Electro-optic measurement of picosecond bunches in a bunch train

Classification (subsystem)

Accelerator Instrumentation: non-destructive electron bunch length measurement, broadly applicable

Personnel and Institution(s) requesting funding

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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. Superconducting technology, next generation linear collider (ILC) designs have bunch lengths as short as 300 μm, or 1 ps, 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 from the depth of focus 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 which could lead to worsening of the effective emittance of the train. In the superconducting linear collider designs, the bunch train can be very long with 2800 to 4900 bunches spaced every 340 ns to 180 ns. Measurement and control of the bunch train becomes all the more important and difficult with so many bunches spaced over the relatively long time of 1 ms. Measurement and control of the bunch train quality is important to free-electron lasers which, for example, generate a laser pulse in an oscillator with bunch 1, amplify it with bunch 60, and bunch 120, all the way to bunch 18000, say. The bunches need quite a tight tolerance to have effective amplification and saturated energy.

Currently measuring electron bunch lengths with coherent transition radiation (or coherent diffraction radiation, or coherent synchrotron radiation), requires scanning a mm-wave interferometer and thus acquires signal over many electron pulses[1]-[2]. 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[3]-[6]. 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. The SLAC SPPS facility has demonstrated the generation and measurement of very short electron bunch lengths of 50 to 80 fs for single bunches.

The goal of this proposal is to perform EO measurements of the length of the electron bunches in the Vanderbilt free-electron laser (FEL). A short pulse Ti:sapphire laser, approximately 15 fs will be used as the probe laser. This should yield an error of less than 240 fs on a single-shot measurement of a 1 ps electron beam (assuming a chirped pulse length of about 4 ps for good signal to noise); chirped for a shorter electron pulse of 0.3 ps (assuming a chirp of 1.2 ps) this would result in a resolution of less than 130 fs. Ref. [6] 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.

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). A laser with a 15 fs pulse length and approximately sub-100 fs synchronization is available. This should happen before the end of the calendar year. The EO crystal holder and the laser beamline to the electron beamline will be designed and built. There is currently operating a diagnostics chamber on the FEL that measures coherent transition radiation and coherent diffraction radiation from the FEL electron bunches[2]. With the electro-optic measurement in the same chamber, this will give three complementary bunch length diagnostics.

For linac physics reasons, as well as for free-electron laser physics reasons, it is interesting to measure the evolution/change of the electron bunch through the bunch train. As mentioned above, FEL's need good quality bunch trains: the electron bunches throughout the train need to be evenly spaced and of equivalent length. The bunch train is affected by the RF fill time in the linac, the quality of the RF pulse, the long range wakefields, and any variation in the electron source.

Single-shot EO measurements will be compared to coherent transition radiation measurements of the bunch length, as well as sampling measurementswith the EO technique (using an unchirped pulse and stepping through the electron bunch) . The electron beam at the FEL has a single pulse charge of 50 pC, however the Compton xray machine at the Center has single bunch charges of 1-5 nC in 8 ps and is available for experiments.

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 electron bunch 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 to generate tunable wavelength light.

Broader Impact

The budget for this project is mostly for a graduate student and two summers of undergraduate help. The graduate student has been invaluable in motivating experiments and data analysis. He is also being trained as an accelerator physicist with talents needed by many existing and planned particle beam machines. Vanderbilt University has a joint physics and astronomy training program with Fisk University, an historically black college. It is part of the plan to be more active in this collaboration and hire undergraduates from Fisk for summer work.

Results of Prior Research

The UCLC collaboration and NSF have kindly supported this effort over the last two years. First with seed money and most recently with a year of salary for a shared graduate student with Dr. Bibo Feng's efforts in the study of coherent diffraction radiation electron diagnostics. This and other linear collider efforts receive broad support from the FEL Center director Dr. David Piston, in the form of support staff, vacuum hardware, and other materials and supplies.

Seed Money for Electro-optic bunch length measurements
Award: NSF PHY-0303702
Award period: September 15, 2003 to February 28, 2005
Award amount: $11,209

This was awarded by the NSF for UCLC work and is administered as a sub-contract with Cornell University. The money was used to purchase a pulse-picker to reduce the 80 MHz Ti:sapphire output to the 30 Hz needed for the probe laser. This will reduce the background on the spectrometer or other detection device. The pulse-picker was received in December 2004 and is being tested with another 80 MHz Ti:sapphire laser in the Center. The grant also paid for a very valuable trip to the Victoria Linear Collider Workshop in July 2004. It was very helpful to see the state of the international research. The remaining portion is being used to purchase electro-optic crystals.

