INNOVATIVE LOW-ENERGY ULTRA-FAST ELECTRON DIFFRACTION (UED) SYSTEM*

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Abstract

RadiaBeam, in collaboration with UCLA, is developing an innovative, inexpensive, low-energy ultra-fast electron diffraction (UED) system which allows us to reconstruct a single ultrafast event with a single pulse of electrons. Time resolved measurement of atomic motion is one of the frontiers of modern science, and advancements in this area will greatly improve our understanding of the basic processes in materials science, chemistry and biology. The high-frequency (GHz), high voltage, phase-locked RF field in the deflector allows temporal resolution as fine as sub-100 fs. In this paper, we show the complete design of a UED system based on this concept, including an optimized electron gun, a high-resolution RF deflector, and the post-interaction imaging system.

INTRODUCTION

Time resolved measurement of atomic motion is one of the frontiers of modern science, and advancements in this area will greatly improve our understanding of the basic processes in materials science, chemistry and biology. One technique under active development in this area is ultrafast electron diffraction (UED), which has several distinct advantages over X-ray diffraction for certain applications. UED utilizes a less expensive source; the electrons are less damaging to the specimen (at comparable energies); the scattering length of electrons better matches the penetration depth of the probe laser; UED is more suitable for gas phase samples; and it allows direct measurement of atomic positions, since the electron scatter mostly from nuclei. UED has already been used to study solid-state phase transitions [1, 2], gas phase reactions [3, 4], strongly coupled systems [5, 6] and surface dynamics [7]. In light of these results, researchers are demanding ever-shorter electron bunches in order to improve the resolution of their UED measurements. However producing intense sub-ps pulses of electrons in the desired energy range (30 - 100 kV) is challenging, due to space-charged induced longitudinal spreading. To date, efforts in this area have concentrated on either minimizing the bunch charge, which reduces the signal-to-noise ratio (SNR), or on using higher-energy electron beams, which reduces the diffraction angle and increases the size and the cost of the system. RadiaBeam, in collaboration with UCLA, is developing an innovative, inexpensive, low to moderate energy UED system which allows to reconstruct a single ultrafast event with a single pulse of moderate energy electrons (100 keV). By implementing a fast Radio-Frequency (RF) deflecting cavity immediately after the sample, the diffracted electron beam can be "streaked," transforming the temporal evolution of the diffraction pattern into a transverse image (see Figure 1). The high-frequency (GHz), high voltage, phase-locked RF field in the deflector allows temporal resolution as fine as 100-fs and below, while the probe electron beam can remain comparatively long (10's of ps), and contain a large number of electrons (~10^8).

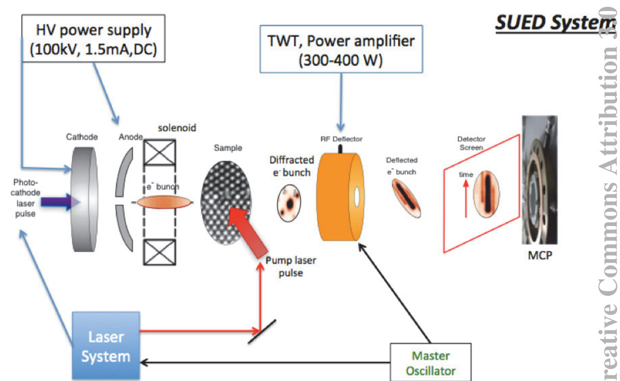

Figure 1: "streaked"- Ultra Electron Diffraction System.

SYSTEM PARAMETERS

The main parameters of the whole SUED system, such as the beam energy, pulse length and deflecting voltage, are listed in Table 1.

Table 1: Main SUED parameters.

Electron energy	100 keV
Number of electrons/pulse	10^7
Pulse length (at the sample)	20 ps
Deflector RF power	1 kW
Deflector nominal voltage	20 kV
Temporal Resolution of system	100 fs

PHOTOELECTRON GUN

The design of the 100 kV photocathode electron gun has been carried out by means of the 2D RF/Static simulation code SuperFish and the 2D gun design code EGUN2. As a starting point, we chose the 100 kV electron gun developed at Eindhoven University of Technology [8].

The main issue, when dealing with high DC field values, is represented by the transition between air and vacuum (vacuum feed-through) as well as the vacuum level inside the gun vessel. Both issues, addressed in the present section, can be the cause of overvoltage and high risk of breakdowns.

