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INITIAL NANOBLADE-ENHANCED LASER-INDUCED CATHODE EMISSION MEASUREMENTS

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Abstract

Nanostructured photocathodes offer a unique functionality not possible in traditional photocathodes, increasing beam brightness by reducing the effective emission area. Inspired by field emitter tips, we examine a possible extension for higher current operation, an extended nanoblade capable of producing asymmetric emittance electron beams. A full understanding of emission is necessary to establish the effectiveness of nanoblades as usable cathode for electron accelerators. Utilizing wet etching of silicon wafers, we arrive at a robust sample capable of dissipating incident laser fields in excess of 20 GV/m without permanent damage. Initial predictions and experiments from the nanotip case predict energies up to the keV scale from electron rescattering and fine features on the order of the photon quantum. We will present initial electron data from 800 nm Ti:S laser illumination and measurements of a focused 1 keV beam.

INTRODUCTION

The National Science Foundation Center for Bright Beams is currently pushing the limits of achievable beam brightness for many applications including, for example, free electron lasers and ultrafast electron diffraction [1]. One promising route under consideration is increasing the initial brightness emitted from the photocathode by manipulating the surface through nanofabrication. In reducing the emission area we expect to obtain a reduced effective laser spot size and a consequent reduction of emittance.

We are foremost inspired by nanotips used for electron microscopy. An incident laser fields is enhanced via the sharp geometry of the tip, dropping the potential barrier and leading to electron emission via strong-field quantum tunneling [2, 3]. A process called electron rescattering then occurs during which electron energies are increased significantly [2–4].

Nanotips in general are low current cathodes and are very sensitive to strong incident laser intensities. The current field limits are in the tens of GV/m range [2, 4]. There are potentially numerous methods of increasing the current from these cathodes to a yield which is sufficient for more accelerator physics applications. Arrays of nanotips are currently being researched, for example, in the form of diamond nanotip arrays. For our work we instead consider a projected tip which forms what we call a nanoblade. The emission area is increased to produce a bright flat beam and the increased substrate area should allow for higher damage threshold by reducing the laser heating of the substrate. The enhancement properties of the structure are still sufficient to achieve fields beyond the damage threshold of nanotips.

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EXPERIMENTAL METHODS

Nanoblade

In our work, we will frequently use the term nanoblade sample. This refers to a 15 mm × 3 mm rectangular diced and etched segment of a silicon wafer. The etched wafer segment is then coated via sputtering with 10-20 nm of gold. The sample is shown to the correct aspect ratio in Fig. 1. The nanofabrication process is simplified if we produce two blades on each sample. The double blade geometry can be seen in the SEM inset of Fig. 1. The blade edge where the field enhancement and emission occurs is on the scale of 10 nm and so is not visible in the micron scale image, but can be seen in Fig. 2. We can also see the small curvature of the blade resulting from the 20 nm gold coating on the atomically sharp silicon substrate.

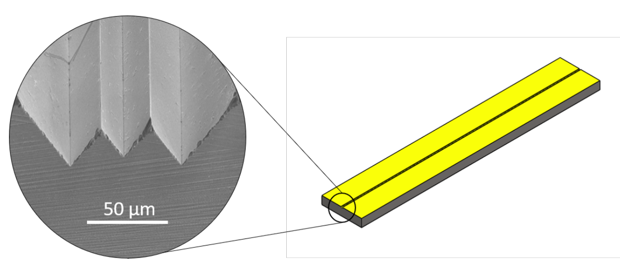

Figure 1: Nanoblade sample geometry with SEM image on 50 micron scale (inset).

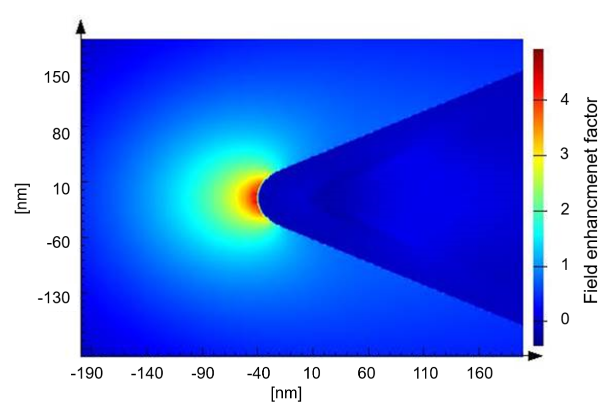

Figure 2: Field enhancement from nanoblade geometry.

