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TUNABLE LASER PULSES ENABLE THE GENERATION OF FEMTO-SECOND ELECTRON BEAMS WITH CONTROLLABLE LENGTHS*

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Abstract

In ultrafast electron diffraction experiments, the electron beam's length is crucial as it determines the timescale for observing ultrafast dynamic changes. Therefore, achieving continuous control over the length of these beams within a specific range is paramount for broadening the research scope in ultrafast science. This regulation ensures the accuracy of diffraction images from diverse samples, precise electron beam length measurement, and effective generation of terahertz radiation. Currently, typical methods employ radio frequency (RF) cavity compression to manage electron beam length. Nonetheless, this approach introduces time jitter and encounters challenges in continuously adjusting the electron beam length due to constraints of the RF cavity structure. This paper focuses on compressing femtosecond laser pulse methods to obtain laser pulses with continuously adjustable pulse widths. Subsequently, further controlling the distribution of photoemission electron beams can enhance the temporal resolution of ultrafast electron diffraction.

INTRODUCTION

The temporal resolution of an Ultrafast Electron Diffraction (UED) setup is primarily influenced by the temporal width of the laser pulse, the temporal width of the electron beam pulse, and the mismatch in speed and timing jitter between these two pulses. To achieve a temporal resolution on the order of 100 femtoseconds (fs), each of these factors needs to be on the order of a few tens of femtoseconds or smaller [1,2]. The temporal width of the electron beam pulse is mainly affected by two factors: first, the temporal distribution of the 266-nm UV laser pulse irradiating the photocathode; second, the impact of space charge fields as the electron beam travels to the sample. The pulse width of the pump laser is affected by dispersion introduced during transmission, which induces chirping (a variation in frequency over time) within the laser pulse, thereby broadening the pump laser's pulse width [3]. This broadening also imparts an initial energy chirp to the initial distribution of the electron beam. Studying the distribution of the laser pulse and adjusting its length is crucial for enhancing the temporal resolution of UED setups. An MeV UED under design and construction at Huazhong University of Science and Technology (HUST) [4,5], a THz resonator is used to compress the bunches, enabling the bunches to reach a near 20 fs (RMS) length at the sample [5,6]. However, subsequent characterization and measurements revealed that the actual bunch length on the photocathode (35 fs, RMS) was significantly greater than the planned bunch length (15 fs, RMS), necessitating a re-evaluation of the resonator's compression results [5]. This paper introduces the methods for measuring the pulse width of 266 nm lasers, techniques for continuous adjustment of the probe laser, and the measurements that allow the final laser pulse width to be adjusted within a range of 145 fs (FWHM) to 220 fs (FWHM). We also analyze the impact of changes in the initial bunch length on the performance of the THz resonator and discusses a potential solution when the THz resonator's compression field strength has decayed or not reached the expected level.

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PULSE WIDTH ADJUSTMENT AND MEASUREMENT

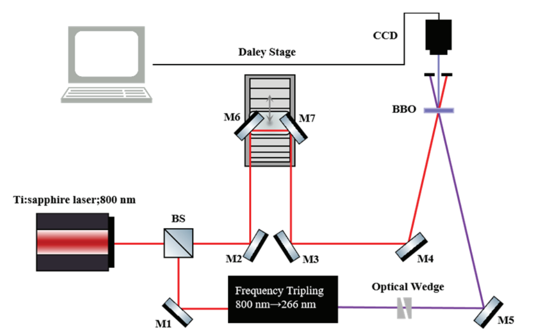

Figure 1: Cross-correlator optical path diagram; Adjusting the height of the optical wedge to adjust the dispersion of the introduced ultraviolet laser.

Ultra-short pulses contain a rich spectrum of frequency components, which propagate at different speeds in dispersive media. For measuring the pulse widths of these wavelengths, the established technologies are available: autocorrelation for 800 nm and cross-correlation for 266 nm [7], as shown in Figure 1. In normal dispersive materials, red light generally travels slower than blue light, causing violet light to gather towards the front of the pulse envelope and red light to move towards the tail. This leads to an increase in pulse width and a decrease in peak pulse power, a phenomenon known as group velocity dispersion (GVD). GVD results in the broadening of the pulse, and materials such as glass exhibit normal dispersion within the 266 nm to 800 nm range. The main parameters of the laser are shown in Table 1.

