertical beam size has a significant contribution from the horizontal emittance. Recently, Venturini and Oide (unpublished) have found that such coupling insertions could actually drive coupling resonances, leading to a worse situation than that caused by space charge forces alone. Hence, coupling bumps may not be the cure for the TESLA space charge problem. Thus, further work on this problem will be needed.

Aside from particle tracking simulations, most of the space charge studies to date have relied on linearized models of space charge forces. For example, employing SAD, the envelope method uses only a linear matrix approximation to find the equilibrium vertical emittance in the presence of space charge plus radiation and skew quadrupole errors. Clearly, a more accurate procedure is needed. Since the main concern is emittance growth and particle losses driven by space charge forces, we propose to develop an analytic model that describes this process and goes beyond the linear approximation. Of course, the ultimate goal of such a model is to specify "safe" operating conditions for the damping rings.

This research project would be divided into two phases:

Phase 1 Development of an analytical model for space charge effects beyond the linear approximation. We will search for an analytical method of converting the beam momentum impulses received from the space charge force into emittance growth rates. Such approaches have been applied successfully in studies of other collective effects, such as intrabeam scattering. Deriving such an approach for space charge effects, would go a long way toward specifying a safe operating regime for a TESLA-style damping ring. We anticipate that Phase 1 will take one year.

Phase 2 Incorporation of the new model into simulation codes. First, a Mathematica code of emittance growth versus time (number of turns) will be developed, much as was done for intrabeam scattering previously [5]. Afterwards, the results will be incorporated into other simulation codes, such as the popular SAD. By using such new and modified simulation codes, we should be able to settle the space charge issues for the TESLA-style damping ring. Phase 2 will take one year.

Broader Impact

This research will be performed with the assistance of one graduate student and one undergraduate student from North Carolina A&T State University (NCA&T). NCA&T has a Masters program in physics; thus, the graduate student working on this project will use her/his work to satisfy the thesis requirement. For the undergraduate student, the project will provide invaluable research opportunities so that she/he can appreciate firsthand the art of basic scientific research. For both the graduate and undergraduate students, the goal will be to encourage them to proceed to the doctorate in physics.

S. Mtingwa is Affiliate Professor of Physics at North Carolina A&T and maintains his affiliation there for the purpose of engaging faculty and students from underrepresented groups in research opportunities afforded by the International Linear Collider. Although he will be leading this research project, he is entered in the proposal as a consultant, since he is no longer a permanent member of the North Carolina A&T faculty.

NCA&T is a public institution that is part of the University of North Carolina System. More importantly, it is one of the Historically Black Colleges and Universities, with both graduate and undergraduate enrollments containing in excess of ninety percent (90%) African-American students. Moreover, the physics program enrolls a number of women students, in some years comparable in number to the number of men students. Thus, this research project will proceed within a student environment that is composed of sizable numbers of underrepresented gender and ethnic groups.

NCA&T's partnership with Lawrence Berkeley National Laboratory (LBNL) will be extremely advantageous for both institutions. Not only will LBNL become better acquainted with the students' abilities, hopefully leading to future recruitment opportunities, but the students will gain a better appreciation of what is needed to perform at the highly competitive level of the national laboratories.

Hopefully, the research results from this project will be implemented at the ILC. In any event, it will be important for other accelerator applications in the future. In the meantime, the results will be presented at physics conferences and workshops and published in premier physics journals.

Results of Prior Research

We recently made substantial progress on linear collider research under two NSF grants: Planning Grant Award numbers PHY-0303702 (9/15/03 - 8/31/04) and PHY-0355182 (9/1/04 - 8/31/06). North Carolina A&T was a subcontractor with Cornell University, and the grants were for an accelerator project entitled, *Damping Ring Studies for the LC*. The goal was to derive more computationally friendly formulas for the phenomenon of intrabeam scattering (IBS). IBS involves multiple small-angle Coulomb scatterings of particles within a bunch. To compute emittance growth rates due to IBS, the theory involves a series of matrix inversions and computations of the determinants of matrices at each of the many lattice points in the damping ring. To compute emittance growth rates versus bunch charge, popular mathematical codes take many hours to give results. Thus, approximations to the theory are necessary to reduce greatly the time needed to compute emittance growth rates. We derived such computationally-friendly approximations and showed that they give excellent agreement with the full theory for damping rings corresponding to both warm and cold linear collider designs. Moreover, our formulae gave excellent agreement with recent data taken at the Accelerator Test Facility (ATF) at KEK [6].

