Proposal to the University Consortium for a Linear Collider

August 30, 2002

Proposal Name

Single-shot, electro-optic measurement of a picosecond electron bunch length.

Classification (accelerator/detector: subsystem)

Accelerator Instrumentation: non-destructive electron bunch length measurement.

Personnel and Institution(s) requesting funding

William E. Gabella, Bibo Feng, John Kozub, Free-electron Laser Center, Vanderbilt University, Nashville, TN 37235.

Collaborators

Court Bohn, Department of Physics, Northern Illinois University.

Contact Person

William E. (Bill) Gabella
b.gabella@vanderbilt.edu
615-343-2713

Project Overview

In next linear collider designs, the effort to create and maintain short electron/positron bunches requires a robust technique to measure bunch lengths. Designs have bunch lengths as short as 100 μm, or 330 fs, and a desirable goal is to measure the length to 10% or better. Short bunches have the advantage of avoiding the "bow-tie" degradation of the luminosity while using strong focusing and small spots at the interaction region. The bunch length also needs to be short compared to the RF wavelength in the linac to avoid nonlinear effects from the accelerating gradient. Control of the bunch length in the magnetic bunch compressor after the damping rings requires accurate measurement of the length. The variation of length with position in the bunch train is also important to create uniform luminosity over the collision time and to correct any "long-range" wakefield or other effects on the bunch train.

Currently measuring electron bunch lengths with coherent transition radiation (or coherent diffraction radiation, or coherent synchrotron), requires scanning a mm-wave interferometer and thus acquires signal over many electron pulses[1]. A technique using the perturbing effects of the passing electron bunch's electric field on a crystal (electro-optic, or EO, effect) measured by a fast Ti:sapphire laser has been demonstrated at the free-electron laser center (FELIX) in the Netherlands[2]-[5]. A non-destructive, single shot measurement of a 1.7 ps long electron beam is performed with an estimated accuracy of 0.37 ps. The wakefields behind the electron beam are also measured with this technique. In Refs.[6, 7], there was difficulty in measuring the direct fields because of the strength of the wakefields following the electron bunch; their charge was much greater than in the FELIX experiment. They plan to build a low-impedance structure to house the EO crystal for future measurements.[1]

[1] See the UCLC proposal by C. Bohn, Northern Illinois University and Fermilab.

The goal of this proposal is to perform EO measurements of both (FEL) laser and electron bunch lengths, but make several improvements. One is to use a shorter pulse Ti:sapphire laser, approximately 8 fs instead of 30 fs, and another is to increase the spectrometer resolution. This should yield an error of less than 180 fs on a single-shot measurement of a 1 ps electron beam (assume a chirped pulse length of about 4 ps for good signal to noise); chirped for a shorter electron pulse of 0.3 ps (assume a chirp of 1.2 ps) this would result in a resolution of less than 100 fs. Ref. [5] gives the minimum intrinsic resolution as $\Delta t = \sqrt{t_0 t_c}$, where t_0 is the unchirped pulse length and t_c is the chirped pulse length. Improvements toward the desired 30 fs resolution could come from improving the sensitivity and resolution of the spectrometer, allowing shorter chirps closer to the actual electron bunch length.

It is important to point out that if timing jitter can be kept smaller than the probe laser pulse length, that length, 8 fs, would be the ultimate resolution in a sampling (many pulse) measurement. This is an important aspect of the research, synchronizing the probe laser to the electron bunch on the 30 fs level.

