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INITIAL RESULTS FROM STREAKED LOW-ENERGY ULTRA-FAST ELECTRON DIFFRACTION SYSTEM

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Abstract

RadiaBeam, in collaboration with UCLA, is developing an inexpensive, low-energy, ultra-fast, streaked electron diffraction (S-UED) system which allows one to reconstruct a single ultrafast event with a single pulse of electrons using and RF deflector. The high-frequency (GHz), high voltage, phase-locked RF field in the deflector enables temporal resolution of atomic events as fine as sub-100 fs. In this paper, we present an overview of the system being developed and the initial experimental results. We also discuss the challenges based on our design of a UED system that incorporates a novel, high-resolution dielectric-loaded RF deflector and a solid-state X-band amplifier.

INTRODUCTION

Time resolved observation of atomic motion is one of the frontiers of modern science, and advancements in this area will greatly improve our understanding of many basic sciences. One technique under active development in this area is ultrafast electron diffraction (UED). UED has already been used to study solid state phase transitions [1], gas phase reactions [2], strongly coupled systems [3] and surface dynamics [4]. To improve the resolution of their UED measurements, researchers need shorter electron bunches and methods increase temporal resolution on the detected electrons. By placing an RF deflecting cavity immediately after a sample, the time-dependant, diffracted electron beam can be "streaked," transforming the temporal evolution of the diffraction pattern from the sample into a transverse image [5]. In this project, we are developing a complete S-UED system based on a dielectric loaded RF deflector and a novel solid-state power amplifier (SSPA), see Fig. 1. The system also includes the requisite electron gun, laser, magnetic optics, and imaging components.

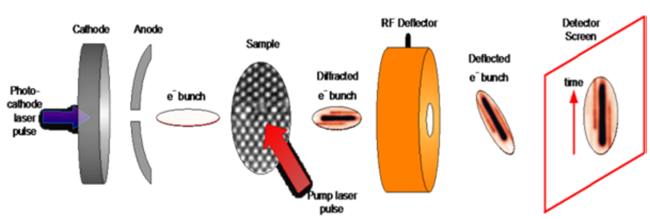

Figure 1: Overview of UED system, from photo-cathode emission on (left), through the sample, then deflector, and finally the streaked image (right).

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HARDWARE

The UED system was assembled in the Pegasus Lab at the University of California, Los Angeles. The beam line was initially installed and commissioned during fabrication of the dielectric deflector. During this time we conditioned the gun to its operating voltage and worked through the alignment procedure for the magnetic optics. The diagnostics were also tested during this time and the results were compared to earlier simulations. The important components of the system are described in further detail below.

Electron Gun

The 100 kV gun shown in Figure 2 was purchased from a Dutch company, AccTech. The HV conditioning and initial photo-beam measurements were carried out without insertion of the radio-frequency deflector in the beam-line to make the initial alignment process less difficult. Although the purchased version of the DC gun is not operable under ultra-high vacuum due to the use of elastomer O-rings, it is appropriate for our UED application which only requires vacuum of 10^{-6} Torr.

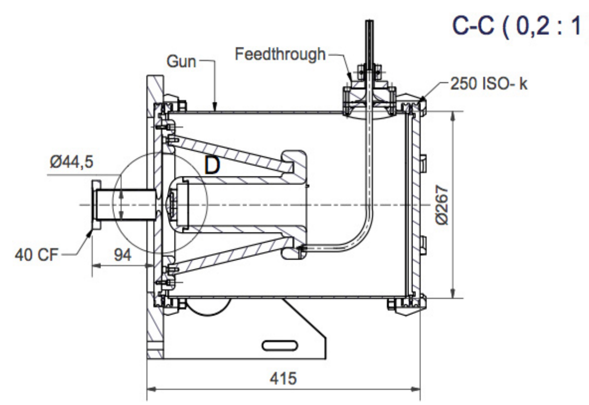

Figure 2: 100 kV electron gun employing a copper photo-cathode purchased from AccTech.

Dielectric Loaded Deflector

The deflector design was performed using the 3D code HFSS. We eventually decided to pursue a dielectric loaded structure since it saved us time and resulted in a device that was easier to manufacture than an all-copper version for such low charge. At the same time, RadiaBeam wanted to develop a medium-power (few hundred watts) RF power source using solid-state devices, and the two technologies were good compliments to each other. Figure 3 shows a 3D model of our 6 cm long

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dielectric RF deflector designed to operate at 8.1 GHz and with low-charge beams (~100 fC in the current S-UED system). Not shown in the model are the side slots, one added on each side, for stabilization of the desired mode polarization, vacuum chamber, and SMA cable.

