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DESIGN FOR HyRES CATHODE NANOTIP ELECTRON SOURCE

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Abstract

A new ultrafast electron diffraction (UED) instrument is being developed by UCLA-Colorado University collaboration for the STROBE NSF Center with the goal of using electron and EUV photon beams to reveal the structural dynamics of materials in non-equilibrium states at fundamental atomic and temporal scales. This paper describes the design of the electron beamline of this instrument. In order to minimize the initial emittance, a nanotip photocathode, 25 nm in radius, will be used. This requires a redesign of the cathode and anode components of the electron gun to allow for the tip to be properly aligned. Solenoidal lenses are used to focus the beam transversely to a sub-micron spot at the sample and a radiofrequency (RF) cavity, driven by a continuous wave S-band RF source, longitudinally compresses the beam to below 100 fs, required for atomic resolution.

INTRODUCTION

By combining X-ray-based and tip-enhanced electron beams for simultaneous measurements of a sample properties, the influence of nanoscale structure and behavior on extended mesoscale structure can be determined. Nanoscale heterogeneity is common in a wide variety of materials. Therefore, being able to study material properties at the nanoscale, map them, and relate them to their effects on the macroscopic behavior is a major challenge to be addressed by modern physics instrumentation developers. In order to address this challenge, plans exist to build a Hybrid Photon-Electron Functional Microscope System (HyRES) at the University of Colorado Boulder that will allow for real-time imaging of nanostructured materials.

The electron-based section of the instrument includes an ultrafast electron diffraction beamline, which will aim to record diffraction patterns from microscale spot sizes with better than 100 fs temporal resolution. Even though relativistic electron diffraction [1, 2] has recently shown, capitalizing on the relativistic suppression of space charge effects, capable of excellent spatial and temporal resolution [3, 4], the electron beam energy for this system is chosen to be below 100 keV as we target systems that can be repeatedly pumped (reversible dynamics), and in order to simplify the compatibility with the X-ray beamline and reduce size and costs.

Due to the brightness limitations of conventional photocathodes [5], it was decided that such resolution could only be produced in a photoemissive source using a nanotip, to minimize the emittance and produce a smaller, more focused beam [6]. This choice causes a variety of challenges in the design of the gun, as the nanotip design requires a high degree of movement precision to ensure its proper position relative to the anode so that the emitted electrons experience the correct on-axis field. This paper addresses the design of the gun source. Dealing with this alignment issue is a critical aspect of the design. Additionally, acceleration and manipulation of the beam is necessary to optimally bring it to the target. The design of the beamline, fine tuned using particle tracking simulations in GPT [7], is addressed to ensure the system can deliver a beam with less than 100 fs duration and less than 1 µm transverse spotsize.

Simultaneously focusing the beam transversely and longitudinally is challenging due to the effects of space-charge repulsion. At the proposed beam energy of 50 keV there is no significant space charge suppression. Accomplishing sufficient simultaneous compression requires optimization of the position and phase of the RF cavity and positions and currents of the solenoids.

BEAMLINE DESCRIPTION

The beamline was designed with the goal of generating a beam shorter than 100 fs and with a transverse spotsize less than 1 µm. Transverse spotsize was mainly controlled through the use of solenoids while bunching was done primarily through the radiofrequency (RF) cavity.

An initial solenoid of lower field strength was placed near the exit of the gun to prevent emittance growth. A stronger solenoid was placed after the compressor such that its focus coincided with that of the RF cavity. The solenoid parameters are given in Table 1.

Table 1: Parameters Used for the Beamline Simulation

Element	Field strength (T)	Centroid position (m)
Solenoid 1	0.0099	0.15
Solenoid 2	0.0118	0.70

The phase of the RF cavity was calibrated so that the front of the bunch is decelerated, while the back is accelerated, effectively compressing the bunch longitudinally. The cavity, placed 60 cm from the photocathode, requires 250 W of power, delivered by a waveguide coupler driven by a CW S-band RF source.

GUN DESIGN

To achieve very low emittance in the electron beam, a copper nanotip is planned to be used as the electron source, as opposed to a flat or curved copper source. The pointlike nature of the nanotip, which has a radius of 25 nm, means that the spatial distribution of the beam at the source is extremely small, greatly reducing emittance. However, using such a tip requires a redesign of the gun holder, as the laser used to generate photoemission must come in from the side of the beamline, not down the z axis of the beamline as it did previously. Additionally, the nanotip is extremely small, so having the flexibility to move the nanotip so that only the tip is being hit by the laser is critical. The nanotip is also very fragile, so having a way to safely insert it in the holder is important. Previous methods involved simply dropping a disk-like sample into a recessed location in the cathode, which requires a significant redesign for our objective.