A Ti:sapphire oscillator will be installed at the Vanderbilt Free-electron Laser Center. It will be synchronized with the electron beam (and FEL laser beam). It appears that a laser with an 8 fs pulse length and approximately 10 fs synchronization are possible[8, 9]. The first measurements will be the longitudinal profile of the FEL laser pulse which is about 1 ps long. On a bench in the lab, refinements will be made to the spectrometer and pulse picker and resolutions estimated. The EO crystal holder and the laser beamline to our electron beam will be designed and built. The chamber design will be aided by the low-impedance chamber effort at Fermilab's AØ photoinjector, a part of the UCLC proposal by Court Bohn. Electron bunch length measurements will follow. For linac physics reasons, it is interesting to measure the evolution/change of the electron bunch through the electron macropulse; this will be an issue with the linear collider too. Comparisons will be made to coherent transition radiation measurements of the bunch length, as well as sampling measurements with the EO technique. At the FEL, a geometrically flat beam can be made with about 10:1 aspect ratio and the bunch length measured; the AØ photoinjector may be available for experiments on truly flat beams with aspect ratios of 50:1, or better. The electron beam at the FEL has a single pulse charge of 50 pC, however the monochromatic xray machine at the Center has single bunch charges of 1-5 nC in 8 ps and is available for experiments.

The current budget below does not yield a complete laser that can be moved from lab to lab for experiments. This would be desirable to explore both flat geometry, different electron pulse energies, and especially very high bunch charge effects. With extended funding, a laser could be made that can be moved around for experiments, or at least, the efforts with Kapteyn and KMLabs should yield a source for such lasers at what appears a more reasonable price than other options.

The EO measurement is sensitive to all externally applied electric fields, including the wakefield the electrons induce in the structure. This can be a novel way to measure the wakefields. It is important to point out the EO bunch length measurements on FEL's do not seem to suffer from excessive wakefield effects; the bunch charge is typically less than 0.2 nC. While in the Fermilab experiment on the AØ Photoinjector, the currents were 1-12 nC and the direct bunch signal was overwhelmed by the wakefields.

The Vanderbilt FEL Center has the needed expertise for these experiments. The Center routinely runs a 45 MeV electron linac with high average power as a driver for the FEL. The Center also runs a tunable, back-scattered xray source that uses a high-charge, 45 MeV electron bunch and a Ti:sapphire driven glass laser capable of 20 TW in 8 ps. The electrons and the laser are synchronized on the picosecond level. An optical parametric generator system capable of tunable light from UV to mid-IR is also run by Center personnel. That system is based on a Ti:sapphire oscillator and amplifiers driving nonlinear interactions in crystals.

FY2003 Project Activities and Deliverables

Activities: Purchase and install a Ti-sapphire laser system, synchronized with the Vanderbilt free-electron laser. Using the infrared laser from the FEL as a convenient picosecond pulse on a bench, perform measurements of the laser pulse length with the electro-optic technique. Refine and explore the single-shot techniques. Design a low-impedance vacuum chamber for measuring the electron bunch length. Measure the electron bunch length using coherent transition radiation (CTR) which is averaged over many pulses of the electron beam.

Deliverables: Papers describing the electro-optic measurement of the FEL laser and exploring methods of single shot measurements (pulse stretching/chirping or geometric). Design of a low-impedance vacuum chamber in collaboration with Court Bohn.

FY2004 Project Activities and Deliverables

Activities: Build and install the low-impedance vacuum chamber for the electron measurements. Also design and build a laser beamline from our laboratory floor to the "vault" containing the electron linac and FEL. Measure the electron bunch length with the EO technique and compare with CTR. Measurement of the wakefield following the electron bunch will also be performed. Measure the bunch length as a function of position in the macropulse on separate succeeding macropulses.

Deliverables: Papers describing the laser beamline, the low-impedance vacuum chamber, and the electron bunch length measurements. Macropulse evolution of the electron bunches will be described.

FY2005 Project Activities and Deliverables

Activities: Continue increasing the resolution of the EO measurement. The ultimate goal is 10 μm for the 100 μm bunch lengths. Measure wakefields for model impedances. Investigate moving laser to Fermilab to measure flat electron beams.

Deliverables: Paper describing any improvements to the resolution. Paper detailing the wakefield measurements.

Budget justification

The first year of the budget is mostly the fast Ti:sapphire laser needed for the experiment. The laser synchronized with a 3 GHz source is the greatest unknown in the budget. H. Kapteyn from the University of Colorado and from KMLabs reports that it is possible to buy such a laser and is interested in working a real bid; this number is just an educated guess. Other resources may need to be drawn on to complete the laser; the laser is seen as a good tool for the Vanderbilt FEL Center.

