UV PULSE SHAPING WITH α-BBO CRYSTALS FOR THE PHOTOCATHODE RF GUN *

Dong Wang[1], Lixin Yan[1], Wenhui Huang[1], Accelerator Laboratory, Department of Engineering Physics, Tsinghua University, Beijing,China

[1]also at Key Laboratory of Particle and Radiation Imaging (Tsinghua University), Ministry of Education, Beijing,China

Abstract

Recently, manipulation with the UV driving laser plays a significant role in high brightness electron beam production by the photocathode RF gun. The method based on pulse stacking with birefringent crystal serials was tried to longitudinally shape ultraviolet laser pulse. Using four or five pieces of α-BBO crystals to stack an input UV pulse with appropriate initial duration into 16 or 32 sub-pulses is able to form quasi flattop UV laser pulse, which can be applied for emittance optimization of the electron beam based on the photocathode RF gun. Moreover, the negative slop of the energy transmittance of a-BBO serials is also revealed to be a passive stabilization mechanism for energy jitter reduction in the driving laser. With appropriate design of a-BBO serials, this method can fulfil the requirements for driving laser in a broad scope of applications such as x-ray FELs and high-power Terahertz(THz) radiation production.

INTRODUCTION

High brightness electron beams based on the photocathode RF gun are playing an increasing significant role in many scientific fields such as UED、Thomson scattering based X-ray light sources、coherent THz production and FEL. Spatially and temporally shaped ultrashort ultraviolet(UV) laser pulses are utilized to illuminate the copper photocathode at our laboratory in order to produce the desired high intensity electron beams[1-3].

It has been assumed that the initial temporal distribution of the electron beam is the same as that of the laser pulse, so electron beams with arbitrary temporal profile can be achieved by laser pulse shaping duo to the negligible emission time of the photocathode illuminated by the ultrashort driving laser pulses. The quasi flattop UV laser pulse formed by shaping method based on the birefringent α-BBO crystal serials can be applied to reduce the initial emittance of the electron beam from the photocathode RF gun[3]. The beam length can also be controlled by changing the initial pulse duration. In practice, for S-band photocathode RF gun the optimal drive laser has duration of about 10ps and the rising/falling edge should be less than 1ps.In recent years, several shaping methods for ultrashort laser pulse have been developed such as frequency domain shaping technique represented by the AOPDF[4]for temporally flattop pulse production. Other methods such as Neumann's method by Fabre–Perot interferometer, pulse stacking by beam splitter plates [5], or by polarizing beam splitter cubes[6] have also been proposed and tested. Due to lack of material that can transmit UV light, the feasibilities of using a-BBO crystals, which can transmit UV light[6-7] has been investigated and employed .

For electron beams another key requirement besides the low emittance is that the rms beam charge jitter should be less than a certain value, typically 2%, so it demands that the UV laser pulse energy jitter should be less than 2% rms. Efforts have been tried to reduce the energy jitter of UV laser. Active stabilizing of the pump lasers is applied to meet the requirement for the UV energy jitter（2% rms）to guarantee the peak current jitter (12% rms) at the undulator in the design of Linac Coherent Light Source(LCLS) Ⅰ and Ⅱ[8]. In the SwissFEL, multiplexing of six ultra-stable diode-based pump lasers and complex pre-compensation loop are applied to achieve 0.54% energy jitter in IR for pulse energy of about 20mJ[9]. In the FERMI system[10], the UV laser energy jitter is designed to be 3% rms to ease the parameter realization. In this paper, a passive mechanism for energy jitter reduction in UV is investigated by taking advantage of the negative slope of the UV energy transmittance in the cascaded pulse stacking system mentioned above employing α-BBO crystals[11].