For the lower energy damping rings for the warm linear collider designs, IBS would be the most important impediment to achieving ultra low beam emittances. Now that the decision has been made to use cold linear collider technology, the damping ring energies are sufficiently high that IBS does not seem to be a big problem, although in some designs it is not negligible and should always be checked. Specifically, the much smaller size of the electron injected beam compared to that of the positron injected beam allows a longer radiation damping time for the electron beam. Since IBS will have a larger effect, IBS studies need to be continued to see if it will be necessary to design a shorter radiation damping time for the electron damping ring than one would need in the absence of IBS. The work performed under our previous grants will play an important role in this exercise.

Our previous IBS work under the NSF grants has been published in Physical Review ST AB [5]. Also, it has been used extensively in studies for the damping ring baseline configuration recommendations [2]. Finally, this IBS work has much broader applicability than to just the ILC. It can be applied readily to hadron colliders and other electron accelerators, such as synchrotron light sources and free-electron lasers.

Facilities, Equipment and Other Resources

This project will involve analytic calculations and computer simulations. As such, the main resource will be the computational facilities available at North Carolina A&T. The university offers mainframes and personal computers in computer labs across the campus, with sufficient computer assistance to satisfy student and faculty needs. Moreover, the Department of Physics has its own computer lab with local workstations that are available to students and faculty.

First year Project Activities and Deliverables

During the first year, we will review the linearized theory of space charge. Then, we will study ways of extending the formalism beyond the linear approximation in a manner that is easy to incorporate into computer codes. Our theory will describe emittance growth and subsequent particle losses that are driven by space charge forces and point the way toward determining safe operating regimes for the damping rings. This will complete Phase 1 of the project, and we will summarize the results of Phase 1 in a written report. Moreover, we will present our results at conferences and workshops and publish the most important results in refereed journals.

Second year Project Activities and Deliverables

After deriving a more complete theory of space charge effects during Phase 1, we will spend the second year of the project incorporating our analytic results into computer codes. First, we will write a code using Mathematica and study space charge effects in the two alternative recommended damping rings, which have circumferences of 6 km and 17,000 km. Then, after gaining confidence in our formalism, we will incorporate it into the more popular codes, such as SAD and MaryLie/Impact. This will allow us to do detailed studies of all seven reference damping ring lattices, and we will propose safe operating conditions for all lattices relative to space charge effects, especially for the TESLA-style lattices, where space charge is a big concern. Our results will suggest techniques for suppressing unwanted space charge effects without driving betatron and synchrobetatron resonances.

Budget Justification

The entire project will consist mainly of computational and theoretical calculations, with heavy use of simulation codes. Each year's budget will provide research assistantships for one (1) graduate student and one (1) undergraduate student; travel to conferences (including two international conferences per year for each Danagoulian and Mtingwa) and travel for Danagoulian, Mtingwa, and collaborators to visit each other's institutions for the purpose of working on the project; miscellaneous materials and supplies, including computer software; and tuition support for one (1) graduate student.

Fringe benefits are 7.65% of $3,000 graduate student summer salary. Other direct cost is tuition for one graduate student. Indirect cost is calculated at North Carolina A&T's 40% rate on modified total direct costs, which excludes tuition.

Two-year budget, in then-year K$

Institution: North Carolina A&T State University

Item	First year	Second year	Total
Other Professionals	0	0	0
Graduate Student	15	15	30
Undergraduate Student	7	7	14
Total Salaries and Wages	22	22	44
Fringe Benefits	0.23	0.23	0.46
Total Salaries, Wages and Fringe Benefits	22.23	22.23	44.46
Equipment	0	0	0
Travel	16	16	32
Materials and Supplies	2	2	4
Other direct costs	13	13	26
Total direct costs	53.23	53.23	106.46
Indirect costs	16.09	16.09	32.18
Total direct and indirect costs	69.32	69.32	138.64

References

[1] A. Umaldi Phys. Lett. 61B, 313 (1976).

[2] http://www.desy.de/ awolski/ILCDR/DRConfigurationStudy_files/DRConfigRecommend.pdf.

[3] http://cbp.lbl.gov/people/wolski/DRConfigRecommendSummary-18Nov2005.pdf.

[4] W. Decking and R. Brinkmann, "Space Charge Problems in the TESLA Damping Ring," Proceedings of EPAC 2000, Vienna, Austria (2000).

[5] K. Kubo, S. Mtingwa, and A. Wolski, "Intrabeam Scattering Formulae for High Energy Beams," Phys. Rev. ST Accel. Beams, **8**, 081001 (2005).

[6] Y. Honda *et al.*, Phys. Rev. Lett. **92**, 054802-1 (2004).