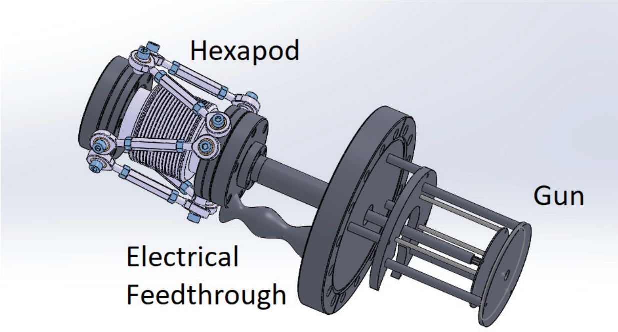

Figure 1: Shows the full design for the gun. At the back is the hexapod, allowing flexibility. The holder for the nanotip can be seen directly before the gun. The L-shape indent allows for easy placement when the anode and cathode are removed. The anode and cathode can then be screwed back on and the whole assembly can be placed under vacuum.

Here, the nanotip is placed on a small L-shaped holder. Since the channel is rather long, the bottom of the nanotip wire can be pushed in and mated with adhesive. By pushing it to a well-referenced angle piece, we can assure that the body of the nanotip is aligned with the gun axis. To get the assembly itself aligned properly, an hexapod, at the back of the design and out of vacuum, can be adjusted. The hexapod has five degrees of motion, which, accounting for the length of the rod attaching the nanotip to the back of the hexapod, allows for the tip to be moved anywhere in a circle of radius 25 mm. Since just rotating the nanotip to account for any tilt in the tip itself actually moves the tip around the surface of a sphere, to ensure the distance between the nanotip and the anode is constant, the hexapod allows for 90 mm of longitudinal movement.

Alignment with the laser is also a critical feature. For this, the chamber holding the gun features fused silica viewports on both sides of the nanotip. This allows a laser to go into the beamline and come out the other side. The laser can be moved around until the shadow of the nanotip is seen. In the sample being built at UCLA, the 800 nm laser has a radius of 5 μm and a stepsize in z and y, the plane in which the tip sits, of 0.04μm.

RF SIMULATIONS

A radiofrequency (RF) cavity can be used to longitudinally compress the electron bunch. At the resonant frequencies of the cavity, the oscillating electromagnetic fields confined within reinforce to form standing waves in particular patterns, known as normal modes.

The pillbox cavity is one of the few designs for which Maxwell equations can be solved analytically. For a pillbox of radius R and length L, the longitudinal component of the electric field of a transverse magnetic (TM_{mnp}) mode in cylindrical coordinates is given by Eq. (1).

$$E_z(\vec{r},t) = E_0 J_m\left(\frac{\beta_{mn}}{R}r\right)\cos(m\varphi)\cos\left(\frac{p\pi}{L}z\right)\cos(\omega t) \qquad (1)$$

Here n is the radial, m the azimuthal, and p the longitudinal mode number, and β_{mn} is the nth root of the Bessel function $J_m(x)$ of order m of the first kind. In turn, the resonant frequency for this mode is given by Eq. (2).

$$\omega_{mnp} = \frac{1}{\sqrt{\epsilon\mu}}\sqrt{\frac{\beta_{mn}^2}{R^2}+\frac{\pi^2 p^2}{L^2}} \qquad (2)$$

Mode TM_{010} is most useful for bunch compression as it consists purely of a longitudinal electric field and an azimuthal magnetic field, which annihilates on axis.

The voltage experienced by the electrons is sinusoidal with respect to the phase of the field. By synchronizing the phase so that the front of the bunch experiences a net deceleration and the back of the bunch is accelerated, the beam can undergo velocity-based bunching [8,9].

While the pillbox cavity is analytically solvable, it is not the most power efficient design and does not include a beamline. Fortunately, however, any cylindrically symmetric cavity shares the same resonant modes as the pillbox, albeit with the form of the fields and frequencies shifted to respect the changed boundary conditions.

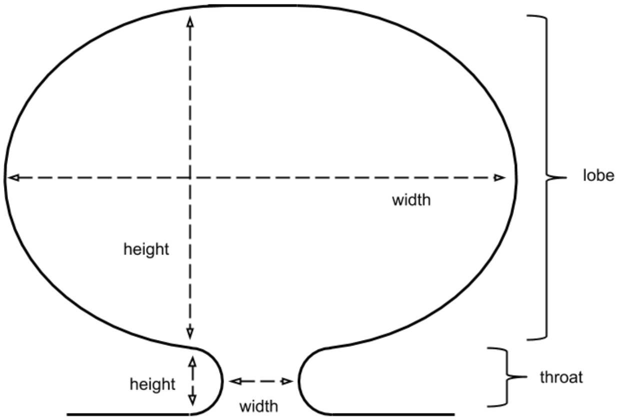

Figure 2: Depicts the compressor cross section designed by van Oudheusden.