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Optics Setup

With regards to the experimental setup we illuminate our cathodes with an 800 nm 35 fs pulse. Peak laser intensities are adjustable between 10^{12} and 10^{13} W/cm^2 and the spot size is 100 µm. Upstream of the blade sample location we have optics to control laser fluence (via neutral density filters), to polarize the beam normal to the blade surface, and to focus on the sample. Downstream we have a CCD camera for initial sample alignment.

The vacuum chamber that houses the cathodes is depicted in Fig. 3. The samples are mounted to a fixture with 8 available locations and is held at a variable potential with respect to the grounded chamber walls. The cathode sample fixture is attached to 3 ultra-high vacuum rated picomotors within the chamber that control the 3 rotational degrees of freedom. A 3 axis step-motor control is then placed outside the vacuum chamber to control the 3 transverse degrees of freedom. We can thus control the blade's orientation with respect to the laser path denoted by the red line in Fig. 3. Emitted electrons here travel to the right in Fig. 3, perpendicular to the laser path. The electrons pass through an einzel lens and are focused on a multi-channel plate (MCP) and phosphor screen detector. The einzel lens is an electrostatic element that, in its idealized geometry, can focus a monochomratic beam without changing the average energy. The particular geometry chosen here is derived from an optimized geometry that is explained more in detail in previous work [5].

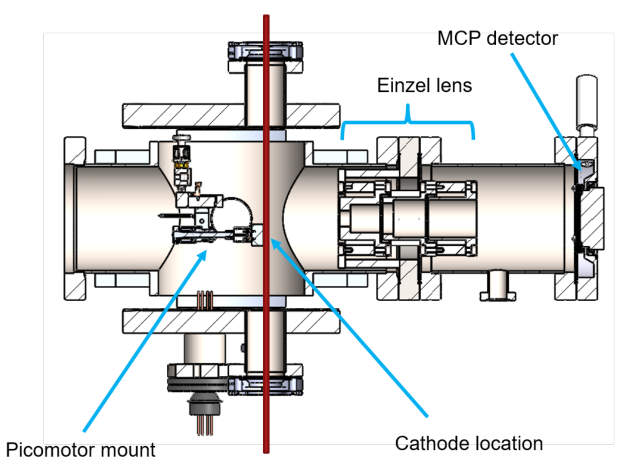

Figure 3: Nanoblade sample experiment chamber geometry.

During emission measurements the sample is at a 0.5 degree angle with respect to the laser path such that it fully intercepts the beam and most of the 15 mm length blade is illuminated.

Particle Tracking Model

As an initial measurement, we use a particle tracking simulation of the relevant chamber and sample geometries in order to reconstruct the emitted beam properties. We model the sample holder as simplified rectangular geometry with a single emission site to represent one of the illuminated blade samples. The sample holder is given perfect electrically conducting (PEC) boundary conditions and is held at a negative bias. The double blades are spaced about 25 microns apart and about 25 microns below the sample substrate where there is no etching in a real sample. Here for simplicity we model this as a uniform flat receded surface 25 microns wide and 25 microns deep. This is illustrated in Fig. 4.