In year 2, several other optical devices need to be built or improved: a stretcher to lengthen and chirp the oscillator pulse, usually one diffraction grating and a mirror are required; a pulse picker which is a fast rise and fall time Pockels cell (10 ns) capable of selecting out one pulse from the Ti:sapphire oscillator train which typically delivers pulses at 80 MHz; and a spectrometer made with a good quality, sensitive CCD camera to image the laser beam after being diffracted. Travel to collaboration meetings is also included as well as general optical mounts under materials and supplies. The vacuum chamber that will house the EO crystal and optics for the electron measurements and the laser beamline to that chamber need to be designed and constructed.

In year 3, equipment is for modifications of those devices or the spectrometer, as needed. Travel in those years includes collaboration meetings and conferences. Half a post-doctorate is budgeted and will be shared with Dr. Feng's effort in the UCLC for generating and measuring diffraction radiation from the electron beam.

Three-year budget, in then-year K$

Institution: Vanderbilt University[2]

[2]Fringe rate used is 25.6% actual is likely to be less; indirect cost rate is 51%. Values rounded to nearest 0.1 k$.

Item	FY2003	FY2004	FY2005	Total
Other Professionals	0	25	25	50
Graduate Students	0	0	0	0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	0	25	25	50
Fringe Benefits	0	6.4	6.4	12.8
Total Salaries, Wages and Fringe Benefits	0	31.4	31.4	62.8
Ti:sapph oscillator with synchronization(est.)	70			70
improve Diffraction grating for pulse stretcher		10		10
improve Diffraction grating and CCD for spectrometer		15		15
improve Pulse picker, 10ns		9		9
electro-optic crystals	6			6
miscellaneous, computers		6		6
Equipment	76	40	0	116
Travel	1	1	1	3
Materials and Supplies	0	10	10	20
Other direct costs	0	0	0	0
Total direct costs	77	82.4	42.4	201.8
Indirect costs (51%)	0.5	21.6	21.6	43.8
Total direct and indirect costs	77.5	104.0	64.0	245.6

References

[1] R. Lai, U. Happek, and A. J. Sievers, "Measurement of the longitudinal asymmetry of a charged particle beam from the coherent synchrotron or transition radiation spectrum," Phys. Rev. **E 50**, R4294 (1994).

[2] I. Wilke, A. M. MacLeod, W. A. Gillespie, G. Berden, G. M. H. Knippels, and A. F. G. van der Meer, "Single-shot electron-bunch length measurement," Phys. Rev. Lett. **88**, 124801-1 (2002).

[3] X. Yan, A. M. MacLeod, W. A. Gillespie, G. M. H. Knippels, D. Oepts and A. F. G. van der Meer, "Application of electro-optic sampling in FEL diagnostics," Nucl. Inst. and Meth. **A 475**, 504 (2001).

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[5] Z Jiang and X. C. Zhang, "Measurement of spatio-temporal terahertz field distribution by using chirped pulse technology," IEEE Jour. Quant. Elect. **36**, 1214 (2000).

[6] M. J. Fitch, A. C. Melissinos, P. L. Colestock, J.-P. Carneiro, H. T. Edwards and W. H. Hartung, "Electro-optic measurement of the wake fields of a relativistic electron beam," Phys. Rev. Lett. **87**, 034801-1 (2001).

[7] M. J. Fitch, A. C. Melissinos and P. L. Colestock, "Picosecond electron bunch length measurement by electro-optic detection of the wakefield," published in the Proc. of the Particle Accelerator Conference 1999.

[8] H. Kapteyn, Dept. of Physics, University of Colorado, Boulder and KMLabs, LLC, *private communication.*

[9] L.-S. Ma, R. K. Shelton, H. C. Kapteyn, M. M. Murnane and J. Ye, "Sub-10-femtosecond active synchronization of two passively mode-locked Ti:sapphire oscillators," Phys. Rev **A 64**, 021802-1 (2001).