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Table 1: Main Parameters of the Laser

Parameters	Value	Unit
Pulse width (800 nm)	6.7	mJ
Pulse energy (800 nm)	35 (FWHM)	fs
Repetition frequency	1	kHz
Pulse energy (266 nm)	0.55	mJ
Pulse width (266 nm)	86 (FWHM)	fs
FFT limit pulse width (266 nm)	51 (FWHM)	fs
Pulse width range	145-220	fs

Both the experimental and theoretical discussions of laser pulses often use Gaussian pulses. If we set the initial pulse width as τ_0 and consider only the second-order dispersion, denoted as β_2, while ignoring higher-order dispersions as well as absorption and scattering in the medium, the output pulse τ_2 can be approximately expressed by the following formula.

$$\tau_{out} = \tau_{in}\sqrt{1+\left(\frac{4\ln 2\cdot\phi''}{\tau_{in}^2}\right)^2} \tag{1}$$

Where, τ_{in} the is the initial laser pulse width, τ_{out} is the pulse width of the output, ϕ'' is the second-order dispersion introduced.

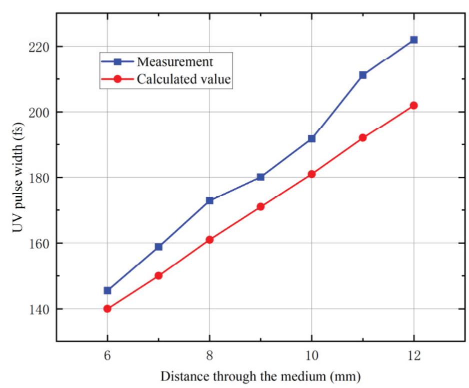

Figure 2: Pulse width varies with length passing through medium; blue is the measured value and red is the calculated value.

The width of the ultraviolet (UV) pulse can be adjusted by changing the thickness of the medium it passes through using an optical wedge. By altering the height of the wedge, the path length of the UV light through the medium changes, thus adjusting the dispersion and the pulse width. This mechanism allows for the UV pulse width to be regulated from 145 fs (FWHM) to 210 fs (FWHM), as shown in Fig. 2. The starting width of 145 fs is due to the minimum thickness of 3 mm of the optical wedge. However, the smallest achievable adjustment in pulse width is about 5 fs, limited by the precision of the measurement equipment and the adjustability of the optical wedges.

ANALYSIS OF ULTRAFAST ELECTRON DIFFRACTION BEAM

The layout of MeV UED is shown in Fig. 3.

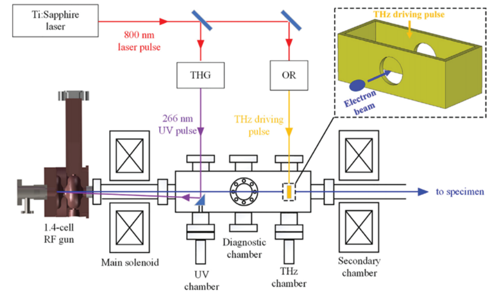

Figure 3: Layout of the MeV ultrafast electron diffraction setup.

UV lasers irradiate a photocathode to produce an electron beam, which is then accelerated by a 1.4-cell electron gun [8]. A solenoid magnet is positioned at the exit of the electron gun to focus the beam transversely. A THz resonator is used to compress the longitudinal length of the electron beams, with the THz signal generated by optical rectification. The ASTRA [9] particle tracking software is employed to simulate the beamline. The main parameters of the simulation are shown in Table 2.

Table 2: Simulation Parameters

Parameters	Value	Unit
Laser spot size (rms)	200	µm
Laser pulse width (rms)	35	fs
Bunch charge	100	fC
Bunch charge after the THz buncher	96.5	fC
Beam kinetic energy	2.96	MeV
Peak THz buncher field	782	MV/m
Cathode position	0	m
Sample position	1.2	m

Without incorporating a bunch compressor at the sample location, by optimizing the parameters of the electron gun, the ultraviolet laser, and the solenoid, the length of the electron beam could be brought down to approximately 100 fs (RMS), with a flight time jitter of about 100 fs. To achieve a temporal resolution within 100 fs, the laboratory designed a THz resonator compressor to compress the bunches. Numerical simulations showed that the bunch length at the sample could be compressed to 15 fs, and the timing jitter could be reduced to 20 fs. The original design planned for an initial bunch length of 11 fs. However, subsequent characterization of the laser revealed that under existing conditions, the initial bunch length was approximately 35 fs, necessitating a reevaluation of the resonator performance, as shown in Fig. 4.

