

HIGH FREQUENCY BUNCH TRAIN GENERATION FROM AN RF PHOTOINJECTOR AT THE AWA*

J.G. Power[#], ANL, Argonne, IL 60439, U.S.A
 C. Jing, Euclid Techlabs, LLC, Solon, OH 44139, U.S.A.
 I. Jovanovic, Purdue University, West Lafayette, IN 47907, U.S.A.

Abstract

An exploratory study for the generation of high frequency bunch trains is underway at the Argonne Wakefield Accelerator facility (AWA). High frequency bunch trains have numerous applications ranging from advanced acceleration methods to THz radiation sources. Recent studies have shown that such trains can be generated when an intensity modulated laser pulse is incident on the photocathode in an RF gun. Using the recently developed technique of temporal pulse stacking with UV birefringent crystals [1] the modulation wavelength obtainable is primarily limited by the UV pulse length. For the AWA photoinjector laser system this limit is currently rms=670 fs; although using commercially available laser systems sub-100 fs pulses can be obtained. We present measurements of an intensity modulated laser pulse created with an α -BBO crystal array, TStep simulations of the electron beam dynamics, and experimental plans to measure the bunch train using an L-band deflecting mode cavity.

INTRODUCTION

The generation of high frequency bunch electron trains has become an active area of research in recent years [2-4]. While conventional microwave linacs are capable of generating electron bunch trains with bunch repetition frequencies on the 10 GHz scale, numerous applications including advanced acceleration techniques and THz generation require frequencies of 100 GHz and more.

Several schemes for generating high frequency bunch trains are currently being pursued. A group at USC and BNL [2] recently demonstrated the generation of a train of microbunches by placing a mask in a region of the beam line where the beam transverse size is dominated by the correlated energy spread. Another group has numerically investigated a method based on the recently proposed transverse-to-longitudinal phase space exchange beamline [3]. A third method is based on generating a laser pulse train, with spectral mask, which impinges on the photocathode [4]; this approach is most similar to the work presented here.

In this paper, we describe a new technique for generating the laser pulse train based on inexpensive UV birefringent crystals. This train then impinges on the photocathode in an RF gun to generate the electron bunch train.

* This work is supported by the U.S. Department of Energy under Contract No. DE-AC02-06CH11357 with Argonne National Laboratory
[#]jp@anl.gov

TEMPORAL PULSE STACKING WITH UV BIREFRINGENT CRYSTALS

A brief description of the method is given here but a more thorough description can be found in [1].

Temporal Walk-Off

Temporal walk-off is the term used to describe the temporal separation (Δt) that develops between the two polarizations (o-ray and e-ray) as they propagate through the birefringent crystal. This loss of temporal overlap is due to the difference in the group index of refraction seen by the two rays. A short laser pulse incident on a birefringent crystal, at an angle with respect to the optical axis, will be split into two pulses separated in time due to the differences in group velocity. The temporal separation (walk-off) is the product of the crystal length, L , and the group velocity mismatch (GVM) of the crystal,

$$\Delta t = L \left(\frac{1}{v_{ge}} - \frac{1}{v_{go}} \right) \quad (1)$$

where $v_{go} (=c/n_{go})$ and $v_{ge} (=c/n_{ge})$ are the group velocities for the o ray and e ray respectively, c is the speed of light in vacuum, and n_{ge} and n_{go} are group index of refraction for the e ray and o ray respectively.

Birefringent Crystals in the UV

The ideal crystal for the pulse stacking application is strongly birefringent (large Δn_g) and transparent at the wavelength of interest. The difficulty with temporal pulse stacking in the UV (AWA laser is 248 nm) is due to the shortage of transparent and strongly birefringent crystals. While calcite's group birefringence is sufficiently strong, $\Delta n_g = 0.47$ at 248 nm, it is not transparent. Fortunately, an examination of commercially available uniaxial crystals revealed two promising candidates: crystal quartz and α -BBO. The Sellmeier equations (n_e and n_o) were provided by the manufacturer, while the values for n_{ge} and n_{go} are calculated by [5],

$$n_g(\lambda) = n(\lambda) - \lambda \left(\frac{dn(\lambda)}{d\lambda} \right) \quad (2)$$

and Δt was calculated using Eq. 1. While crystal quartz is slightly more transparent than α -BBO (90% vs. 80%), we chose to use α -BBO due to its larger GVM (0.180 vs. -0.957 ps/mm).

Pulse Stacker

In general, a Temporal Pulse Stacker (TPS) using N birefringent crystals will transform a single Gaussian pulse into a stack of $2N$ Gaussians output pulses and then recombine them into the single desired pulse. (i.e. 2 crystals make 4 pulses, 3 crystals make 8 pulses, etc.)

