Z-SHAPER: A PICOSECOND UV LASER PULSE SHAPING CHANNEL AT THE ADVANCED SUPERCONDUCTING TEST ACCELERATOR*

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Abstract

Many accelerator applications require a longitudinally-shaped electron beam profile for studies ranging from THz generation to dielectric wakefield acceleration. An electron beam profile can be shaped through many techniques in both electron beam generation, such as with a DAZZLER or in ellipsoidal pulse generation, and beam transport, using an emittance exchanger or linearizing harmonic cavity. Shaping of a UV pulse with length on the order of picoseconds was demonstrated using alpha-BBO crystals in the Advanced Superconducting Test Accelerator (ASTA) drive laser using this relatively economical solution to effect a predictable and tunable longitudinal bunch shape, profiles have been generated and observed using a Hamamatsu C5680 streak camera, and the results are compared with the analytical theory.

INTRODUCTION

Particle beams are not ideal even under the best of laboratory conditions. The e-beam at ASTA is no exception.[1] There are always fluctuations in the beam density and beam energy. Thus, efforts to model and understand these fluctuations have long been a focus of intense beam research. Typically, these fluctuations appear due to various factors external to the bunch dynamics such as cathode roughness, laser jitter, RF fluctuations and other limitations in the instruments. Recent experiments have shown that a hight-brightness beam along a linac can also be a source of modulations both in energy (introduced primarily by longitudinal space charge impedance) and in density (generated by compression using dispersive elements)[2]. Such effects can adversely affect the beam quality and can create havoc to accelerator operations primarily beam diagnostics. One possible way to understand the effects of such modulation is to deliberately introduce perturbations on the e-beam and study the evolution of the beam along the linac. Shaping electron bunches can be done several ways. To have precise control over the longitudinal bunch profile, shaping is best done by shaping the photocathode drive laser. Ultrashort (fs - ps) laser shaping is a separate field of R&D and a wide variety of techniques are possible. Typically, such techniques are done in the IR and are at kHz repetition rate[3]. For modern accelerators based on superconducting technology, UV pulse shaping based on α-BBO crystal is a cheap, compact, power-efficient technique that is also scalable to MHz repetition rates[4, 5, 6]. In this paper, we briefly review the theory behind the technique, describe our experimental results and conclude with a proposal for future experiments.

THE ASTA LASER

The ASTA drive laser is a diode-pumped laser system using either a Yb-Fiber Amplifier seed or a Time Bandwidth Nd:YLF seed at 1054 nm with single-pass amplifiers and conversion stages. The laser ($\lambda = 263$ nm) is currently able to deliver UV (100 microseconds limited by permit) to the photocathode at 3 MHz and can deliver up to $\sim 5\mu$J per pulse for up to 3000 pulses in a pulse train. The laser is able to generate up to 81.25 MHz allowing for flexibility through future upgrade. With the measured average QE of 1%, the amount of laser energy is sufficient to generate the ASTA requirement. The schematic of the laser is shown in the Fig. 1 below.

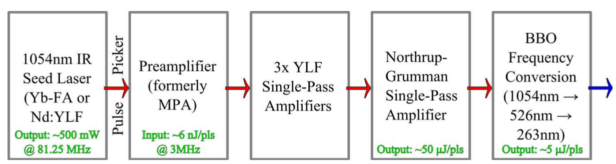

Figure 1: Schematic of the ASTA drive laser system.

THEORY OF PULSE SHAPING

Materials that exhibit anisotropy in the refractive indices for two different polarizations of the incident light are called birefrigent crystals. In such crystals, a temporal separation between the ordinary ray (perpendicular to the optical axis) and the extraordinary ray (parallel to the optical axis) occurs as the light travels through the crystal. The separation is proportional to the group velocity mismatch due to the two different indices of refraction. A very important point to note is that the group index of refraction $n_g = n - n\frac{dn}{d\lambda}$ should be used in this calculation. Therefore, the time separation between the pulses after passing through a crystal of length L can be written as $\delta t = L\frac{\delta n_g}{c}$. In practical units, $\frac{\delta t}{L}$ is equivalent to delay per unit length of the crystal. For an α-BBO crystal at λ =263 nm, the theory along with appropriate Sellenmeir equation predicts

