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PHOTOCATHODES R&D FOR HIGH BRIGHTNESS AND HIGHLY POLARIZED ELECTRON BEAMS AT CORNELL UNIVERSITY*

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Abstract

Cornell University is a leader in the development of photocathode materials for the production of high brightness electron beam sources for applications in large scale accelerators and small scale electron scattering experiments. During the last year we have also included Mott polarimetry to investigate long lifetime spin-polarized photocathodes materials. Another thrust of our laboratory is the exploration of ultra low emittance photocathodes at cryogenic temperatures, for which we are building a novel LHe cryogenic electron source. We will review updates from our lab across each of these areas.

INTRODUCTION

The last decade has witnessed intense experimental and theoretical efforts on the development of bright electron sources demonstrating that in the limit of negligible space charge, as the energy of the exciting photons approaches the threshold energy of electron emission, the mean transverse energy is predicted to asymptomatically approach the limits imposed by the temperature of the electrons kT_e [1]. Numerical simulations and preliminary experimental results confirmed that lowering photocathode temperature can lead to brighter beams at the expense of a reduced efficiency of the photoemission process [2], [3] determining a trade off amongst the lowest achievable emittance and the laser induced heating of the electron gas [4]. As the photoelectron kinetic energy is approaching zero the approximation of sudden photoemission is no longer valid. The DeBroglie wavelength of an electron with 2 meV kinetic energy (which is the kT_e at 25 K) is about 30 nm. As the electron is extracted into the vacuum with such low energy any non-uniformity within this range of distance at the surface of the vacuum interface but also in the bulk can affect the photoelectron dynamics [5]. The search of new materials with pristine quality of the vacuum interface or with tailored electronic band structures allowing the leverage of a low electron effective mass For application requiring high degree of spin polarization the generation of such beams is based on the use III-V semiconductors technology. Due to the extreme vacuum sensitivity of the surfaces activated to NEA the use of polarized electron source is limited only to DC photoguns where the extreme vacuum condition necessary to achieve a sufficient long lifetime for the operation of such sources [6]. A photogun laboratory equipped with state-of-the-art electron guns now complement the photocathode laboratory allowing wide range of experimental activities aimed at producing electron beams with unprecedented brightness and test new protective coating on III-V based cathodes for polarized electron beam.

EXPERIMENTS AND RESULTS

Cryogenic TEmeter

Inspired by the demonstration that under proper experimental conditions the intrinsic emittance of photoelectron is limited by the the lattice temperature and by the interest of studying the experimental production of electron beams at temperatures in the range of interest of SRF electron gun we have designed and we are in the process of building a new cryocooled transverse emittance meter (TEmeter). The design is largely based on the successful demonstration of Cornell University cryogenic high voltage DC gun (up to 200 keV electron beam while the photocathode is held at a temperature about 40 K) [7]. In the early design of the cryogenic HV DC gun the temperature at the cathode surface was limited to about 40K by the cooling power of the used cryostat, the absence any thermal shield surrounding the cathode electrode and by the large heat sink due to the electrical connection between the inverted ceramic insulator and to the the HV feedthrough. Detailed numerical simulation have been performed using ANSYS® indicating that in the new TEmeter the cathode surface should reach a temperature of about 5 K when the second stage of the cryostat is at 4 K and the radiation shield connected to the first stage held at 30 K. In addition to that the new TEmeter use a sample holder geometry directly derived from the Scienta Omicron flag sample holder and hence compatible with commercial instruments dedicated to surface science studies (see inset in figure 1) and to last generation Molecular Beam Epitaxy growth chamber allowing exploration of new photocathode materials. The electrostatic design is largely derived from the HV cryogenic DC gun with a sapphire rod providing thermal contact between the spherical cathode electrode and the cryostat head and at the same time the required electrical insulation. The cathode to anode gap is designed to be 5 mm at the maximum operating voltage of 60 kV. The cathode electrode is surrounded by a thermal radiation shield connected to the first stage of the cryostat and held at 30 K. The required cooling power required to cool the radiation shield and second stage from room temperature have been estimated to be 9.2 W and 0.65 W for the first stage and second stage respectively. A cryostat from ARS (model CS-215-SB-1200) will provide the required cooling power (up

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to 1.5 W at the second stage at 4.5 K) as well as a vibration damping to sub-micron level. Figure 1 shows a cross section of the electrode structure with the results of the ANSYS® thermal simulations indicating that cathode temperatures of few K can be achieved. The TEmeter beamline is being