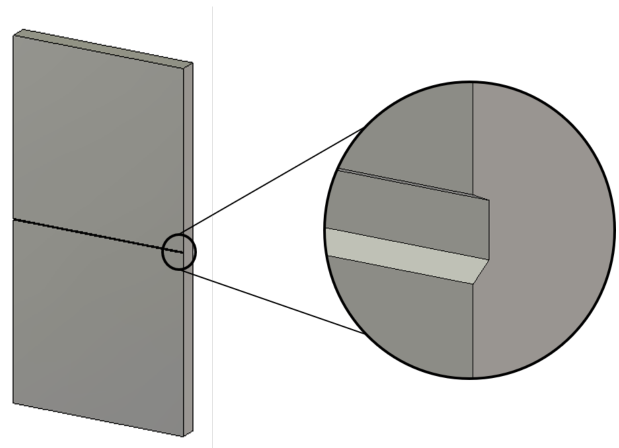

Figure 4: Nanoblade sample holder model for simulation, necessary due to the defocusing effect of a nonzero potential on the sample holder, which is needed for the purpose of successfully extracting electrons.

The outer vacuum chamber is also a PEC boundary condition, grounded at 0 volts. We add this explicitly to ensure that no significant number of emitted electrons are pulled into the walls via image charge effects rather than propagated in the forward direction towards the detector. For the particle tracking simulation an absorbing condition at the end of the simulation, here called z max position, serves as a stand-in for the MCP detector.

RESULTS

Simulation Results

We generate a number of simulations of idealized emission and focusing using this experimental setup. Simulations were run with various monochromatic beams ranging from 0 eV to 1 keV and a uniform energy distribution between 0-1 keV for various sample holder biases up to -500 V. As a result, the highest beam energy simulated for comparison was 1.5 keV. The unique einzel lens geometry was successfully characterized. One feature to note is that there is implicit energy filtering for electrons with energies below the lens focusing voltage. When the lens is held at −500 V for example, total energies below 425 eV do not pass through the lens and are thus not detected.

Figure 5 plots the beam envelope of a monochromatic beam of 1 keV total energy for a number of focusing biases on the einzel lens.

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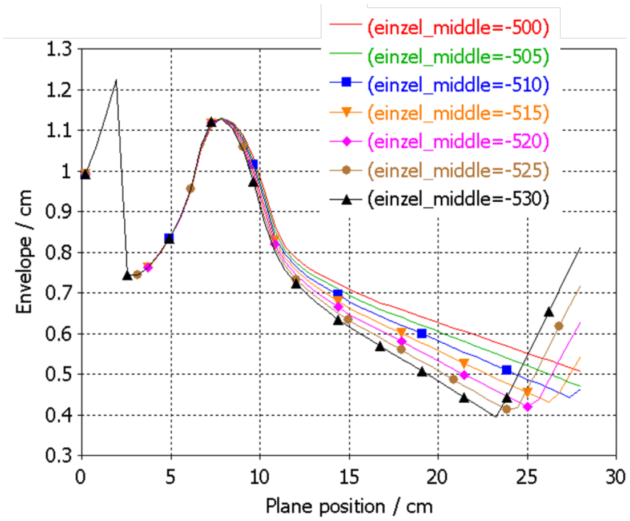

Figure 5: Beam envelope evolution of a monochromatic beam of 1 keV total energy for a number of focusing biases on the einzel lens.

Lens Scan Measurements

The reason why we chose the values used in Fig. 5 is as a comparison to the specific experimental measurement of a beam waist that we present in Fig. 6. This figure contains an experimentally obtained image on the MCP phosphor screen for -520 V on the einzel lens. This corresponds to a focal length of ≈ 29 cm so we can then conclude that this is a beam of electrons with total energy of ≈ 1 keV.

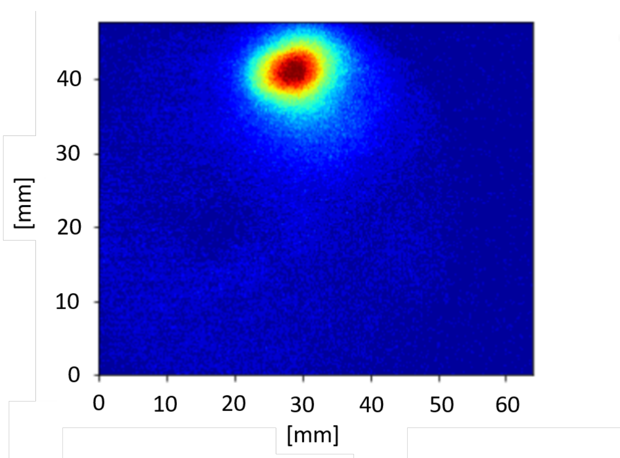

Figure 6: Nanoblade sample experiment chamber geometry.