* Fermi Research Alliance, LLC operates Fermilab under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy
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a delay of 0.864 ps/mm. Therefore, the distance between the two outgoing pulses is fixed by the length of the crystal which is not a free parameter during the experiment. An illustration for α-BBO is shown in Fig. 2. The pulse length of the individual pulse remains unaffected as the group velocity dispersion along the polarization direction is small. The flexibility of this technique stems from the fact that by rotating the crystal on the plane perpendicular to the direction of propagation, the amplitude of each of these pulses can be changed. For example when the incident light is 45 $^\circ$ to the optical axis, two pulses of equal intensity are generated, whereas only one pulse is generated when the incident light travels directly along the axis. By adding multiple crystals, one can generate a pulse train, each pulse separated in time with variable amplitude. Many experiments have demonstrated this technique[7]. The number of crystals used in the experiment is limited practically by the laser energy and transmission efficiency. Ultimately at some point, the length of the pulse becomes large compared to RF-wavelength for ps-lasers and mm-sized crystals. It is worth pointing out that instead of crystal length, thermal effects can be used to change the birefringence of the crystal[8]. Alternatively, one way of achieving finer control over the length of the crystal would be to use a wedge shaped crystal as in a Soleil compensator. But practical implementation of a wedge might be limited only to translation motion which will still introduce a transverse offset to the laser path. Rotating a wedge will be more challenging since it requires re-alignment of the laser to the cathode for every position.

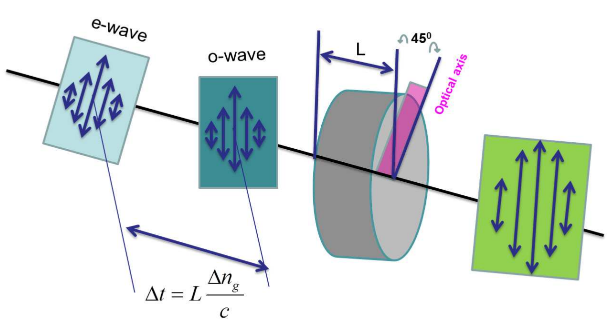

Figure 2: Illustration of pulse shaping through an α-BBO crystal

EXPERIMENTAL SETUP

Our experimental setup included three crystals of length 4.5 mm, 9 mm, and 18 mm collectively referred as Z-Shaper. Each of the crystals was 5 mm x 5 mm transversely. They were mounted in remotely controllable open-loop rotary stages driven by a networked controller integrated into the Fermilab control network (ACNET). The crystals were AR-coated for 263 nm. We used the Hamamatsu C5680 streak camera in a dual-sweep configuration. The vertical deflection was provided by the synchroscan unit which was phase locked to 81.25 MHz, and the horizontal deflection was provided by the M5679 unit. At 800 nm, the intrinsic tube resolution was 0.6 ps σ, but at the UV wavelength the resolution is $\sim$ 1 ps. When operating on the fastest sweep range, the phase-locked mode provided low jitter ($<$ 1 ps) of the streak images so synchronous summing of the micropulses could be done. We also used the C6878 phase-lock delay unit to provide the phase stability of the operation over 10's of minutes. The calibration of the four synchroscan ranges were done by selecting different delays from the Colby delay unit and tracking the centroid position changes. The fastest ranges were $R2 = 0.45 ps/pixel$ and $R1 = 0.15 ps/pixel$.

Experimental results with one crystal

While most manufacturers of α-BBO crystals provide a birefringence, it is typically not with the group velocity dispersion. So, it is better to actually measure the birefringence of the crystal in the laboratory. In order to measure the birefringence of the crystal, we mounted only a single crystal and rotated it from 0 to 90 degrees and measured the peak intensity variation in the streak camera. The results are shown in Fig. 3.The distance between the two pulses remains constant at 20.5±0.9 ps and thus allowed us to measure 0.2275 ps/mm as the delay per unit length of the crystal. In all of these experiments the bunch length was σ = 5.1 ps.

