Final Report for May 1 2004 to April 30 2005 and renewal request for the experiment # 1042511

Electro-optical detection for the temporal characterization of sub-picosecond beam bunch

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Reporting Period: July 1, 2004 – March 1, 2005

1.0 Purpose To develop a novel, single-shot, non-destructive method of determining the time structure of the relativistic electron bunch length in the sub-picosecond resolution. Using an electro-optical flash (EO-flash) detection technique, we will demonstrate that the electron bunch length can be converted from time to spatial information. An additional task added for the continuation is advanced topics of particle acceleration in vacuum with high-power lasers.

2.0 Approach

2.1 Electro-Optical Detector

The electric field of a traversing electron bunch induces a time dependent change in the birefringence at different spatial location on an EO crystal. By focusing a synchronized femtosecond light pulse to a line focus on the EO crystal and using a pair of crossed polarizer, this induced birefringence can be converted to an intensity variation across the line focus. Therefore the temporal shape of the electron bunch is transformed to a spatial intensity distribution on a CCD detector, hence EO-flash technique, as indicated in Figure 1. The timing jitter between the laser pulse and the electron beam bunch can be observed as a variation in the spatial intensity distribution. When the length of the laser line focus is longer than the sum of the electron bunch

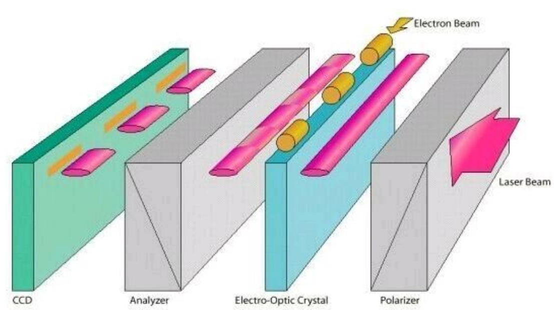

Figure 1. Schematic of the experiment

length and the timing jitter, this single shot EO-flash technique can tolerate a large amount of timing jitter. The temporal resolution of the measurement system is limited by the laser pulse duration and the thickness of the EO crystal inasmuch they determine the extent of the electron bunch beam motion during the time that the laser light is passing through the crystal. The experiment is to be done at the Accelerator Test Facility (ATF) in Brookhaven National Laboratory. A 45 MeV electron beam in a bunch length of ~0.5 picosecond with a single bunch charge of up to 250 pC will be focused to a beam size of ~ 200 μm in diameter. The electron beam field is then analyzed by a thin 10x10x0.25 mm ZnTe <110> single crystal.

2.2 Advanced topics of particle acceleration in vacuum with high-power lasers.

Energy recovery in a laser accelerator: Transient control and stability of a system that contains a feedback loop as is the case in the energy recycling in an optical linear collider will be determined. In addition electron dynamics, signal to noise-ratio and instabilities require systematic investigation. According to the results of this analysis it will be necessary to examine the emittance as well as the overall luminosity of this scheme.

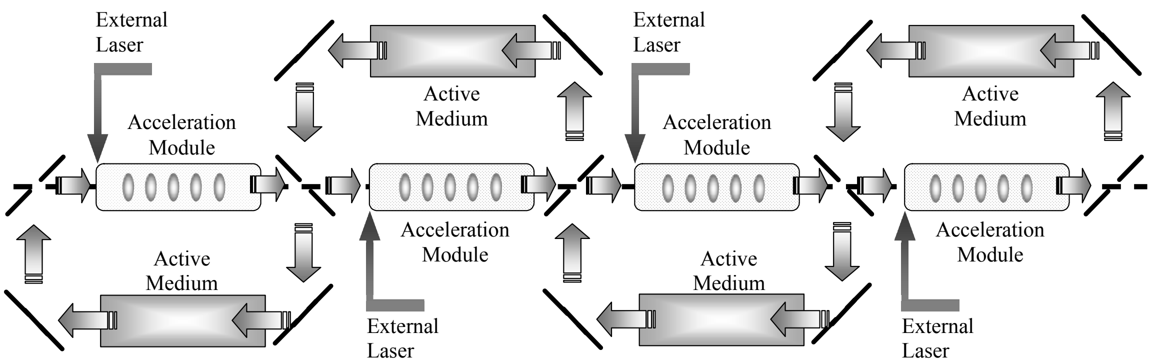

Figure 2.1: Energy recovery in an optical linear collider.

Optical acceleration structures: Beyond the basic design of dielectric accelerating structure and its electromagnetic properties it is necessary to establish its sensitivity to manufacturing errors, temperature variations and non-linear effects.