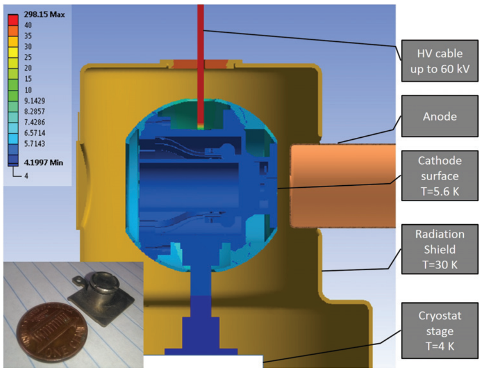

Figure 1: Thermal simulations have been performed using ANSYS®. Results indicate that a few K can be achieved at the cathode surface. The inset shows the new photocathode holder derived from the Scienta Omicron flag style.

designed to measure electron beam mean transverse energies with a resolution of 1 meV using the solenoid scan technique. Dedicated simulations have been performed to estimate that the required resolution in the measures of beam sizes are achievable. Based on our numerical simulations we expect to generate electron beam with an rms size larger than 8 micron for an initial spot size of 25 micron rms and 1 meV MTE. In order to accurately measure such small spot sizes We foresee the use of large CMOS sensors (35 mm Sony IMX304) with 3.45 micron size pixel size based cameras.

La:BaSnO$_3$ Ordered Photocathodes

We performed photoemission measurements on La:BaSnO$_3$. This ordered material belongs to the family of perovskite structure oxides and is a n-type doped compound with high carrier density (10^{20} cm^{-3}) with an effective mass in the conduction band of about 0.2 m_e [8]. Leveraging such high carrier density we generated electron beams exciting only the electrons in the conduction band as shown in figure 2(a). MTEs corresponding to the transverse momentum spread of the conduction band electrons, excited with photons above the photoemission threshold, are shown in Fig. 2(b). We performed QE and MTE measurements on samples with air-exposed surfaces as well as Cs-activated surfaces. The results for a non-activated sample, whose photoemission threshold energy is found to be 3.95 eV, are reported in Fig. 2(c). These preliminary results pave the way to the study of photoemission from samples with ordered surfaces, aimed at taking advantage electron transverse momentum conservation, and in general to new schemes of electron beam generation from low effective mass conduction band states (More details in poster TUPML027).

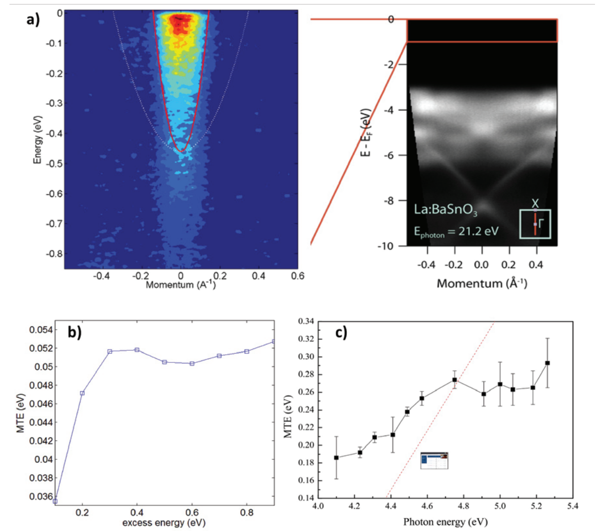

Figure 2: A) Measured band structure of the La:BaSnO$_3$; B) Predicted MTEs from the measured band structure; C) Measurements of MTEs as function of photon energy.

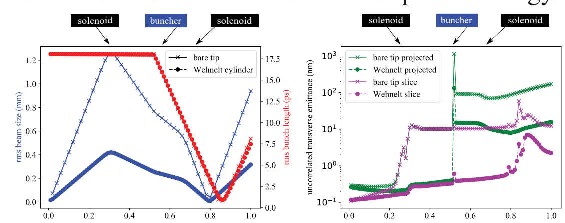

Figure 3: Plots showing the effect of a focusing Wehnelt electrode on a cathode with a field-enhancing tip. The left plot shows the beam size and bunch length the one on the right shows the emittance as a function of the position of the beam on the beamline (bunch charge is 11 fC).

Microtip Cathodes

A drastic reduction in the size of the electron source can lead to beams with improved brightness [9]. Leveraging the large electric field enhancement attainable using microsized tip photocathodes allows extracting high charge density electron bunches even in the low field gradient typical of DC gun. The accurate control of the electron bunch dynamics in non linear fields in the proximity of the microtips has to be achieved to preserve the small beam emittance achievable in this configuration. We are exploring use of novel simulation techniques for application in ultrafast electron microscopy. Figure 3 compare plots of beam size, duration and emittance using a cathode with a field-enhancing tip with and without a focusing Wehnelt electrode. Results have been promising in this particular case, and even more exotic cathode geometries will be explored (More details in poster TUPML029).