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Special attention must be put on the feed-through design. A safe configuration would be to lay a high-insulating material around the inner conductor that will be electrically attached to the aluminum cathode holder. Also the interface geometry (such as an exponential cup filled with a dielectric) will be necessary.

The 2D profile used in simulations is given in Figure 2. The cathode is a flat disc with a 1 cm diameter. The holder, a hollow cylinder, allows for both back and front illumination and replaceability of the cathode piece itself. In the same figure, the axial electric field distribution is also shown. The field value at the cathode is about 9.8 MV/m. The maximum value is located at the round edge of the holder (11.8 MV/m). The above mentioned values of electric field are safe as far as breakdown is concerned, according to experimental results [9], showing that a high voltage of 250 kV is considered the safety threshold value inside a gap (cathode-anode) of about 1cm.

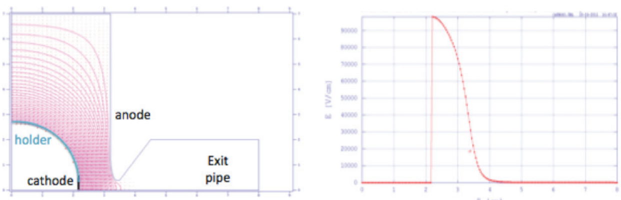

Figure 2: Left, 2D model from SuperFish (equipotential lines and field arrows are also shown); the cathode area is flat (1 cm dia.). Right, axial electric field (9.8 MV/m at the cathode).

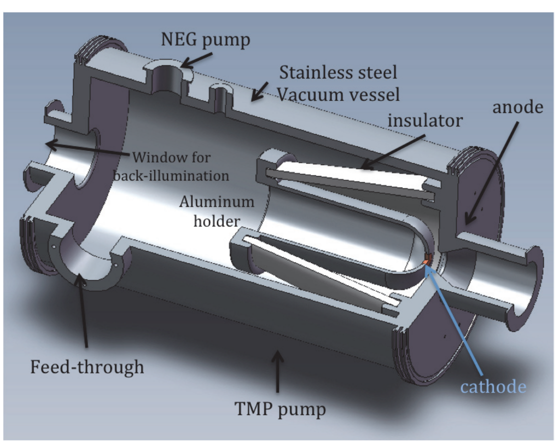

Figure 3: SolidWorks 3D model of the 100kV photo-gun.

A 3D mechanical model of the photo-gun, from SolidWorks, is shown in Figure 3. The replaceable cathode sample is made out of copper. The hollow cylindrical body that holds the cathode is made out of aluminum while the vacuum vessel, that the anode electrode is attached to, is stainless steel. In order to obtain very high vacuum level inside the gun (up to 10^{-14} mbar), a Non Evaporable Getter (NEG) pump will be used. The high-voltage feed-through, the NEG pump, the TMP pump and the window for back-illumination are attached to the vessel. The isolation between cathode anode is realized by using an insulating cone made out of Macor®.

HIGH-RESOLUTION DEFLECTOR DESIGN

RF Deflectors (RFDs) are commonly used to measure the temporal distribution (or longitudinal profile) of charged particle beams. This is possible by the correlation, between the longitudinal and transverse coordinates, that is created by the voltage inside the RF cavity [10].

The optimized cell geometry is shown in Figure 4. The use of nose cones allows the concentration of the field toward the center of the deflecting gap, which creates a stronger field and better deflection, especially in our case of slow electrons (β=0.54). The main RF parameters are listed in Table 2. The needed deflecting voltage V_T is about 20 kV in order to achieve a sub-100fs resolution.

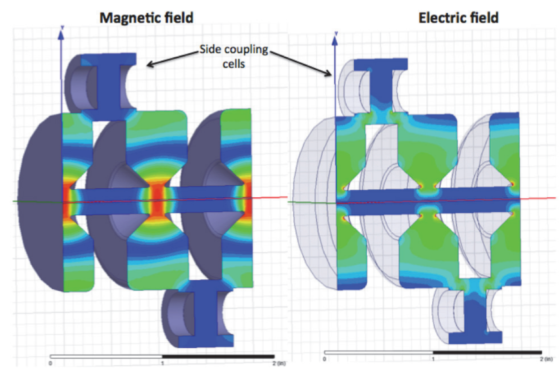

Figure 4: Side-coupled cells with nose cone.

Table 2: Main RF parameters of the UED deflecting cell.

