R&D OF AN ULTRAFAST PROBE APPARATUS BASED ON MeV ELECTRON DIFFRACTION AT TSINGHUA UNIVERSITY*

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Abstract

An ultrafast probe apparatus based on MeV ultrafast electron diffraction is developed at Tsinghua University. It aims at generating 1.5 to 3 MeV pulse with sub-pC charge and sub-ps pulse length for pump-probe experiments. It consists of an S-band 1.6-cell radiofrequency photocathode gun, a solenoid, a sample chamber, a deflecting cavity, a detection system and otherdiagnostics tools.Simulations show the position of solenoid coil affects the spot size on detection screen and the charge of collimated bunch significantly.The collimator is found to be helpful to stabilize the charge of collimated bunch and reduce its normalized emittance.The construction of the apparatus is almost finished and the commissioning test will start soon.

INTRODUCTION

Ultrafast electron diffraction (UED) has been proved as a powerful tool for real-time structural studies. Compared with the X-raysources,electron sources havethe advantages of large crosssection and tabletopscale[1, 2]. The UED schemes employ static electric field to accelerate electron bunches to tens of keV as the probe. But for the limited break-down static electric field at about 10 MV/m, the bunches expand and lose theirultrashort property due to strong space-charge effects, thus limiting the electron flux per bunch and demanding more samples to accumulate enough signal-noise ratio (SNR)[3]. Solutionshave been put forward such as employinganradiofrequency compressing cavity[4]. An alternative method to mitigate space charge effects is accelerating electrons to MeV energy by radiofrequency field[5]. In the MeV scheme, the accelerating field can reach 100MV/m and boost the electrons to relativistic energy in several centimetres. As proved by experiments[6, 7, 8], the MeV UED is promising for ultrafast process detection with the huge advantage of 2~3 orders of magnitudes of electron density over keV UED.

After a proto-type of MeV UED setup been tested successfully in Tsinghua University at 2009[8], adedicated apparatus, the Tsinghua MeV UED system is designed aiming for better performance in detection of ultrafast and atomic-level process. The construction is almost finished and the commissioning test will start soon. In this paper, we present the layout and some simulation results of the system.

SYSTEM LAYOUT

The schematic of the Tsinghua MeV UED system is shown in Fig. 1. Electrons generate from the cathode of aBNL/SHI/KEK S-band 1.6 cell radiofrequency gun.At the exit of the radiofrequency gun, a solenoid coil is installed for transverse focusing, whose central position is 21.37 cm from the cathode.Two cubic chambers (72 mm ×72mm ×72mm) are installed after the focusing area. The first chamber with UV-transparent viewports contains a pair of UV mirrors, which are designed to reflect UV lasers onto the centre of the cathode and allow the electrons to propagatethrough the central gap. The second chamber is reserved as a diagnostic chamber.A barrel-shaped sample chamber is placed after the cubic chambers. Two independent actuators are mounted on the top of the sample chamber, which move a Faraday cup and a sample holder respectively. The sample holder is 79 cm from the cathode, and four TEM grids with film samples can be loaded on the sample holder at the same time. The samples can be covered with a thick copper plate with pinholes with diameter of 1mm, acting as collimators. An S-band deflecting cavityworking atTM110 mode is placed after the sample chamber. The field at zero degree in the cavity kicks the head and the tail of the bunch into opposite directions, so the temporal structure of the bunch can be investigated. The deflecting cavity also plays a key role in the continuous-time-resolved mode in a pump-probe experiment[9, 10]. On the focus plane of the solenoid, a detection screen is placed in the detection chamber at 379 cm from the cathode. To detect the weak signal, an electron-multiplying charge couple device collects signal in an optical coupled method. To steer the bunch onto the centre of the detection screen, several pairs of steering coils are mounted along the beamline. A picture of the apparatus is shown in Fig 2.

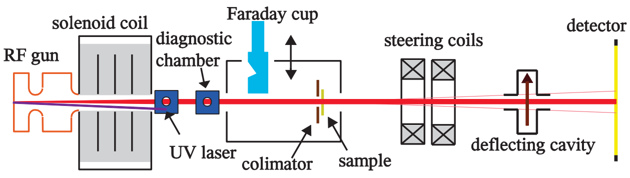

Figure 1: Schematic of the MeV UED system.