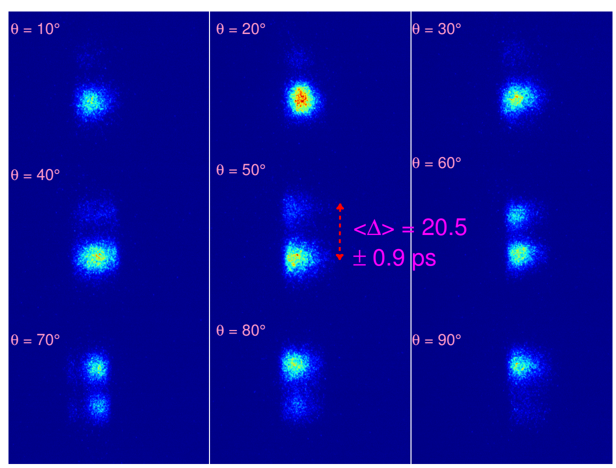

Figure 3: Experimental results from measuring birefringence of a single crystal. The intensity of the two outgoing pulses changes as a function of the rotation angle while the distance between them remains constant allowing a way to measure the birefringence.

Experimental results with three crystals

The most interesting case occurs with all three crystals due to the range of pulse shapes that can be generated. We generated a profile with a density perturbation (longitudinal hotspot) Fig. 4, a profile with modulated charge density Fig. 5, and a profile with flat-top distribution Fig. 6.

There is very good agreement between prediction and measurement. Though only three profiles are shown, there are numerous other interesting profiles that could be generated such as a ramp-like profile with different slopes. We sometimes observed transverse birefringence while doing the experiment for certain angles and those angles must be avoided when running an electron beam experiment.

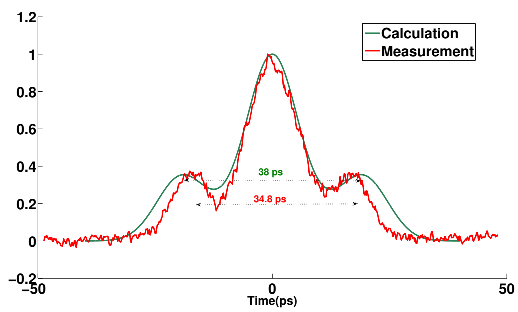

Figure 4: Longitudinal density perturbation generated and compared with the calculation.

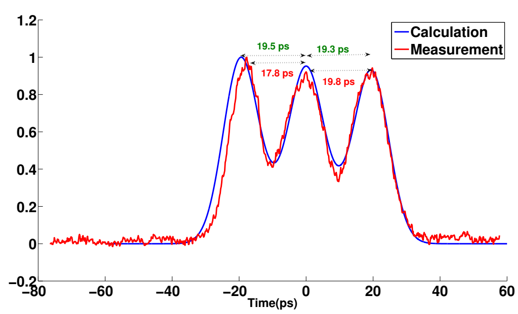

Figure 5: A longitudinally modulated distribution generated and compared with the calculation showing good agreement. Such pulses can be used to see the conversion of the density modulation to the energy modulation in a linac.

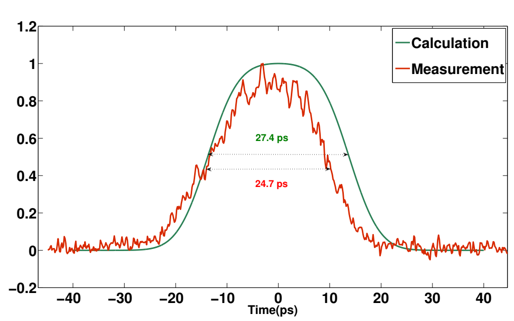

Figure 6: A flat-top distribution generated compared with the calculation, showing good agreement.

CONCLUSION AND FUTURE WORK

The laser pulse length during this experiment was slightly longer than the ASTA baseline value due to a multipass amplifier which has now been replaced with the preamplifier shown in Fig 1 reducing the pulse length to 3.6 ps. Though the dynamics of a single laser pulse is fairly constant, the laser pulse length can start to make a substantial difference when we have three or more crystals. We also experienced difficulty due to the open-loop rotational stages and so the crystals will be mounted in a closed-loop stage for more precise control on the crystal rotation. Our ultimate goal is to illuminate the cathode with a shaped laser profile and perform controlled studies on profile evolution in a superconducting linac. ASTA is being developed with the requisite diagnostics to do such a measurement. For example, a gun-phase scan with the Z-shaper could already be performed at 5 MeV and used as a control to eventually compare with the bunch profile at the end of the low-energy linac at 40 MeV.

ACKNOWLEDGMENTS

The authors of this paper would like to acknowledge those working to make ASTA a reality, especially colleagues in the SRF Electron Linac Department, Accelerator and Technical Divisions, and Fermilab management. One of us (J. T.) would like to thank J. Power of ANL for helping with question on the crystals.

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