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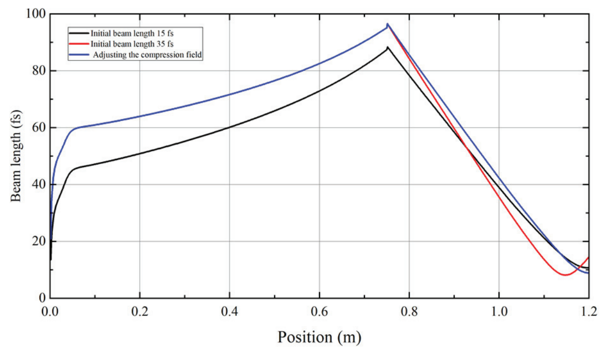

Figure 4: The black and red lines represent the changes in bunch length during transmission process when the initial beam width changes from 15 fs and 35 fs, respectively; Blue color represents the change in bunch length when initial 35 fs is focused on the sample to adjust the field strength of the compressed field.

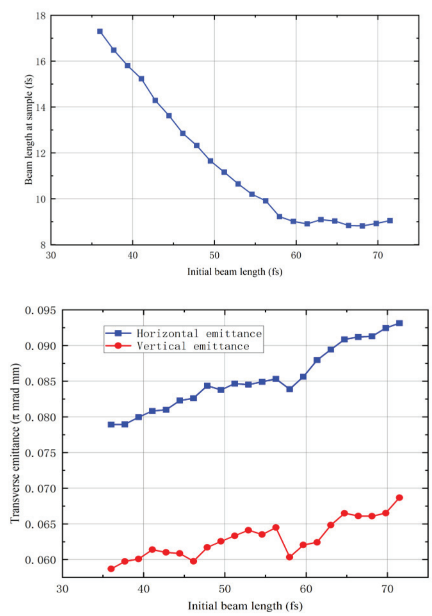

Figure 5: (top) Variation of bunch length at the sample with initial bunch length; (bottom) Variation of transverse emission with initial bunch length.

When the initial bunch length increases from 15 fs to 35 fs, the resonator's longitudinal focus point shifts to 1.13 meters. At the sample, the bunch length is 15.3 fs. By adjusting the pulse compression field strength, the focus point aligns with the sample location, reducing the bunch length to 8.3 fs, a small change from the initial 12.1 fs. By choosing an initial pulse width of 65 fs (equivalent to a 153 fs FWHM laser pulse width) and adjusting the compression field strength, the bunch length at the sample is further reduced to 8.1 fs. If the compression field strength is constant and the bunch length increases from 35 fs to 85 fs (equivalent to a 200 fs FWHM laser pulse width), the resultant changes in bunch length at the sample are shown in Fig. 5.

When the compression field strength is fixed, changes in the initial bunch length (either increasing or decreasing) cause the longitudinal focus point to shift before (or after) the sample. This change in the initial bunch length leads to an increase in the bunch length at the sample location, but the increase is small. For example, even if the initial bunch length is reduced to 45 fs, the bunch length at the sample only increases by 0.2 fs, resulting in a bunch length of 12.3 fs compared to the previously focused condition of 12.1 fs at the sample.

As the initial bunch length decreases, both the transverse and longitudinal emittances of the beam increase. Therefore, reducing the bunch length with a fixed compression field setting can achieve lower emittance. When the initial bunch length is set to 45 fs, there is minimal change in the device's temporal resolution, but the horizontal emittance decreases from 0.092 to 0.081 and the vertical emittance from 0.067 to 0.06, reductions of 12% and 11%, respectively. These improvements in emittance without affecting the UED temporal resolution are important for future beam optimization efforts..

CONCLUSION

Using a cross-correlation apparatus, the pulse width of ultraviolet laser pulses was measured, and a pair of optical wedges were used to continuously adjust the laser's pulse width. However, there is substantial potential for optimizing the pulse adjustment method, such as by customizing the optical wedges to minimize the laser's shortest passage distance. Since the measured pulse width of the ultraviolet laser at 36 fs (RMS) greatly exceeds the originally planned setting of 15 fs (RMS), it is necessary to analyze the performance of the THz resonator. During this analysis, it was found that it is possible to reduce the initial pulse width without reducing the temporal resolution of the ultrafast electron diffraction setup, while also decreasing the transverse emittance.

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