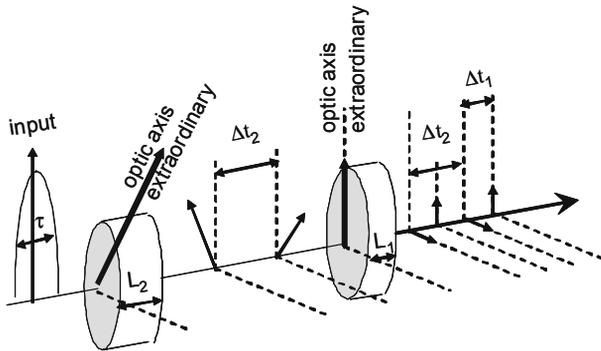


Figure 1: Schematic diagram showing 2 birefringent crystals used to produce 4 stacked Gaussians. The input pulse is split into two intermediate pulses, separated by Δt_2 , after the crystal of length L_2 . The intermediate pulses are further split and delayed by Δt_1 by the crystal of length L_1 to produce the 4 output pulses.

Consider a 2 crystal α -BBO-based TPS used to transform a Gaussian seed pulse of FWHM= τ (rms= $\sigma=\tau/2.35$) into a stack of 4 Gaussian pulses that approximate an overall flat-top (Fig. 1). Let the input Gaussian pulse be linearly polarized in the vertical direction while the optic axis of crystal #2, of length L_2 , is tilted at a 45° angle relative to the vertical. For α -BBO (a negative uniaxial crystal), the e-ray (component parallel to the optic axis), will move ahead of the o-ray (component perpendicular to the optic axis) by the amount, Δt_2 for crystal length L_2 . In this case ($n_e < n_o$), the extraordinary axis is the fast axis. The 45° orientation creates equal intensity e-ray and o-ray. (Notice that the relative intensity between the two rays can be controlled by a simple rotation of the optic axis which leaves open the possibility for ramped pulse generation.) The two (intermediate) pulses emerging from crystal #2 are now themselves oriented at 45° to the vertical. The next crystal (crystal #1) has its optic axis oriented in the same direction as the input pulse; i.e. in the vertical. When the two intermediate pulses pass through crystal #1, they are each further divided into 2 more pulses separated by Δt_1 with crystal length L_1 , thus producing the 4 output pulses.

LASER PULSE TRAIN MEASUREMENTS

The maximum pulse train frequency occurs when the individual pulses overlap which, in turn, is limited by the seed pulse length and dispersion in the optics. For the AWA laser system the shortest seed pulse available is $\sigma=0.64$ ps, the value used throughout this paper. Later in the paper we discuss a technique to overcome the limitation due to dispersion.

We now consider two examples to illustrate the typical pulse trains that can be generated with an α -BBO-based TPS. In all cases we use a-cut, α -BBO crystals with GVM= -0.957 ps/mm at $\lambda= 248$ nm and implicitly ignore the group delay dispersion (GDD). The choice of a-cut means that there is no spatial walk-off since the optic axis is perpendicular to the direction of propagation.

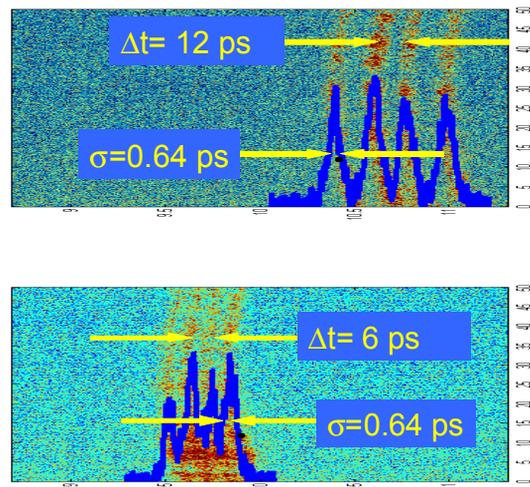


Figure 2. Streak camera measurements of the 83 GHz train (top) and the 167 GHz train (bottom).

The first pulse train measured (Fig. 2, top) consisted of 4 pulses separated by 12 ps (train frequency of 83 GHz). The TPS used 2 α -BBO crystals $L_1=14$ mm, $L_2=25$ mm. The pulses are well separated since $\sigma \ll \Delta t$. The small overlap seen in the figure is due to the streak camera resolution, rms \sim 2ps. The second pulse train measured (Fig. 2, bottom) also had 4 pulses but the separation was reduced to 6 ps (train frequency of 167 GHz). Here the TPS used 2 α -BBO crystals $L_1=7$ mm, $L_2=14$ mm. In this case there is significant overlap observed partly because the 3σ tails of the individual pulses nearly overlap, but mostly due to the streak camera resolution.