The High-Frequency Structure Simulator (HFSS) from Ansys was used to numerically solve for the electromagnetic fields within the cavity [10]. We started with the design proposed by van Oudheusden [11], with basic cross section shown in Fig. 2. The simulation reported maximum

Table 2: Dimensions of the RF Cavity

Part	Dimension	Extent (mm)
Throat	Width	7
	Height	0*
Lobe	Width	44
	Height	28

* Note that in practice the height of the throat will be greater than zero due to machining limitations

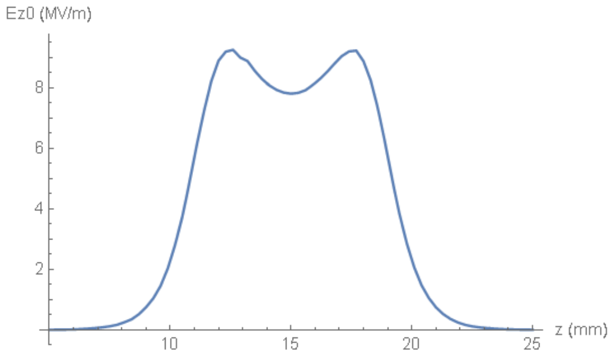

Figure 3: Shows improved compressor electric field profile on axis.

accelerating voltage $V_{z,max}$ = 59.9 kV for a bunch of 50 keV electrons.

By manipulating the geometry of the cavity to maximize the electric field on axis and stored energy within the cavity, the accelerating voltage was raised to $V_{z,max}$ = 71.6 kV. The optimal dimensions are shown in Table 2. Reducing the throat height (Fig. 2) rendered a sharper cusp at the throat, increasing the electric field there. Increasing the throat width spread the field distribution, allowing for a higher total voltage. However, the throat width needed to be small enough to concentrate the fields sufficiently at the center of the cavity. Increasing the lobe width relative to the height gave a sharper cusp at the throat, again increasing the field on axis. The lobe was kept as spherical as optimal to maximize the volume to surface area ratio of the lobe and hence reduce power dissipation through surface currents.

BEAM DYNAMICS

General Particle Tracer (GPT) from Pulsar Physics was used to simulate the trajectories of electrons traveling through the compressor in order to determine its effectiveness in practice [7]. The software solves for the effects of electromagnetic fields due to external sources, as well as space charge, and produces various statistical properties of the electron bunch. The electron bunch was initiated as a collection of 500 macro-particles with total charge 0.1 fC, spotsize 25 nm, pulse length 100 fs, and energy 0.4 eV, simulating the effect of the laser pulse on the nanotip cathode. The bunch is produced with uniform position distribution in the xy-plane and gaussian in time, and uniform velocity distribution throughout.

The electron beam is accelerated by a custom field map obtained from Poisson Superfish, by the Los Alamos Accelerator Code Group [12], electrostatic simulation of the gun, of length 1 cm and voltage 50 kV. The beam is transversely focused by two solenoids: one 15 cm from the photocathode with current 1.35 A, and another at 70 cm and 1.6 A. Each solenoid has radius 3 mm, length 5.61 cm, and coil density 117 turns per centimeter. The electric field profile from HFSS was converted into a one-dimensional transverse magnetic field map to represent the oscillating electromagnetic fields within the compressor. The compressor, 40 mm in length, was placed 60 cm from the photocathode.

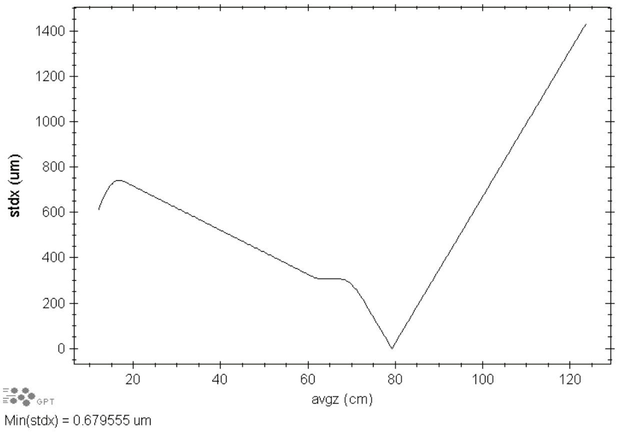

Figure 4: Depicts the transverse standard deviation over distance with minimum.

With these beamline elements the electron bunch was reduced to duration τ = 55 fs and spotsize σ_r = 0.7 um, satisfying the design requirements. σ_r is depicted as a function of position in Fig. 4. The first solenoid occurs early in the beamline to prevent uncontrolled emittance growth. The focusing effect of the second solenoid is clearly visible and brings the transverse spotsize to a minimum. Figure 5 depicts the bunch length coming to a focus at the same point.

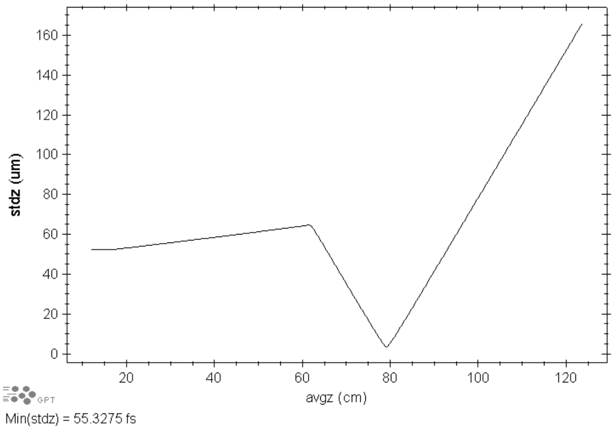

Figure 5: Depicts the longitudinal standard deviation over distance with minimum.

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