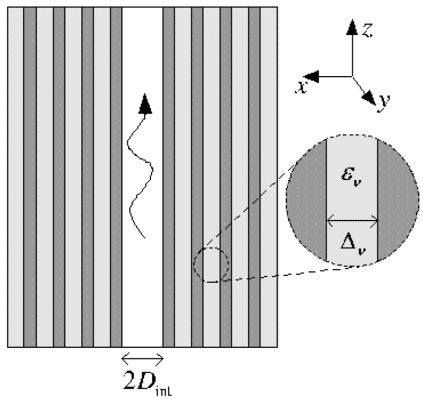

Figure 2.2: Planar Bragg Accelerator. The field propagates in the *z*-direction and decays exponentially in the transverse (*x*) direction.

Wakes in dielectric structures: We contemplate evaluation of wakes in various dielectric structures and their use for beam position monitors or bunch characterization (length and cross-section).

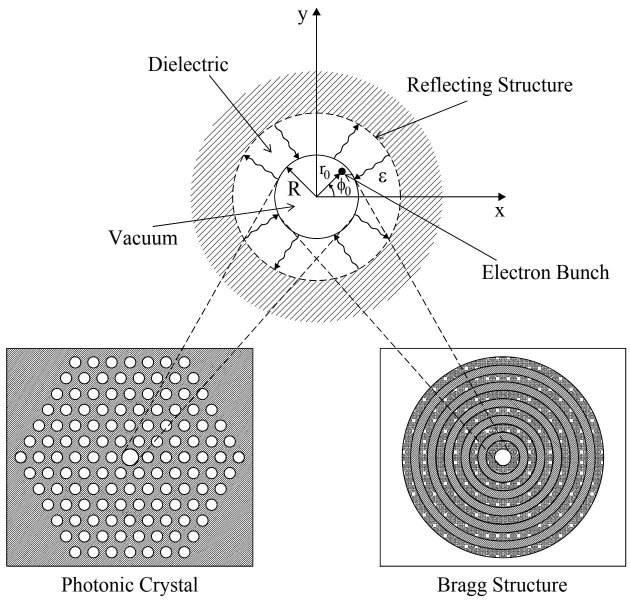

Figure 2.3.: Evaluation of the wake field generated by a bunch in a dielectric structure which is uniform in the direction parallel to the motion of the bunch. The transverse confinement is ensured by either a Bragg structure or a photonic band gap structure.

3.0 Technical progress to date

3.1 Laser source At the ATF facility, the rf photoinjector light pulse is 6 ps long which is much longer than the anticipated 0.5 ps electron beam bunch to be measured using the EO technique. In order to characterize a sub-picosecond electron beam a sub-picosecond light pulse is required. We have identified a femtosecond Yb-glass laser oscillator at the ATF as the photon source in our EO detection scheme. The synchronization of the electron beam and the light pulse has been achieved by phase-locking the master rf clock of the ATF to the Yb-glass femtosecond laser. This passively mode-locked laser emits at the center wavelength of 1.05 μm with an average optical power of 100 mW at the repetition rate 81 MHz in a pulse duration 210 fs FWHM. Therefore it has 1.2 nJ/pulse with a peak power of ~6 kW/pulse. Using a Pockels cell a single pulse was successfully sliced out of the phase-locked pulse train to be used for EO measurements, see Figure 2. However, the laser oscillator alone delivers only $\sim 10^9$

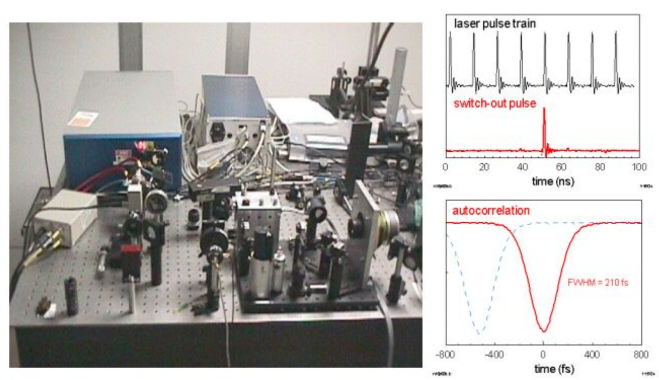

Figure 2: Yb-YAG glass laser in ATF laser room

photons/pulse for EO measurements. Considering at best EO signal modulation of 10%, a 10^{-4} extinction after cross polarizers, and an optical loss of 50%, we anticipated only ~10^4 signal photons to be observed on a CCD in a line focus. For a 512 pixel element CCD, each pixel receives only ~23 signal photons riding on 10 times more unmodulated (dc) photons. Significantly more photons are needed to achieve good SNR after image processing. Therefore, effort is being made and necessary equipment are required to amplify the light pulse from 1 nJ to ~10 μJ using one or two stages of fiber amplifiers. The IR light pulse will then be frequency doubled to the visible spectrum and sent to the EO measurement station. A gated, intensified, CCD camera will be used to collect the spatial intensity distribution. Image subtraction with and without the electron beam on will be performed to obtain the electron bunch length information.