The energy of emission (total energy minus what is gained from the sample holder bias) we can say that the electron beam should be at least 425 eV. The classical energy cutoff calculations for electrons emitted at 425 eV implies that we have peak enhanced fields of over 70 GV/m on our nanoblade surface. Single particle quantum simulations from Mann et al. give similar high fields [6].

Based on our peak intensity of 5×10^{12} W/cm^2 for this lens scan, we arrive at a field enhancement factor of around 10, significantly higher than our simulation of field enhancement based on the smooth idealized geometry depicted in Fig. 2, which may be evidence for field enhancement hot spots. It is worth noting that this intensity is significantly higher than the peak fields achieved with nanotips at moderate enough intensities to avoid damage [2]. Our results come without affecting the electron yield after many shots.

CONCLUSION & FUTURE WORK

More analysis of additional beam waists as a function laser fluence is ongoing. We are also building more accurate particle tracking and realistic emission models [7].

We have further developed a hemispherical deflection analyzer for sub eV energy resolution in order to resolve the fine features of the rescattered electron energy spectrum. Progress is ongoing. Recent attempts at measurement yielded signals too low to be seen so we suspect there is a possible beam steering issue. We are currently in the midst of a move to a larger lab space so before the 800 nm laser is recommissioned we will continue analyzing the large amount of data taken in the last run. We will additionally attempt to calibrate the HDA with a tungsten filament thermionic cathode with known emission properties.

We have successfully produced keV electron beams from gold-coated nanoblade cathodes via electron rescattering with 35 fs pulse length. We have measured beam waists for various initial cathode biases and show that nanoblades are more robust than nanotips. Finally, we will continue work on commissioning our high resolution hemispherical energy spectrometer.

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REFERENCES

[1] C. M. Pierce *et al.*, "Low intrinsic emittance in modern photoinjector brightness", *Physical Review Accelerators and Beams*, vol. 23, p. 070101, Jul. 2020. doi:10.1103/PhysRevAccelBeams.23.070101

[2] M. Krüger, M. Schenk, P. Hommelhoff, G. Wachter, C. Lemell, and J. Burgdörfer, "Interaction of ultrashort laser pulses with metal nanotips: A model system for strong-field phenomena", *New Journal of Physics*, vol. 14, no. 8, p. 085019, Aug. 2012. doi:10.1088/1367-2630/14/8/085019

[3] S. Thomas, G. Wachter, C. Lemell, J. Burgdörfer, and P. Hommelhoff, "Large optical field enhancement for nanotips with large opening angles", *New Journal of Physics*, vol. 17, no. 6, p. 063010, Jun. 2015. doi:10.1088/1367-2630/17/6/063010

[4] G. Wachter, C. Lemell, J. Burgdörfer, M. Schenk, M. Krüger, and P. Hommelhoff, "Electron rescattering at metal nanotips induced by ultrashort laser pulses", *Physical Review B*, vol. 86, p. 035402, Jul. 2012. doi:10.1103/PhysRevB.86.035402

[5] G. Lawler *et al.*, "Electron Diagnostics for Extreme High Brightness Nano-Blade Field Emission Cathodes", *Instruments*, vol. 3, no. 4, p. 57, 2019. doi:10.3390/instruments3040057

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB097

[6] J. Mann, G. Lawler, and J. Rosenzweig, "1D Quantum Simulations of Electron Rescattering with Metallic Nanoblades", *Instruments*, vol. 3, no. 4, p. 59, 2019. doi:10.3390/instruments3040059

[7] J. I. Mann, G. E. Lawler, J. B. Rosenzweig, T. Arias, and J. K. Nangoi, "Simulations of Nanoblade-Enhanced Laser-Induced Cathode Emissions and Analyses of Yield, MTE, and Brightness", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper WEPAB147, this conference.