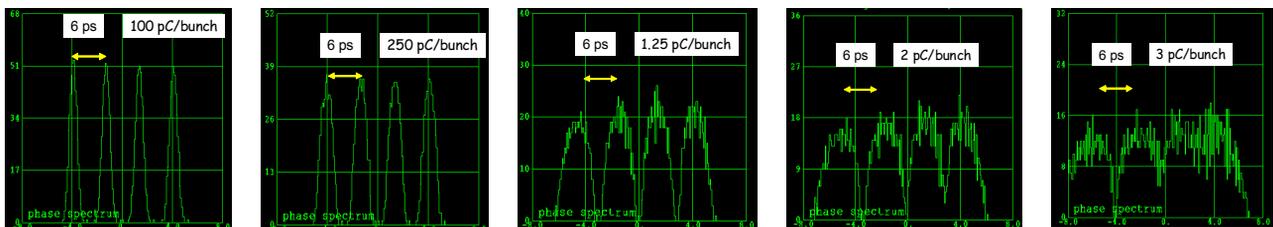


Figure 3. Temporal Profile of the 167 GHz bunch train at the end of the beamline as a function of charge in the individual bunch.

Sources and Injectors

T02 - Lepton Sources

ELECTRON PULSE TRAIN SIMULATIONS

The above two laser pulse train formats were used to generate the initial electron distribution at the photocathode of the AWA RF gun and tracked through the AWA beamline [6] with the beam dynamics code TStep [7]. At low charge and large separation the spatial modulation of the electron bunch train is easily maintained throughout the beamline (Fig. 3). The high charge per micropulse limit occurs when space charge at the photocathode washes out the spatial modulation (Fig. 3). A method to overcome this high charge limitation based on the use of a magnetic chicane compressor has been proposed in [4].

EXTENDING TPS TO HIGHER FREQUENCY PULSE TRAINS

The AWA laser system seed pulse is currently limited to $\sigma=640$ fs and hence, to avoid pulse overlap, the separation is approximately limited to 6σ or repetition frequencies of $1/6\sigma = 260$ GHz. Fortunately, many commercial laser systems are available with much shorter σ . Therefore, this is not the major limitation to extending α -BBO technique into the THz regime. However, when the seed pulse duration approaches 100 fs and below, the positive GDD in the α -BBO crystals causes an appreciable pulse broadening. For example, an initially unchirped $\sigma_0=30$ -fs pulse at 267 nm, the GDD of the crystal are $= +355$ fs²/mm ($+538$ fs²/mm) for the e(o)-polarization, and the length of the crystal $= 10$ mm, then $D_2 = 3550$ (5380) fs² for e(o)-polarization, and the pulse is broadened according to [8],

$$\sigma = \sigma_0 \sqrt{1 + \left(4 \ln 2 \frac{D_2}{\sigma_0^2} \right)^2} \quad (3)$$

which yields an output seed pulse duration of $\sigma=300$ fs (500 fs) for e(o)-polarization. This can be a severe limitation when the number of crystals, and hence the total distance the laser pulses travels through the dispersive material, increases.

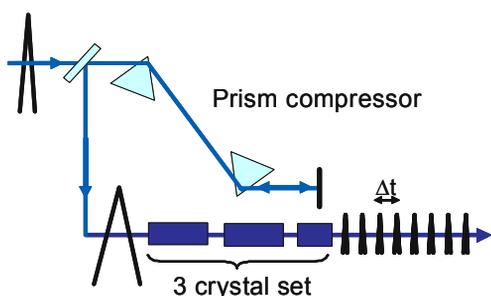


Figure 4. Prism-based compressor imparts a negative chirp to pre-compensate for the positive chirp of the crystals.

Dispersion Compensation

Fortunately, there is a well known solution to the problem of pulse broadening due to positive GDD in the optics called dispersion compensation. This can be accomplished with either a prism-based compressor or grating-based compressor that pre-compensates for the positive dispersion of the crystals by imparting a negative chirp on the seed pulse. The prism compressor (Fig. 4) must be inserted before the crystals since it requires a linear polarization in a particular direction.

FUTURE WORK

Now that the laser pulse train has been successfully demonstrated and initial electron beam simulations have been done, the next step will be to use the train to generate the electron beam and characterize its temporal structure with the 1.3 GHz RF deflecting cavity soon to be installed on the AWA beamline. After the quality of the electron beam pulse structure and high charge limit have been established, a plan for a dielectric wakefield acceleration test with a structure frequency of ~ 100 GHz will be planned and carried out.

CONCLUSION

A method for generating high frequency bunch trains based on laser pulse stacking with α -BBO crystals is underway at ANL. Laser pulse generation up to 167 GHz has been demonstrated and electron bunch train experiments will begin next.

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