Proposal to the
University Consortium for a Linear Collider

July 30, 2002

Proposal Name

Improved simulation codes and diagnostics for high-brightness electron beams.

Classification (accelerator/detector: subsystem)

Accelerator: injector, linear accelerator.

Personnel and Institution(s) requesting funding

C. Bohn, Department of Physics, Northern Illinois University.

Collaborators

H. Edwards, Fermilab

X. Yang, Fermilab and Northern Illinois University

I. Sideris, Northern Illinois University

U. Happek, University of Georgia

B. Gabella, Vanderbilt University

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Project Overview

The first component of this proposal is the development of improved simulation codes for high-brightness photoinjectors. The ultimate goal is to have a code that correctly couples the motion between the longitudinal and transverse dynamics. One possibly fruitful approach would be to generalize the treatment of coupled envelope equations recently formulated at SLAC [1]. The ongoing flat-beam experiment at the Fermilab/NICADD Photoinjector Laboratory (FNPL) [2], of which H. Edwards is the Facility Manager, provides an excellent basis for exercising such a code. The second component of the proposal is centered on interferometric and electro-optic diagnostics for measuring bunch lengths and density profiles. The first device under consideration is a high-bandwidth far-infrared (FIR) interferometer to detect coherent transition radiation from bunches passing through a thin viewfoil, and coherent synchrotron radiation emitted during bunch compression. The second device is an electro-optic crystal in which the dielectric tensor changes as the electric field of a beam bunch passes through it, a process that can be monitored by measuring polarization changes in laser light incident on the crystal. These instruments will be commissioned at FNPL.

Linear colliders call for an injected electron beam with high bunch charge, low normalized transverse emittance, and short bunch length. A generic desire is to optimize the beam brightness to minimize the need for beam "cooling" like that done with a damping ring, and this is the underlying motivation for the aforementioned flat-beam experiment. Ideally, the injected beam would have bunch charge well exceeding 1 nC, a normalized emittance of order 1 μm, and a bunch length of a few mm (which gets compressed by an order of magnitude at higher energies). These parameters push the beam-brightness frontier. Accordingly, to understand the underlying beam dynamics likewise pushes the frontier of injector-simulation tools. For example, one must account more accurately for intricacies of space charge and wakefield effects. As a matter of principle this can be done with an N-body code, but N would need to be large and the computational time correspondingly long. To explore the parameter space in developing first designs of injectors, fast codes are needed, and to be used with confidence, these codes must comprise sufficiently accurate models of the beam physics. This is the context of the simulation effort discussed herein.

One of the challenging aspects of simulating the production of high-brightness beams more accurately is to abandon the canonical simplifications of cylindrical beam symmetry and zero longitudinal-transverse coupling. As to removing the restriction of cylindrical symmetry, two possibilities appear to be most promising for the near-term, especially in that they involve long-standing collaborations with code authors. One is to generalize ASTRA [3], which is DESY's injector-dynamics code authored by Klaus Floettmann. The other is to generalize HOMDYN, which is a code authored by Massimo Ferrario based on the Serafini-Rosenzweig theory of space-charge-dominated beams [4]. Ferrario is presently working on a flat-beam version of HOMDYN.

We propose to obtain these generalized injector codes, test them, apply them to FNPL, and compare the results against those of experiments, in particular the flat-beam experiment. We may also work in parallel with Floettmann toward generalizing ASTRA. In parallel, we propose to explore the aforementioned possibility of developing a new code based on a generalization of the formalism in Ref. [1]. If the outcome is favorable, then we propose to develop the corresponding new code. In developing new code, C. Bohn will generally do the underlying theoretical work, and I. Sideris (a postdoctoral computational physicist slated to arrive at NIU on 15 August) will generally do the programming. We request funding to support a graduate student in doing simulations.

The length of an electron bunch is an important parameter for high-energy linear colliders. Wakefields depend on the bunch shape and are a limiting performance factor. Plus, the luminosity at the interaction point depends on the phase spaces of the colliding beams. One approach for measuring the longitudinal density profile of the bunch is to measure and analyze the coherent radiation produced either by transition, diffraction, or synchrotron radiation. A generic instrument for doing so is an interferometer [4]. In addition, monitoring and controlling nonlinear influences, such as wakefield effects, on a beam requires excellent time resolution. Linear-collider applications call for a time resolution of about one-tenth the root-mean-square bunch length, which for the NLC works out to be $\sim$10 μm. Moreover, single-shot capability is required for monitoring bunch-to-bunch fluctuations. Conventional techniques, such as streak-camera measurements, have much coarser time resolution, typically $\sim$1 ps, i.e., $\sim$300 μm. The same comment applies to existing interferometers, in that they typically operate in the wavelength region above $\sim$200 μm, which means accessing bunch lengths shorter than $\sim$500 fs has not been possible. Accordingly, these interferometers are also limited in their ability to distinguish fine structure in the longitudinal density profile.

Prof. Uwe Happek and his group at the University of Georgia have designed a number of interferometers; they are in operation at Cornell, Vanderbilt, UCLA, Argonne, and Jefferson Laboratory. The Northern Illinois Center for Accelerator and Detector Development (NICADD) recently contracted with Happek for a new interferometer that is designed to push down the lower limit of the accessible bunch length by an order of magnitude, i.e., to about 20 μm. However, it will average over many bunches; it is not single-shot. A next-generation interferometer that incorporates mirage detectors will be developed in connection with this proposal. The mirage detector uses a thin metal film as a spectrally flat absorber. The film heats the air above its surface, and a diode-laser beam probes the heated air. Changes in the refractive index deflect the laser beam, and a position-sensitive photodetector monitors the beams location. The devices sensitivity is accordingly limited by thermal fluctuations, similar to a Golay cell. A big plus, however, is that the mirage detector offers the potential for a multichannel device in combination with a single-shot autocorrelator.