PRINCIPLE

Pulse Stacking by α-BBO Crystals

The α-BBO crystal is a kind of negative, uniaxial crystal with the centrosymmetric crystal structure, which is excellent material for linear optics due to its large birefringence over the broad transparency range from 190nm to 3500nm and its extraordinary axis lies in its surface and perpendicular to the incident laser pulse. Its Sellmeier equation for ordinary and extraordinary light are expressed as:

$$n_0(\lambda) = \sqrt{2.7471 + \frac{0.01878}{\lambda^2 - 0.01822} - 0.01354\lambda^2} \quad (1)$$

$$n_e(\lambda) = \sqrt{2.3171 + \frac{0.01224}{\lambda^2 - 0.01667} - 0.01516\lambda^2} \quad (2)$$

---

* Work supported by the National Natural Science Foundation of China (NSFC Grants No. 11475097) and the National Key Scientific Instrument and Equipment Development Project of China (Grants No. 2013YQ12034504).

† email address: yanlx@mail.tsinghua.edu.cn

Where the λ is the central wavelength. For the UV driving laser at central wavelength 266.7nm， $n_0(\lambda) = 2.031, n_e(\lambda) = 1.778$. So the relative retardation T（in ps）after propagation in the crystal for length L（in mm）between two types of linear polarized light centred at wavelength 266.7nm satisfies $L = cT/(n_0 - n_e)$ where $c(2.99792458 \times 10^8 m/s)$is the velocity of light in vacuum, as show in Fig.1. A crystal with a thickness of 1mm can make the relative retardation to be 0.856ps.

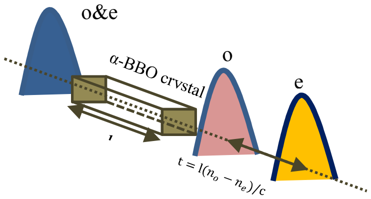

Figure 1: The principle of birefringent crystal: the relative retardation will be produced between ordinary light(o) and extraordinary(e) light through α- BBO crystal.

As described above, if linear polarized sub-ps UV laser pulse entered at 266.7nm is normally incident on the left surface of α-BBO crystal, with the angle between the polarization direction and extraordinary axis to be 45° then 1mm thick α-BBO crystal will split the input pulse into two perpendicular polarized sub-pulse with 0.856ps duration. Suppose there is four pieces of α-BBO crystals with thickness $L_0/2^n$ （n=0.,1,2,3）placed successfully as depicted in Fig.2.

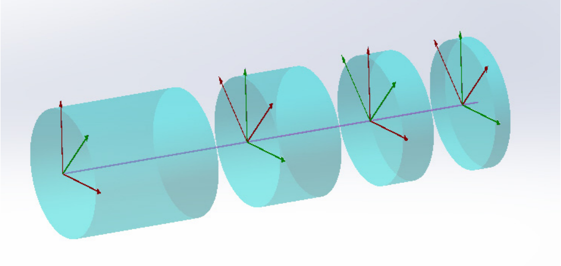

Figure 2: schematic of four pieces of a-BBO.

The extraordinary axis of the odd crystals is parallel with the original input pulse polarization direction, while the extraordinary axis of the even crystals is tuned to be 45° with that of adjacent crystals. The crystal serials will produce such pulse train including 16 alternatively varied polarization sub-pulses with equal spacing and amplitude, shown in Fig.3. The appropriate design of initial incident pulse length can make the stacking pulse to be quasi flattop laser.

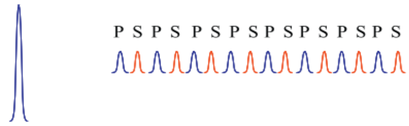

Figure 3: The incident UV pulse can be split into 16 subpulses with alternatively varied polarization by a-BBO crystal serials.

Energy Jitter Reduction by α-BBO Crystals

The experimental set-up is also shown in Fig.2. The incident laser is generated by the terawatt Ti:sapphire laser system and the adjacent frequency tripler with central wavelength of 266.7nm. The schematic of four pieces of a-BBO can make the stacking pulse to be quasi flattop laser. Only part of the incident laser energy can be transmitted in cascaded crystals. The transmittance which is defined as the ratio of the transmitted pulse energy to the incident pulse energy can be influenced by the thickness of the crystals, line-width and peak intensity of the incident laser.