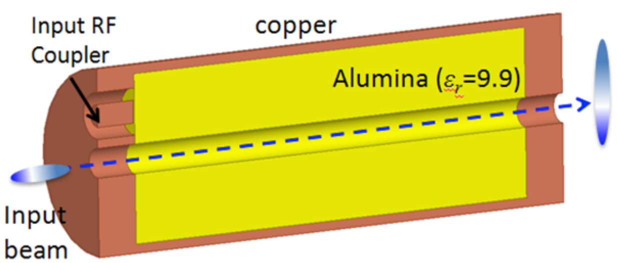

Figure 3: Model of a 6 cm long, 2 cm diameter dielectric-loaded deflector designed and fabricated for this project.

The distributions of the electric and magnetic fields on the mid-plane of the deflector are given in Figure 4 (a) and (c). The field propagates along the z-axis and deflects the beam onto the y-axis. In Figure 4 (b), we plot the on-axis field profiles, the transverse electric component E_y and magnetic B_x, while Figure 4 (d) shows the net deflecting force Ft (Lorentz force) seen by the e-beam traveling along the z-axis. In our design, for an RF input power of 400 W, it is possible to obtain a net deflecting voltage of about 20 kV, which is sufficient for a longitudinal beam resolution of 500 fs, as determined by the following equation [6]:

$$\sigma_t \geq \frac{K}{2\pi c} \frac{\lambda E}{eV_T} \sqrt{\frac{\gamma \varepsilon_n}{\beta_d}}$$

Where σ_t is the resolution, E is the electron beam energy, V_T is the peak deflecting voltage inside the deflector, γ is the relativistic factor, ε_n is the beam's transverse normalized emittance, β_d is the betatron function at the deflector, and K is a proportionality constant, usually at least two (2-sigma resolution).

Solid-State Power Amplifier

The RF amplifier we designed and built for this project is attractive for its compact footprint and great tuning flexibility. Another reason we chose to pursue developing a SSPA for this project is that kW and sub-kW solid-state technology is not commercially available but is of significant interest, e.g., as a driver and preamplifier for high power X-band klystrons developed at SLAC. A block diagram of the key components for the SSPA is presented in Figure 5.

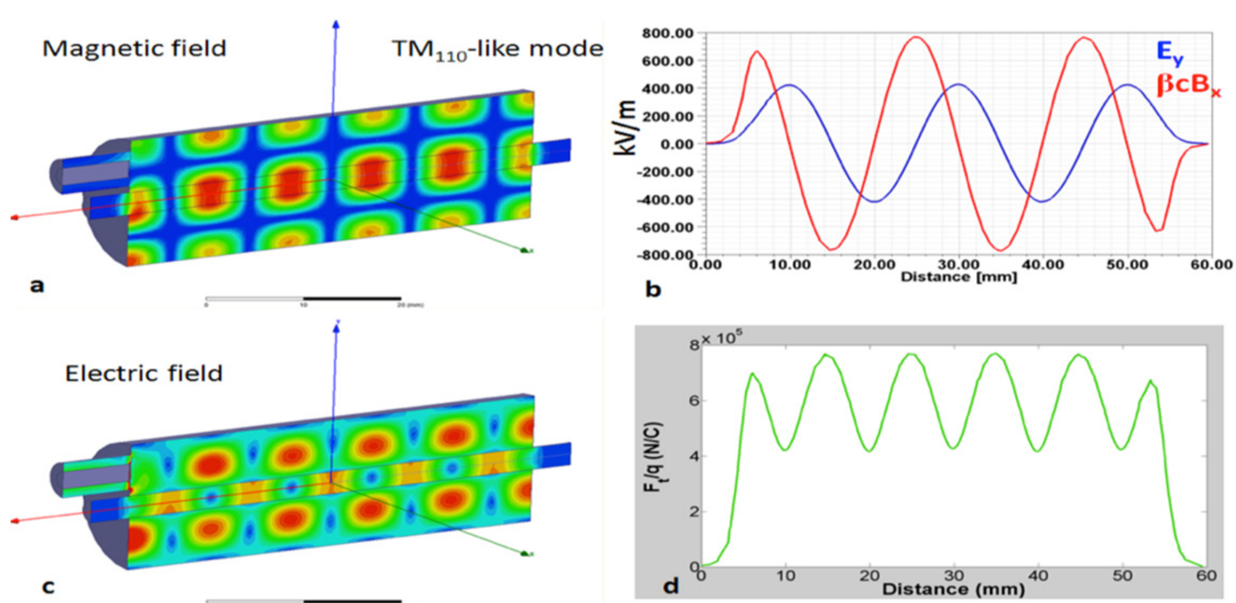

Figure 4: Simulation results from dielectric deflector showing (a) magnetic field distribution, (b) on-axis electric and magnetic components contributing to the Lorentz force, (c) electric field distribution, and (d) total Lorentz force seen by a 100 keV electron beam.