3.2 EO testing preparations In preparation for the EO-flash detection of sub-picosecond electron beam bunches, the validity of the optical design shown in Figure 1 was tested at the Instrumentation division at BNL. The light source was an amplified 250 femtosecond Ti:sapphire laser system running at the center wavelength of 800 nm. The light output was attenuated to 2-50 μJ/pulse for use in the experiment. The synchronized electron beam field was simulated by applying a 2-50 ns pulsed high voltage of up to 0.5 kV across a pair of parallel electrode plates. A <110> ZnTe crystal was placed between the plates so that a time dependent birefringence could be produced in the EO crystal. Because the temporal width of the simulated electron beam field is much larger than the light pulse, instead of a line focus the laser beam was not focused on the EO crystal. After a pair of crossed polarizers, the extinguished beam was recorded on a conventional CCD camera. Single images with and without pulsed high voltage were captured on an 8-bit video frame grabber. After image subtraction, the beam field induced spatial image was clearly revealed, left images shown in Figure 3. The line graphs of the column sum of each images is plotted on the right side of Figure 3. The un-extinguished beam propagated through the crossed polarizers is mostly due to the residual birefringence of the EO crystal, while the non-Gaussian like spatial beam profile is a result of a mixture of the residual birefringence and the quality of the ZnTe EO crystal. These results clearly suggest that for pulse width measurements relying on the temporal to spatial transformation, not only the spatial quality of the light pulse is important, good optical quality of the EO crystal is also essential. Furthermore, the scheme required ~μJ/pulse of light intensity to achieve reliable signal after image subtraction, hence single light pulse emitting directly from a laser oscillator is inadequate for temporal characterization. Also, because the temporal information depends on images subtraction an intensified CCD with >12-bit of dynamic range would significantly improve the SNR.

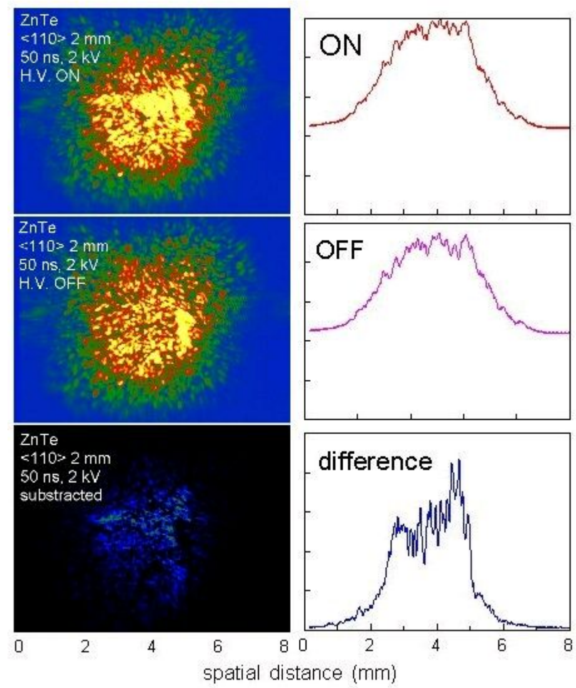

Figure 3. Test of EO modulation with crossed polarizers

4.0 Planned accomplishments on the remaining FY2005

A free space optical beam transport will be designed for use in the experimental hall at the ATF facility. Experimental Safety Review documentation will be drafted for the EO experiment to be done at ATF. An appropriate CCD array will be identified and purchased for this experiment. Additional optical components will be purchased to amplify the laser oscillator light pulse to ~10 μJ/pulse. Harmonic generation crystals will be purchased to frequency double the NIR to the visible. The EO-flash technique will be tested in the laboratory using the newly acquired, gated, intensified CCD prior to its deployment at the ATF experimental hall. We'll also investigate the possibility of using GaSe crystal for the EO-flash detection. This nonlinear crystal has a larger EO coefficient and nearly twice the bandwidth of ZnTe, ideally suitable for the detection of sub-100 fs electron beam bunched.

5.0 Funding

5.1 Electro-Optical Detector:

	Request	Spent (ending March 1, 2005)
FY2005	$125,000	$35,210
FY2006	$55,000	----
Total	$180,000	$35,210

5.2 Advanced topics of particle acceleration in vacuum with high-power lasers:

	Request
FY2005	$29,500
FY2006	$23,520
FY2007	$23,000
Total	$76,020