In this experiment, the duration(FWHM) of the pulse with 9nm bandwidth is compressed to 1.1ps with residual nonlinear chirp by the grating compressor before it is injected into the cascaded crystals. The effective beam diameter is around 9mm. The maximum pulse energy achievable is around 1mJ. In our set-up, the thicknesses of the crystals are 4.8, 2.4, 1.2, 0.6mm separately.

In a practical laser system, there are many elements that contribute to the unwanted energy jitter of the output UV pulse, such as energy jitter of the oscillator, the fluctuation of the pump power and other environmental factors. Another property of α-BBO crystal about UV laser energy-absorbing can be applied to build a passive mechanism for energy jitter reduction in UV. Assuming that the energy of transmitted UV laser is given as $E_{out} = \eta(E_{in})E_{in}$, where the $\eta(E_{in})$ is the function of the incident laser energy E_{in}, therefore, the relation of energy variation can be obtained via differential manipulation.

$$\frac{dE_{out}}{E_{out}} = \frac{d\eta(E_{in})}{\eta(E_{in})} + \frac{dE_{in}}{E_{in}} \tag{3}$$

As is show in Eq.(3), besides the energy jitter of the incident laser, the energy jitter of the transmitted laser is also partially determined by the relative variation of the energy transmittance of UV laser. Therefore, if the transmittance decreases with the increasing incident laser intensity, the UV energy jitter can be reduced to produce more stable electron beams. Defining R as the ratio of the relative energy jitter of the transmitted laser energy compared to that of the incident laser, thus,

$$R = \left|\frac{dE_{out}}{E_{out}} \middle/ \frac{dE_{in}}{E_{in}}\right| = \left|1 + \frac{d\eta(E_{in})}{dE_{in}} \frac{E_{in}}{\eta(E_{in})}\right| \tag{4}$$

In the function, $d\eta(E_{in})/dE_{in}$ represents the slope of the energy-transmittance curve, therefore negative slope of the energy transmittance can reduce the energy jitter of the transmitted laser which is required to produce the high quality electron beam.

EXPERIMENTAL RESULTS

Pulse Stacking by α-BBO Crystals

As mentioned above, the desired UV laser has duration of 10ps and the rising/falling edge should be reduced to less than 1ps. The initial UV pulse length should be designed appropriately as shown in Table 1.

Table 1: The Stacking Result with 16 Gaussian Pulse in Different Parameters

Pulse duration （ps）	pulse interval (ps)	rising/falling edge （ps）	Fluctuation (%)	quasi flattop pulse duration(ps)
0.625	0.625	0.46	11.4%	9.97
0.65	0.60	0.52	6.13%	9.58
0.70	0.55	0.59	1.25%	8.79
0.70	0.60	0.59	3.15%	9.59
0.80	0.675	0.69	2.69%	10.79
0.80	0.60	0.67	0.71%	9.60
1.00	0.60	0.80	0.02%	9.60

As shown above in Table 1, the initial pulse with FWHM duration range from 0.65ps to 1.0ps while the pulse interval equals 0.6ps can satisfied the ideal requirement. While the input pulse duration range from 0.80ps to 1.0ps, the fluctuation is smaller and the stacking result is most similar to the quasi flattop UV laser pulse as shown in Fig.4(Left).

In the experiment , the initial UV pulse temporal profile was measured by cross-correlation method. The stacking result can be obtained by stacking the measured profile, as shown in Fig.4(Right).

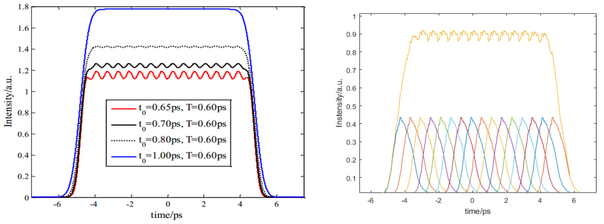

Figure 4: Left: the stacking result with 16 Gaussian pulse in different parameters(t_0:Gaussion pulse FWHM duration, T:pulse interval between pulses) Right: the actual stacking result（t_0=1.1ps, T=0.505ps.