Specifically, the plan is to develop a multichannel interferometer that will permit studies of single bunches, as opposed to properties averaged over many bunches. Existing multichannel FIR detectors are very large and cumbersome, making their use in accelerator beam lines impractical. By contrast, an array of mirage detectors would enable compact devices, of roughly the size of the new interferometer (30 cm x 15 cm x 15 cm) that Happek is supplying. The interferometer is also generically "flexible" in that it can be used to measure either coherent transition radiation emitted as the beam passes through a thin foil (an invasive measurement) or coherent diffraction radiation emitted as the beam passes through a hole in the foil (a noninvasive measurement). A portion of the funding for materials and supplies will likely be used in developing mirage detectors for interferometric applications. Prof. Happek will do most of the development of the single-shot instrument.

Electro-optic (EO) sampling is a noninvasive technique offering picosecond time resolution of the electric field at the EO material [5]. It is based on the Pockels effect. When an electric field is applied to a certain class of crystals the refractive-index ellipsoid is modified, and as a result retardation (phase shift) is introduced between two orthogonally polarized components of a pulse of light traversing the crystal. This retardation can be detected by observing the change in the polarization of laser light transiting through the crystal. By using short laser pulses and varying the delay between the "probe" pulse and the pulse that produced the electron bunch, the "pump" pulse, one can sample the time dependence of the electric field.

In principle, the EO technique permits direct time-domain measurements of both beam-induced wakefields and the electric field from a single bunch itself. The technique was recently applied at FNPL in the former connection, specifically, to measure the beam-induced wakefield of a six-way cross [6]. The direct field of the bunch itself could not be resolved; the prevailing conjecture is that it was concealed by the arrival of the early-time wakefield at the crystal. The conjecture makes sense from simple time-of-arrival considerations pertaining to the geometry of the cross and the location of the crystal within the cross.

The design of the vacuum chamber housing the EO crystal is key to measuring the direct field of the beam. One possibility is to use a tapered vacuum chamber for low wakefields. We propose to design, build, and (in collaboration with Fermilab personnel) implement such a chamber, and thereby access the beam field. Part of the program will be to cross-correlate the density profile extracted from the EO-measured field against that from the interferometer and the projected longitudinal density obtained by use of a deflecting-mode cavity (once it is installed). These cross-correlations should go far toward validating the interferometric and electro-optic techniques. C. Bohn will do the theoretical work to design the vacuum chamber for the EO diagnostic. X. Yang, a newly hired postdoctoral laser and optics expert will be key in commissioning and operating the new diagnostics. We request funds to purchase components for the interferometric and electro-optical diagnostics and to support a graduate student in commissioning the devices. In addition, we will collaborate with Dr. Bill Gabella of Vanderbilt University toward improving the time-resolution of the diagnostic. In particular, Dr. Gabella will be working to develop an improved short-pulse probe laser.

FY2003 Project Activities and Deliverables

Activities: Testing of generalized version of HOMDYN presently being developed by M. Ferrario of INFN Rome, and possibly of ASTRA with assistance from K. Floettmann of DESY. Development of formalism to couple transverse and longitudinal dynamics and, if successful, begin developing a corresponding simulation code. Design the single-shot interferometer based on tests of mirage detectors. Design low-impedance vacuum chamber for the electro-optic diagnostic and begin its fabrication.

Deliverables: Technical papers on HOMDYN and ASTRA simulations, and on coupled dynamics. Design of the single-shot interferometer. Design of the low-impedance vacuum chamber.

FY2004 Project Activities and Deliverables

Activities: Finish the development of the generalized simulation code. Construct the single-shot interferometer and begin testing it at FNPL. Finish the low-impedance chamber and install it in FNPL; configure electro-optic diagnostic and begin testing.

Deliverables: Generalized simulation code, single-shot interferometer, low-impedance vacuum chamber.

FY2005 Project Activities and Deliverables

Activities: Benchmark the generalized simulation code against FNPL experiments. Characterize beam with the interferometric and electro-optic diagnostics and cross-correlate their results. Improve the temporal resolution of the electro-optic diagnostic pending the successful development at Vanderbilt of a short-pulse probe laser.

Deliverables: Benchmarked simulation code. Papers on experiments involving the interferometric and electro-optic beam diagnostics.

Budget Justification

Successful completion of this proposal requires dedicated participants, both professional staff (not budgeted here) and two graduate students. It also requires modest hardware investments for the interferometric and electro-optic diagnostics, mostly toward the former. Most of the hardware costs appear in the first year (for the interferometric mirage detectors and the electro-optic vacuum chamber). Modest funds for design modifications are requested for the second and third year as part of bringing the diagnostics to maturity.

Three-year budget, in then-year K$

Institution: Northern Illinois University

Item	FY2003	FY2004	FY2005	Total
Other Professionals	0	0	0	0
Graduate Students	36	37.8	39.69	113.49
Undergraduate Students	0	0	0	0
Total Salaries and Wages	0	0	0	0
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	36	37.8	39.69	113.49
Equipment	0	0	0	0
Travel	0	0	0	0
Materials and Supplies	15	7.5	7.5	30
Other direct costs	0	0	0	0
Total direct costs	51	45.3	47.19	143.49
Indirect costs	11.96	11.128	11.619	34.707
Total direct and indirect costs	62.96	56.428	58.809	178.197

References

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