Single-shot, electro-optic bunch length measurement of a picosecond electron bunch length
Award: NSF PHY-0355182
Award period: September 1, 2004 to August 31, 2006
Award amount: $18,082

This is also an award by the NSF for UCLC work and is administered as a sub-contract with Cornell University. The money is being used to pay a graduate student. He is shared with Dr. Bibo Feng and is working on electro-optic and diffraction radiation diagnostics. The diffraction radiation experiment is currently taking data[2].

Facilities, Equipment and Other Resources

The FEL Center is a world-class free-electron laser facility at Vanderbilt University. Within the Center there are ten staff engineers, scientists and technicians. Their specialties include mechanical engineering and mechanical design, high-vacuum engineering, operation and maintenance of high power pulsed lasers, RF/microwave engineering, data acquisition, electronics and pulsed power, data analysis, and more. The Center houses the FEL which is based on a 45 MeV, a Compton backscattered xray source which uses a photocathode RF gun and a 20 J, 8 ps laser, and an optical parametric amplifier laser system. Center staff operate, maintain, and upgrade these machines.

Vanderbilt University has very good talent and equipment in the scientific machine shop which the Center routinely uses and has subsidized access to.

FY2005 Project Activities and Deliverables

This year the fast Ti:sapphire laser will be installed. There will be a variety testing and diagnostics performed. The detector for the electro-optic measurement will be rehabilitated and tested. It is an older, but high quality CCD spectrometer.

First bunch length measurement could occur on the Compton xray machine due to easy accessibility. It is a self-shielded linear accelerator, with staff working around the machine while it is pulsing. This gives easy access to optics near the beamline.

The design and start of construction for the laser beamline from the second floor to the first floor (FEL vault) will occur. This is a longer run and will involve several remote controlled mirrors. It has the added difficulty of maintaining the fast laser pulse, and large bandwidth which is easily disturbed even by passage through air.

These activities will be reported on at the linear collider and collaboration workshops. Students will be collaborating on all linear collider experiments with analysis work on the coherent diffraction radiation and coherent transition radiation measurements.

Graduate students will attend the U. S. Particle Accelerator School.

FY2006 Project Activities and Deliverables

The electro-optic measurements of bunch length of the FEL electron beam will be carried out. Multi-pulse measurement, stepping through the electron bunch train will be performed. With other electron bunch length monitoring, and FEL laser bunch length monitoring, there will exist a plethora of measurements to compare.

These activities will be published in appropriate journals and reported on by the students at conferences and workshops. Students will attend the U. S. Particle Accelerator School.

Budget justification: Vanderbilt University

The budget is dominated by support for a graduate student and for summer students. This will train new accelerator physicists at a time when there appears a current and future need. The summer students will be introduced to a research intensive environment and to linear collider and laser activities. Currently, there exists a joint scientific training grant between Fisk University, an historically black college, and Vanderbilt University. This relationship is being explored for possible summer students and collaborators.

The new graduate student will need a computer for data analysis.

At the FEL Center travel budgets are small, so for the students and this author to report on activities, two to three trips are budgeted. The graduate student should attend the U. S. Particle Accelerator school each year. This is not only instructive, but it allows her to make connections and to appreciate the breadth and depth of accelerator physics and beam dynamics.

The materials and supplies envisioned are for fast laser optics, *i.e.* lenses, mirrors, vacuum windows, all must have very small dispersion.

Three-year budget, in then-year K$

Institution: Vanderbilt University, Nashville, TN

Item	FY2005	FY2006	Total
Graduate Students	13.7	21.2	34.9
Undergraduate Students	2.6	2.7	5.3
Total Salaries and Wages	16.3	23.9	40.2
Fringe Benefits, Health Insurance	1.6	1.6	3.2
Tuition Share (no overhead)	4	0.6	4.6
Total Salaries, Wages and Fringe Benefits	21.9	26.1	48
Computer	2	0	2
Travel	4	4	8
Materials and Supplies	4	3	7
Total direct costs	31.9	33.1	65
Indirect costs(1)	14.5	17.2	31.7
Total direct and indirect costs	46.4	50.3	96.7
(1) Vanderbilt University has 52% rate FY05 and 53% FY06.			

References

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