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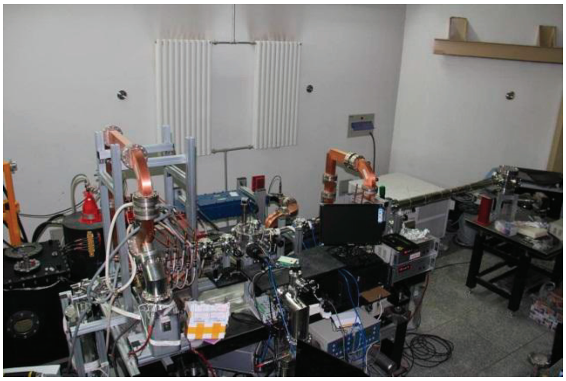

Figure 2: Photo of the Tsinghua MeV UED system.

SIMULATION STUDY

The performance of anMeV UED system can be evaluatedin terms of the spatial resolution and the temporal resolution. The temporal resolution can be expressed as [11]

$$\tau_{total} = \sqrt{\tau_{laser}^2 + \tau_{e-bunch}^2 + \tau_{jitter}^2 + \tau_{vm}^2} . \qquad (1)$$

Where τ_{laser} and $\tau_{e-bunch}$ are the duration of pump laser and the length of probe electron bunch. τ_{jitter} means the fluctuation of the time interval between the arrival of laser and electron at the sample, and τ_{vm} is the time spread caused by the mismatch of the velocities of laser and electrons when passing through the sample. Adescription of temporal resolution of MeV UED can be found in Ref [12]. We use the particle tracking code ASTRA [13] to study the system.The simulation parameters are listed in Table 1. To make the mechanism more explicit, we perform the simulation without diffraction and investigate the evolution of the bunch first.The simulation results are helpful in understanding the processes and optimizing the parameters. We also perform the simulationwith diffraction and achieve consistent results.The simulation shows that the bunch length at sample increases as initial charge increases (Fig. 3).

Table 1: Parameters of MeV UED System

Parameter	**Value**	**Unit**
Bunch parameter at cathode		
Bunch length (Gaussian, rms)	0.30	ps
Bunch radius(uniform)	0.20	mm
Normalized emittance	0.10	um
Initial charge	1.00	pC
Operation Parameter of rf gun		
Gun RF field amplitude	60	MV/m
Electron launching phase	20	degree

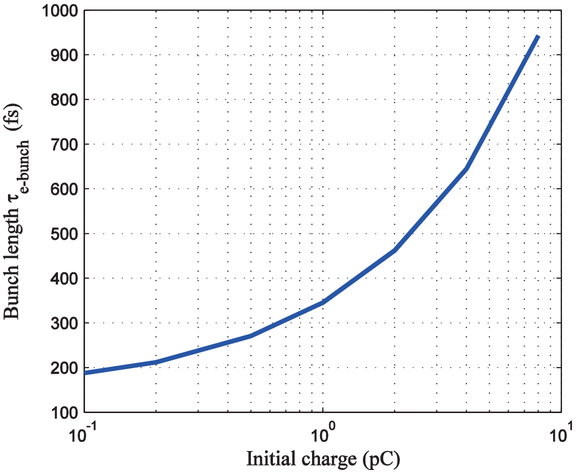

Figure 3: Bunch length (rms) at sample as a function of initial charge.

In terms of the spatial resolution, or the sharpness of the diffraction rings, we find itdepends on parameters of solenoid coil and collimator significantly. First we perform the simulation of scanning the optimal strength of the solenoid to obtain a minimum spot size on the detection screen. Then we move the solenoid coil downstream by a distance of-5 cm (upstream), +10 cm and +20 cm and adjust the solenoid to the optimal strength for each position. The simulation results (Fig. 4) show that moving the solenoid downstream can reduce the spot size on detector screen effectively, however the chargesof the collimated bunches also decrease dramatically to 0.57 pC, 0.53 pC, 0.31 pC and 0.13 pC.

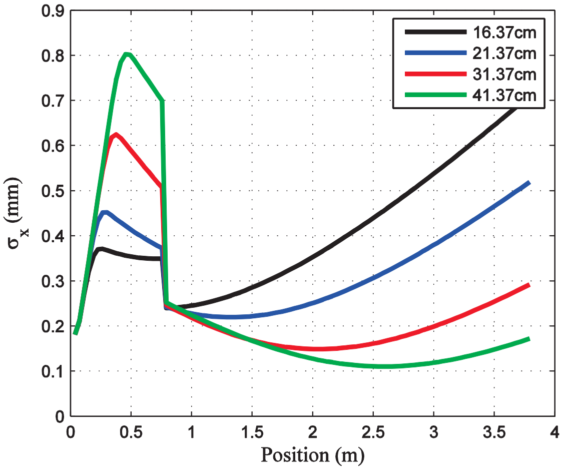

Figure 4: Evolution of transverse size of bunch for different positions of solenoid.

