ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPGW043

CONCEPTUAL DESIGN OF A MeV ULTRAFAST ELECTRON DIFFRACTION BASED ON 1.4 CELL RF GUN

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Abstract

Ultrafast Electron Diffraction (UED) is a powerful tool to investigate the dynamic structure with temporal scale of 100 femtoseconds and spatial scale of atomic length. To achieve high quality diffraction patterns, the transverse emittance and the longitudinal length of electron bunches should be reduced. MeV UED, using photocathode RF gun instead of traditional DC gun, is being developed to produce high quality electron bunches with lower emittance and shorter length. We are developing a MeV UED facility based on a 1.4 cell photocathode RF gun that can provide higher acceleration gradient at Huazhong University of Science and Technology. In this paper, the conceptual design of the MeV UED is proposed with typical parameters of the system, as well as the ASTRA simulation results of optimization.

INTRODUTION

Ultrafast Electron Diffraction (UED) has the potential to probe structural dynamics with temporal scale of 100 femtosecond and spatial scale of atomic length (sub-1 Å). This may significantly contribute to the research into ultrafast phenomena, especially in the field of biology, physics and chemistry.

UED is a typical pump-probe device, which uses a femtosecond pump laser to activate samples and a precisely controlled electron bunch to probe dynamic process.

Conventional UED is driven by DC gun, which can only provide the electrons of the energy of keV level (commonly below 100 keV). Due to the low energy, keV electron bunches suffer from strong space charge force that seriously broadens transverse and longitudinal phase space during propagation [1]. To get a sub-ps electron beam, keV UED has to reduce the number of electrons, typically few thousands of electrons per bunch, which unavoidably reduce the signal to noise ratio (SNR) of diffraction patterns.

To overcome the space charge effects, mega-electron volt ultrafast electron diffraction (MeV UED) was proposed [2], which employed photocathode radio frequency (RF) gun instead of DC gun. Photocathode RF gun can provide higher accelerating gradient and increase electron energy to MeV level, so the space charge effect is remarkably suppressed. Relativistic electrons can significantly suppress the space charge effect because the transverse and longitudinal space charge effect respectively scale as $1/\beta^2\gamma^3$ and $1/\beta^2\gamma^5$ [3], where β is the relativistic velocity and γ is the electron energy. Theoretically, RF gun can deliver up to 10^7~10^8 electrons in a single 100-fs bunch [4]. The brightness of beam generated by an RF gun is at least four orders of magnitude larger than that of a DC gun, which makes the single-shot diffraction possible.

Another crucial advantage of RF gun is lower velocity mismatch. Electrons emitted from the photocathode will be accelerated to the speed of light in the gun quickly, greatly suppressing the velocity mismatch between probe electrons and pump laser. In addition, the elastic mean free path (MFP) length is larger that means thicker samples can be researched.

In this paper, we present a conceptual design of the MeV Ultrafast electron diffraction at Huazhong University of Science and Technology (HUST), including main layout of the facility, as well as the typical system parameters. We also approach the use of 1.4 cell photocathode RF gun due to its higher accelerating gradient at the photocathode.

LAYOUT OF THE MEV UED

Figure 1 is the schematic diagram of the MeV ultrafast electron diffraction facility at HUST. The ~100 fs electron bunch is generated from the photocathode by a femtosecond laser pulse and accelerated in an S-band 1.4 cell RF gun. The beam is focused by a solenoid to control emittance. A RF deflector is placed downstream of the sample chamber. Moreover, a phosphor screen and an EMCCD are used to detect diffraction patterns.

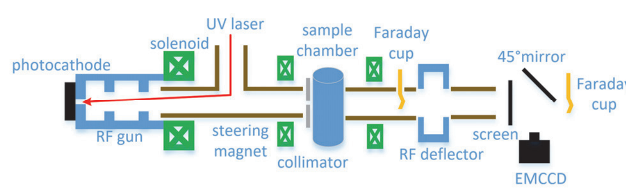

Figure 1: Schematic diagram of the MeV ultrafast electron diffraction at HUST.

RF Gun and Solenoid

The photoinjector uses an S-band 1.4 cell photocathode RF gun specifically designed for the MeV UED. The accelerating gradient is 75 MV/m, allowing electron energy to 5 MeV. RF gun is driven by a 5 MW klystron. A low level RF (LLRF) system is designed to guarantee the high stability of RF power source for the control of the pump-probe timing jitter.

In order to obtain low emittance beams, a solenoid magnet is placed at the exit of the RF gun that provide 0.2684T magnetic field to compensate for the transverse emittance growth caused by space charge effect during the transport beamline. Beams are focused to phosphor screen for high quality diffraction patterns.

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An alterable-size collimator with 1 mm/0.6 mm/0.4 mm diameter is located 0.72 m downstream from the cathode, aiming for electron beams with small beam size and high brightness. Another function of the collimator is a block to ineluctable dark current to improve the SNR of diffraction patterns.