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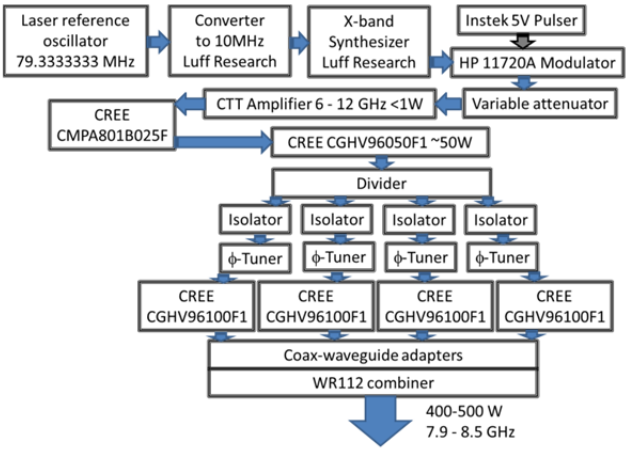

Figure 5: Simplified RF schematic for the solid-state X-band amplifier system developed for this project. DC supplies, computer control, diagnostics, and cooling systems are not shown.

For a controllable oscillator, we used an X-band synthesizer from Luff Research which is locked to a 10 MHz reference. The laser control system is locked to a 79.333333 MHz reference, so a rational-ratio converter was required to phase lock the synthesizer to the laser oscillator. Luff Research was able to develop such a device by implementing the corresponding 238/30 rational number for the frequency conversion. An HP 11720A modulator enabled us to run the high power CREE CGHV9650F within their average power ratings by running in pulse mode vs CW.

To-date, we have been unable to reliably run the 4-channel setup of Figure 5, especially at full power. The problem was electrical breakdown of the output DC-blocking capacitor on the CGHV9650F boards. Eventually, half of the PCBs failed. In order to explain such failures of the boards, we performed full-wave simulation of the output circuit. We found that in this region the local EM field, enhanced by the 50 V supply voltage, achieved a significant fraction of breakdown threshold for such a thin substrate (0.020" Taconics). As a solution, we decided to apply a drop of transformer oil around the capacitor so that it could flow under beneath it and reduce the electric field gradient in the region that was prone to arcing. We applied such a drop and indeed it enabled us to get rid of the breakdown in this region for the undamaged CREE evaluation boards. Currently, only one board shows a satisfactory performance, producing 76 W at 8.1 GHz. Because of the rigid timeline and limited budget we decided to perform the experiment using only one amplifying channel using the single good transistor (without the combining explored above).

INITIAL EXPERIMENT

In light of the difficulties generating >100 W of RF using our SSPA, we were limited in terms of what experiments we could produce. However, we were still able to definitively deflect the beam, as shown in Figure 6.

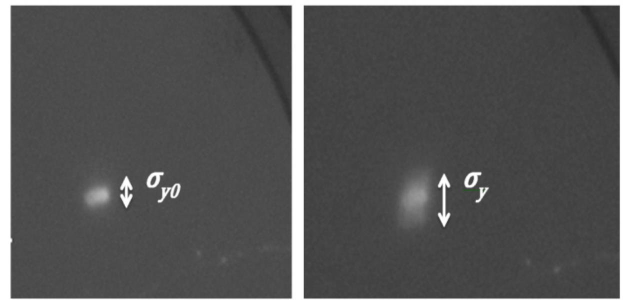

Figure 6: Beam spot as imaged with the MCP having the deflector turned off, $\sigma_{y0} \approx 300$ µm (left) and turned on, $\sigma_{y0} \approx 1000$ µm (right).

The synchronization scheme did not provide the required amplitude and phase stability for the beam and it was therefore not possible to perform a calibration of the RF deflector. Nevertheless, we compared the measured beam spot size at the screen (MCP) with deflector ON and OFF and obtained reasonable agreement with the deflecting voltage V_T as determined by simulations and analytical analysis. We found $V_T \approx 10$ kV from the spot size measurements, which corresponds to an RF input power of about 100 W (with 76 W being measured previously).

CONCLUSION

We have designed, fabricated and assembled a compact, comparatively inexpensive, streaked ultra-fast electron diffraction (S-UED) system. Initial experimental output demonstrated the feasibility of this system as a scientific tool. Our current implementation would benefit from a better stabilization of the RF power source, which RadiaBeam is actively doing. With the other essential components already in place, this is the remaining obstacle to solve before we begin to generate diffraction patterns from actual samples.

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