The experiments have proved that collimator is indispensable for MeV UED system [7].The collimator filters the electrons in the transverse centre and scraps the others. The filtered beamlet with smaller spot size and smaller emittance is preferred for diffraction [14]. On the other hand, there is a floor level of the charge passing through the collimator, which depends on the detection system to accumulate sufficient signal-noise ratio (SNR). From Fig. 4 we know that the transverse size of bunch increases before the collimator as the solenoid moves downstream, leading todecreasing percentages of transmitted electrons. In a similar way, the transverse size of bunch before the collimator also increases as the initial charge increases, due to the space charge effects, so the percentage of the transmittedelectrons decreasesas initial charge increases. To find appropriate initial charge and collimator diameter, we perform the simulation of different initial charges and calculate the corresponding transmitted charges and their normalized emittance as a function of the radius of collimator. As shown in Fig. 5, when a collimator with radius of 0.3 mm to 0.5 mm is implemented, the transmitted charge is at sub pClevel. The charge at sub pC level is now sufficient to construct a good diffraction pattern with a detection system [15]. Another interesting phenomenon is that the increasesof the transmitted charge are insensitive to the increasing of the initial charge when an appropriate collimator is chosen, as shown in Fig. 4. For a collimator with radius of 0.3 mm, when initial charge varies from 0.5 pC to 4pC, the corresponding charge of transmitted electrons is from 0.22 pC to 0.28 pC. This phenomenon means a collimator will mitigate the fluctuation of signal from the fluctuation of the energy of cathode laser to a certain extent, making the system more robust. Regarding to the emittance, the effect of collimator is significant when the radius is in the range of 0.3mm to 0.5mm for initial charge of pC range (see Fig. 6). For example, in the case of initial charge of 1 pC , the scaling factor is 0.71 and 0.44 for radius of 0.5 mm and 0.3 mm respectively. Larger charge will reduce the emittance further, but the length of the collimated bunch will also increase dramatically, deteriorating the temporal resolution badly according to Eq. 1 and Fig. 3.

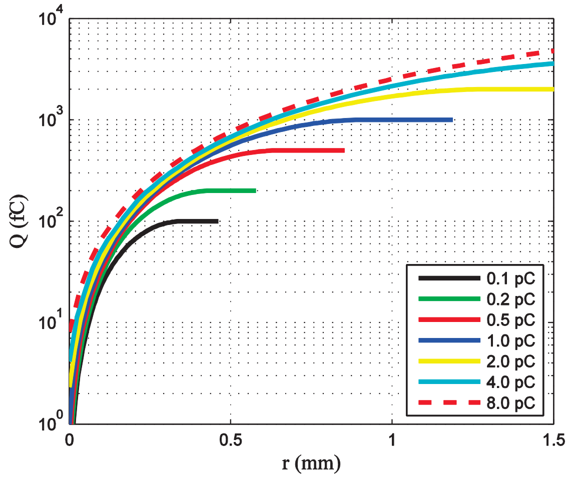

Figure 5: Charge of the collimated bunch as a function of collimator radius for different initial charge with solenoid strength of 0.122 T.

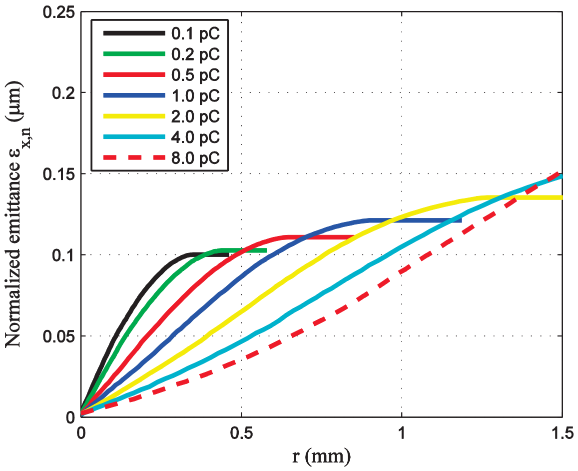

Figure 6: Normalized emittance of the collimated bunch as a function of collimator radius for different initial charge with solenoid strength of 0.122 T.

SUMMARY

The layout of the Tsinghua MeV UED system is presented in detail. The simulations show the position of solenoid coil affects the spot size on detection screen and the chargeof collimated bunch significantly.The collimator is found to be helpful to stabilize the charge of the transmittedelectrons and reduce the normalized emittance.The construction of the system is almost finished and the commissioning test will start soon.

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