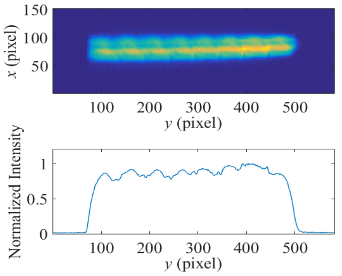

Figure 5: The electron longitudinal distribution produced by the stacked UV laser.

The electron longitudinal distribution measured by RF deflecting cavity at low beam charge is shown in Fig.5. As mentioned above, the UV temporal distribution is quasi flattop distribution and as agrees with that of the laser pulse.

Energy Jitter Reduction by α-BBO Crystals

The experimental results are shown in Fig.6 and 7. As can be seen in Fig.6, the energy transmittance decreases and the energy absorptivity increases monotonically from lower energy to higher energy. As has been shown in Fig.7, the energy jitter of the input UV pulses (blue curve) is almost a constant around 1.6%. However, the energy jitter of the transmitted quasi flattop UV laser pulse (orange curve) is almost same as that of the input pulse for low UV energy but then decrease almost linearly to 0.6% with high UV energy. This effect shows that the negative slope of the transmittance can be applied for passive stabilization of the UV pulse energy.

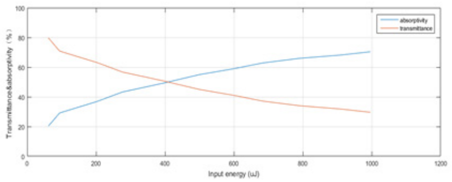

Figure 6: The transmittance and absorptivity of α- BBO.

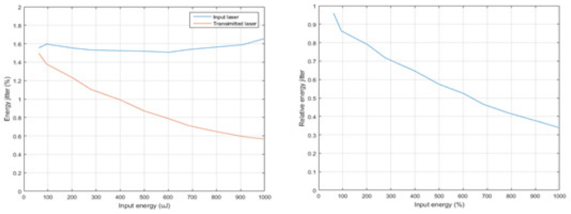

Figure 7:Left: the energy jitter of input laser and transmitted laser. Right: the relative energy jitter of input laser and transmitted laser.

CONCLUSION

In this paper, the pulse stacking method using birefringent crystal of a-BBO serials and corresponding the passive energy jitter reduction mechanism can be applied to directly shape UV laser pulse into a 10ps-spaced quasi flattop pulse and the energy jitter can be reduced into nearly half of input laser which is required to obtain flatter pulse plateau and better beam quality.

REFERENCE

[1] Zhou F, Brachmann A, Emma P, et al. Phys.rev.st Accel.beams, 2012, 15(9):162-167
[2] Li Y, Chemerisov S, Lewellen J. Physical Review Special Topics - Accelerators and Beams, 2009, 12(2):64-64
[3] Tomizawa H, Dewa H, Taniuchi T, et al. Nuclear Instruments & Methods in Physics Research, 2006, 557(1):117－123
[4] Verluise F, Laude V, Cheng Z , et al. Optics Letters, 2000, 25(8):575-7
[5] Siders C W, Siders J L W, Taylor A J, et al. Applied optics, 1998, 37(22): 5302-5305
[6] Tomizawa H, Dewa H, Hanaki H, et al. Quantum Electronics, 2007, 37(8): 697
[7] Sharma A K, Tsang T, Rao T. Physical Review Special Topics-Accelerators and Beams, 2009, 12(3): 033501
[8] Heinz-Dieter Nuhn. Linac Coherent Light Source (LCLS) Conceptual Design Report[J]. Arthur J, 2002
[9] Alexandre T, Paul P M, Fabien P, et al. Optics Express, 2011, 19(21):20128-20140
[10] Bocchetta C J. Sincrotrone trieste, 2007
[11] Yan L, Huang Z, Du Y, et al. Laser Physics Letters, 2014, 11(7): 075403.