Multi-photon Emission And Electron Heating

Operating near the photoemission threshold can yield small intrinsic emittances at the cost of significantly reduced quantum efficiency. In modern femtosecond photoemission sources, this requires very high laser intensity (10s

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of GW/cm^2) to extract a useful quantity of electrons. The electron occupation function becomes far from equilibrium rapidly evolving on a sub-ps timescales. Thus, ultrafast laser heating and multiphoton photoemission effects may play a significant role increasing the minimum achievable emittance. We used a Boltzmann equation approach to calculate the non-equilibrium occupation function evolution in time for a copper photocathode, yielding a prediction of quantum efficiency and mean transverse energy (MTE) as a function of input intensity (Fig. 4). While we were able to reproduce at lower intensity the spectral response of a copper cathode that very well agrees with experimental results, at higher laser intensities we predict non-monotonic behavior of MTE as a function of photon energy due to multi-photon absorption (More details in poster TUPML026).

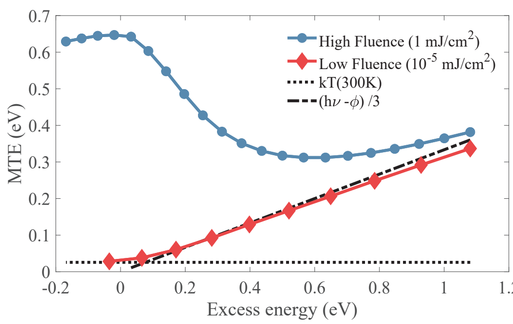

Figure 4: MTE calculated based on time evolving occupation function for different laser fluence. At low fluence, the result agrees with conventional three step model prediction while high fluence result shows non-monotonic behavior due to multi-photon absorption.

GaAs Photocathode Activated by Cs_2Te

High intensity and highly spin-polarized electron source is of great interest to the next generation Electron Ion Colliders [10]. GaAs prepared by the standard Cs and oxygen or NF_3 "yo-yo" activation method, which is the most widely used spin-polarized photocathode, is notorious for its vacuum sensitivity and relatively short operational lifetime. We activated GaAs using a very thin layer of Cs_2Te, a material well known for its robustness. We confirmed the Cs_2Te layer forms negative electron affinity on GaAs and we measured a factor of 5 improvement in lifetime under similar conditions. Furthermore, we show that the new activation method had no adverse effect on spin-polarization of electrons (Fig. 5). Considering Cs_2Te forms much thicker activation layer (~2 nm) compared to the standard activation layer (~monolayer), our results trigger a paradigm shift on new activation methods (More details in poster TUPML025).

Emittance Growth In Beam Transport

Low MTE photocathodes will not matter if no beamlines exist that may translate cathode emittance into usable beam brightness. A greater understanding of the physics of emittance growth is essential for the future of bright beams. To this end, we developed a new metric to determine the source

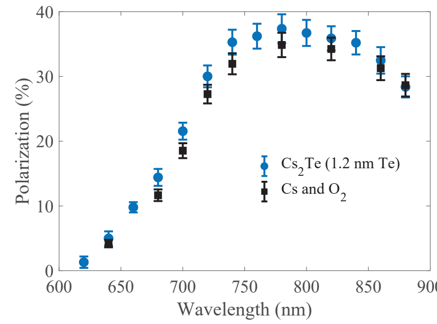

Figure 5: Spin polarization measured from GaAs samples activated by Cs_2Te and Cs and O_2 as a function of the laser wavelength.

of emittance growth in simulated particle beams. The emittance can be split into components that may be attributed to the space charge force, the force of beamline elements, and the non-force causes of emittance change. By comparing the contribution of each component towards the final emittance, the source of emittance growth in the beamline may be understood. In Fig. 6 the emittance components are plotted against time for a highly optimized ultrafast electron diffraction (UED) beamline. The results suggest that the final emittance is limited by the space charge force. (More details in poster THPAF024)

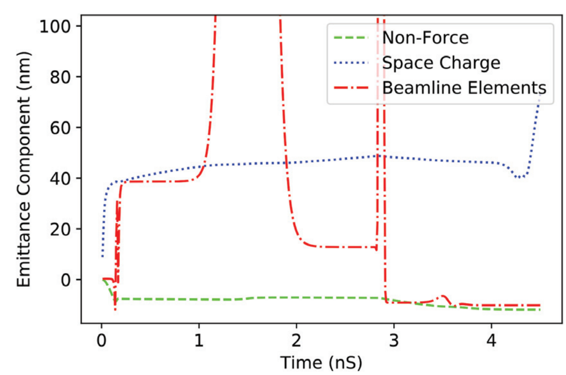

Figure 6: Emittance components along a highly optimized ultrafast electron diffraction beamline. The space charge component's large contribution to the final emittance suggests that it is the limiting factor in this system.

CONCLUSION

The need for increased brightness in electron beams for ultrafast electron microscopy and x-FEL is driving research directions towards the use of new materials and operating conditions as well as to the use of new modeling tools capable of describing the electron beam dynamics in these new regimes. Research direction and new devices aimed at generating electron beams with such ultimate brightness and aimed at improve the lifetime of photocathodes for highly polarized electron beams have been illustrated.

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