RF parameters (single cell)	Value
Frequency	9.3 GHz
β (E=100keV)	0.54
Transverse Eff. Shunt Impedance R_T	0.13 MΩ/cell
Q unloaded	9,200
Beam Pipe aperture (dia)	0.22in
Kick/√(power)	0.36 kV/√(W)

In Figure 5, we show the needed power for a given deflecting voltage and number of cells. In our case (V_T=20 kV), we would only need 3 cells by using an input RF power of 1kW, which can be provided by a commercially available X-band TWT.

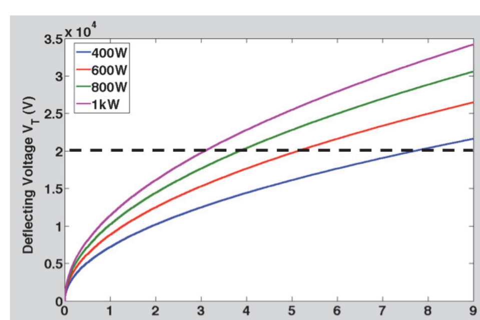

Figure 5: Deflection voltage V_T as function of the number N of cells.

DETECTOR SYSTEM

The micro channel plate (MCP) detector that will be used to image the beam is shown in Figure 6. The MCP basically works as an electron amplifier in which the incoming electrons generate secondary electrons. In this case, the incoming electrons enter channels in which they are accelerated by an electric field and generate the secondary electrons.

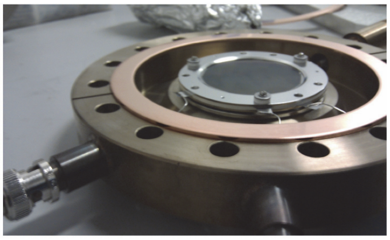

Figure 6: Multi Channel Plate Detector

The MCP is equipped with a phosphor screen that is imaged 1:1 onto the CCD camera, allowing a spatial resolution up to 12 µm. The relation between the bunch duration and the length of the streak on the phosphor screen is obtained by integrating the Lorentz force that is acting on the electron bunch during its travel along the axis through the deflecting cavity. The MCP is located at the focusing point of the solenoid, in order to obtain a sharper diffraction pattern.

ENGINEERING OF THE SUED SYSTEM

The preliminary rendering of the SUED system, modeled in SolidWorks, is shown in Figure 7.

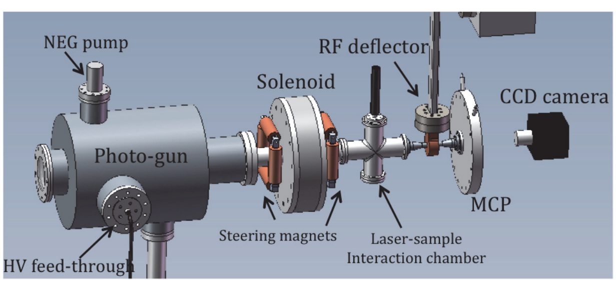

Figure 7: Rendering of the SUED system.

The cathode location is at z=0m. The solenoid is positioned at about z=35cm allowing a beam focusing point at z=1m. The sample is located at z=45cm and the deflector at z=50cm. Between the deflector and the MCP, there is about a distance L=50cm, as assumed previously in resolution calculations.

The beam rms transverse size at injection is σ_y=100µm. In Figure 8, the evolution of the beam size and the horizontal emittance are shown. Emittance compensation is obtained after the solenoid (0.3µm from z=0.45m to z=1m).

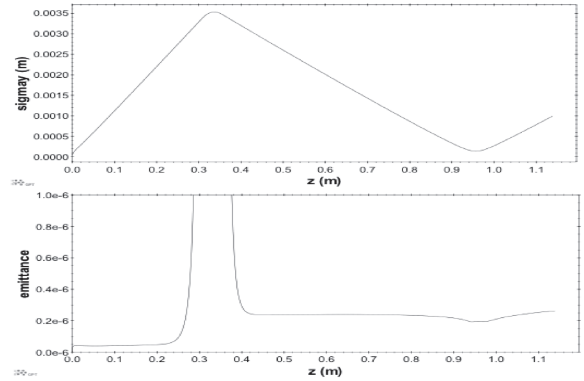

Figure 8: above, transverse rms beam size; below, transverse emittance.

CONCLUSIONS

The UED technique has already been used to produce groundbreaking results in a number of areas of materials science and chemistry. It has been described as providing the capability to "make a movie" of events occurring on the atomic scale. Clearly, such a technology has the potential to enable new discoveries. The SUED system we are developing, with improved resolution and SNR, would enable even further breakthroughs in the understanding of ultrafast phenomena, stimulating new innovations in material science, chemistry and biology.

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