Two pairs of steering coils are respectively placed upstream and downstream the sample chamber in order to rectify the misalignment of the installation and tune particle trajectory. The first steering magnet focus the beam onto the collimator centre, while the second steering magnet focus the beam onto the screen centre.

Driven Laser

A Ti:Sapphire femtosecond laser system operates at the frequency of 1 kHz provides UV and pump lasers. UV laser at 266 nm is injected on-axis to drive the photocathode for electron generation, with 20° injection phase. Pump laser is tripled at 800 nm. Laser system is time-synchronized with the RF source with a sample-lock technology. Our proposal is to limit the timing jitter less than 100 fs.

Detector

A Faraday cup is placed downstream the sample chamber to measure bunch charge.

A RF deflecting cavity is installed to measure the length of electron bunch. The rectangle-type single-cell RF deflecting cavity is operated at the frequency of 2856 MHz, and its temporal resolution is less than 100fs.

The detector system consists with a phosphor screen, a 45° mirror and an electron-multiplying CCD (EMCCD).

The typical parameters of the MeV UED are listed in Table 1.

Table 1: The Typical Parameters of the MeV UED

Parameter	Value
Accelerating gradient	75 MV/m
Gun cavity frequency	2856 MHz
UV pulse duration, FWHM	100 fs
UV spot size, rms	70 µm
Laser injection phase	10°
Bunch charge	1 pC
Kinetic energy	2.76 MeV
Collimator diameter	600 µm
Solenoid field	0.2684 T
Normalized emittance at sample	60.04 nm rad
Beam size at sample, rms	0.147 mm
Bunch length at sample, rms	333 fs
Energy spread, rms	0.356%

1.4 CELL PHOTOCATHODE RF GUN

The spatial resolution can be expressed as

$$\Delta s = \frac{2\pi}{\lambda_e}\frac{\varepsilon_n}{\sigma_x}. \quad (1)$$

where $\varepsilon_n = \beta\gamma\sigma_x\sigma_y$ is the rms emittance and λ_e is the Compton wavelength of electrons [4]. The spatial resolution is strongly related to transverse emittances. The emittance consists of the initial emittance (thermal emittance) and the emittance growth caused by space charge forces. Solenoid is used to reduce the beam divergence for compensating for emittance growth. For a given amount of charge, an effective method to reduce the initial emittance is increasing accelerating gradient at the photocathode due to its great effects on the minimum initial beam spot size [5].

Compared with the 1.6 cell RF gun that originally designed for large charges (~1 nC) in FEL, 1.4 cell RF gun can provide higher accelerating field at the photocathode.

We design a 1.4 cell photocathode RF gun under the KEK collaboration. Figure 2 shows the on-axis field of the 1.4 cell RF gun and a typical 1.6 cell RF gun. We simulate the evolution of a given electron bunch under these two RF gun with ASTRA code [6]. The simulation results of the rms beam sizes are shown in Figure 3, with the distance of 0.3 mm downstream photocathode. Smaller beam size can be achieved by 1.4 cell RF gun.

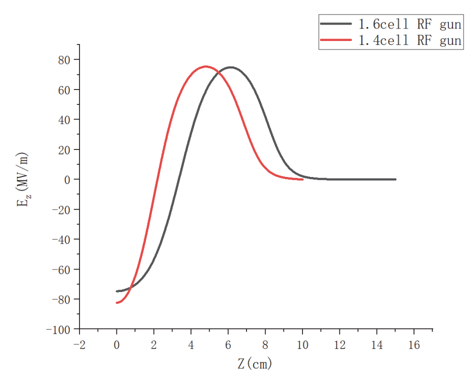

Figure 2: On-axis accelerating field of the 1.6 cell and 1.4 cell RF gun.

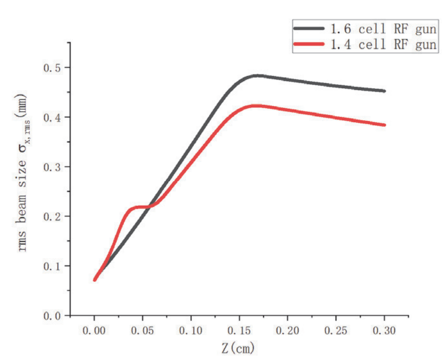

Figure 3: Simulation results of rms beam size under 1.4 cell and 1.6 cell RF gun.

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SIMULATION RESULTS

In general, the fields of the RF gun and the solenoid magnet are calculated by Poisson Superfish. The beam dynamic simulations are generated from ASTRA, considering into space charge effects, with 100,000 micro-particles used.

The main target of the optimization for the design of the MeV UED facility is to find the optimized parameters of the system for high temporal and spatial resolution. At the stage of conceptual design, we do not consider the bunching cavity.

Figure 4 shows the simulated rms horizontal beam size and rms bunch length during the propagation. The beam size is focused by the solenoid and cut off at the collimator. At the sample, rms horizontal beam size is 0.147 mm, while the bunch length is 333 fs, with the charge of 310 fC.

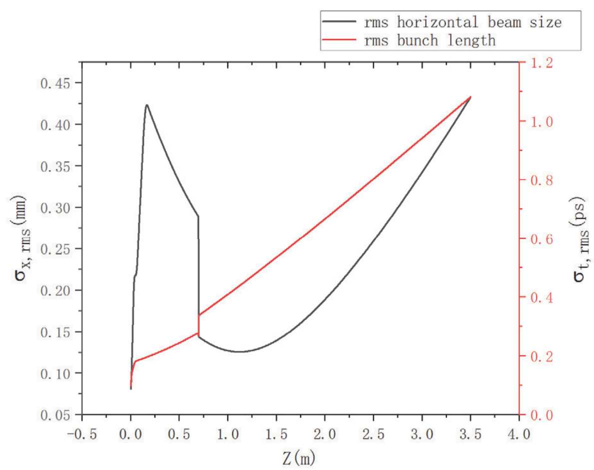

Figure 4: Simulated rms horizontal beam size and rms bunch length as function of distance from photocathode.

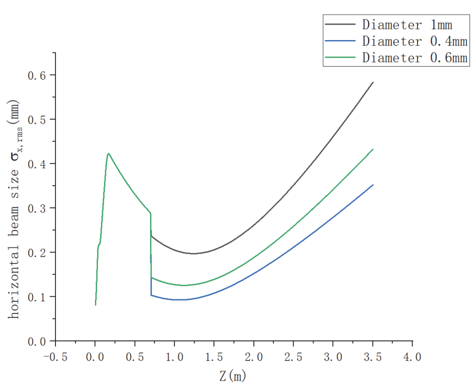

Figure 5: Simulated RMS horizontal beam size as a function of collimator diameter.

In the UED beamline, electron beam is only focused by a solenoid magnet. We use an alterable-size collimator to directly control the beam size in front of the sample chamber. Figure 5 shows the rms horizontal beam size as function of collimator diameter. For 1 pC charge bunch and the collimator with a diameter of 1 mm, 0.6 mm, 0.4 mm, the amounts of charge after the collimator are respectively 748fC, 301 fC and 154 fC.

Simulated rms bunch length as function of bunch charge is shown as figure 6. In order to achieve the balance between temporal solution and bunch charge (it means the repeat number for a high quality diffraction pattern), we choose 1pC bunch charge and corresponding bunch length is 311 fs.

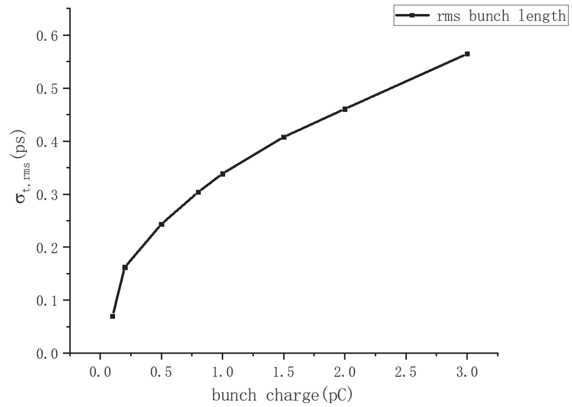

Figure 6: Simulated rms bunch length as function of bunch charge.

CONCLUSION

In summary, we have made a conceptual design of a MeV ultrafast electron diffraction facility at HUST. High brightness electron bunches with the energy of 2.75 MeV and the charge of 1 pC are generated from a new designed 1.4 cell RF gun, which provides much higher accelerating field at the photocathode than a 1.6 cell RF gun. To achieve sub-100fs electron bunch, a bunching cavity is being designed.

REFERENCES

[1] P. Musumeci et al., "Relativistic electron diffraction at the UCLA Pegasus photoinjector laboratory", *Ultramicroscopy*, vol. 108, 1450-1453, Oct. 2008. doi: 10.1016/j.ultramic.2008.03.011

[2] X. Wang, D. Xiang, T. Kim and H. Ihee., "Potential of femtosecond electron diffraction using near-relativistic electrons from a photocathode RF electron gun", *JOURNAL-KOREAN PHYSICAL SOCIETY*, vol. 48, pp. 390~396, Mar. 2006. doi: 10.1016/j.ultramic.2008.03.011

[3] M. Reiser, *Theory and design of charged particle beams*. Hoboken, NJ, USA: John Wiley & Sons, 2008.

[4] S. Weathersby et al., "Mega-electron-volt ultrafast electron diffraction at SLAC National Accelerator Laboratory", *Review of Scientific Instruments*, vol. 86, p. 073702, 2015. doi: 10.1063/1.4926994

[5] P. Musumeci and R. Li., "High brightness electron sources for MeV ultrafast diffraction and microscopy", *Proc. SPIE 9198, Ultrafast Nonlinear Imaging and Spectroscopy II*, 91980S, Sep. 2015. doi: 10.1117/12.2062997

[6] ASTRA, http://www.desy.de/~mpyflo/s