ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPC67

NaKSb PHOTOCATHODE TESTS IN A HIGH GRADIENT S-BAND PHOTOINJECTOR *

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Abstract

The photoemission properties of sodium potassium antimony (NaKSb) photocathodes grown at Cornell were measured at high gradients in the UCLA Pegasus S-band photoinjector. These measurements were enabled by the flexible suitcase-loadlock system which has been developed in the last few years based on the INFN-style design and cathode plugs. Preliminary measurements have been carried out using UV (266 nm) laser pulses which were readily available to illuminate the cathode. The quantum efficiency was measured to be 1.5% at 266 nm and was shown to have a degradation time of around 4.5 days. The MTE was also measured and calculated at 266 nm using solenoid scans and linear beam transport to be .7 ± 0.2 eV. Dark current was measured with accelerating gradients of up to 75 MV/m.

INTRODUCTION

High brightness photoinjectors drive many accelerator applications such as probing ultrafast structural dynamics with UED/UEM or seeding light sources, such as the LCLS - II XFEL [1] [2]. A promising pathway to increase beam brightness is by increasing the QE and reducing the intrinsic emittance, so called thermal emittance, associated with the photoemission process [3]. Advanced photocathode technologies has shown that significant reduction in the MTE (mean transverse energy), a quantitative figure to measure thermal emittance, can be achieved. In order to ripe the fruit of these advances, it is important to understand how these cathodes would behave in very high fields which are the other necessary ingredient to maximize the beam quality out of the photoinjector. An increase in brightness would improve spatial resolution of UED/UEM system and can extend the wavelength range of future XFELs, such as the LCLS - II HE upgrade, further into the hard x-ray regime [4].

We report on the quantum efficiency, thermal emittance and dark current of an NaKSb photocathode operating in a 75 MV/m.

The Pegasus photoinjector, seen in Fig. 1, is a 1.6 cell cavity operating in the S-band at 2.856 GHz that can achieve accelerating gradients of up to 75 MV/m at the cathode. UHV of around 4×10^{-10} Torr is kept in the gun when not operational. When in use vacuum rises to around 3×10^{-9} Torr. Cathodes grown on INFN style plugs can be inserted into the gun via a backplane which has been specially modified to allow using removable cathodes. The load lock chamber behind the gun has two transfer arms to slide the carriage out of the suitcase to exchange cathodes.

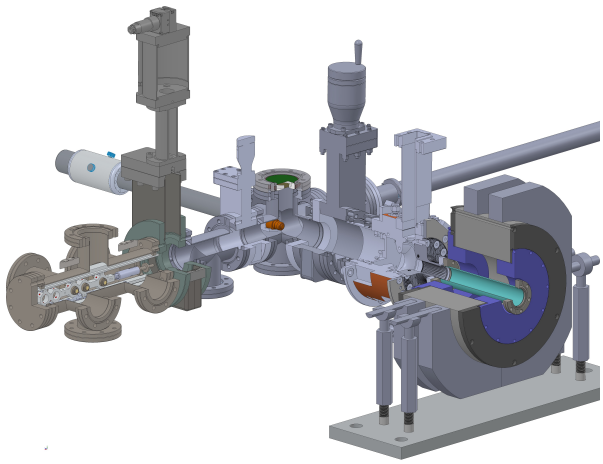

Figure 1: Pegasus photoinjector consisting of the RF gun and solenoid for beam production and transport as well as the UHV suitcase and load-lock chamber for cathode exchange.

The UHV suitcase allows for the cathodes to be transported from the growth chamber in Cornell to the UCLA laboratory while maintaining $<1 \times 10^{-10}$ Torr. The carriage inside the suitcase can hold 4 INFN style plugs, but only 3 slots are accessible at UCLA due to the dimensions of the transfer arms. For these tests two plugs were used (an empty spot was needed to store the plug already installed in the gun). A collection coil in front of one of the cathodes can be positively biased to collect charge for low field QE measurements.

NaKSb is an multi-alkali antimonide semiconductor shown to be a good photoemitter in the 1950s [5]. These air sensitive crystals form in stoichiometery of M_3Sb, where M is an alkali metal [6]. The work function is expected to be around 1.75-2 eV [6][7][8][9]. Of the two NaKSb photocathodes grown at Cornell and transported at UCLA, one on a molybdenum substrate plug and the other on a copper plug, likely with stoichimetry NaK_2Sb. Theses were flown to UCLA in the UHV suitcase for testing at high gradients.

* This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams.
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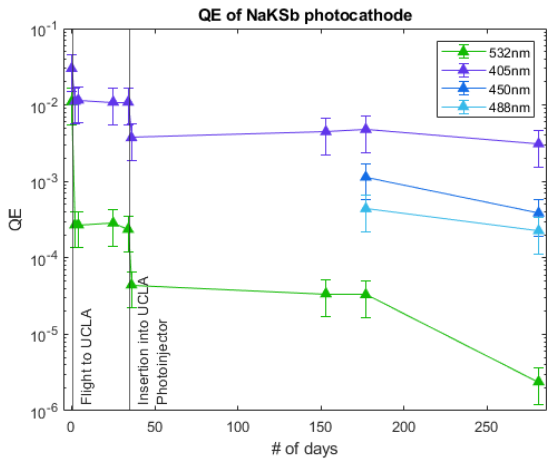

Figure 2: QE measured in the UHV suitcase using diode lasers from 405-532 nm.

MEASUREMENTS

Quantum Efficiency

The molybdenum plug cathode was visibly accessible in the suitcase and was used to monitor the degradation of the QE over time, shown in Fig. 2, by reading the photocurrent created when a diode laser is focused onto the cathode. Wavelengths from 405-532 nm were used to The largest decreases were observed at the times corresponding to transport to UCLA and transfer into the gun.

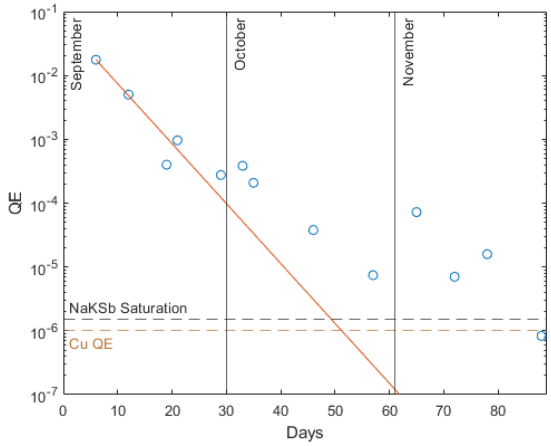

Figure 3: QE measured at 266nm during the cathodes lifetime in Pegasus.

After installing the copper plug cathode in the Pegasus gun, we used the 100 fs 266 nm laser pulse from the photoinjector drive laser to test the cathode properties. An initial QE of 1.5% was measured at 75 MV/m peak field. Using the SQL database that logs data from Pegasus, we have been able to passively monitor the QE over multiple days while the facility was running for other experiments obtaining a characteristic lifespan of 4.5 days, shown by the solid line fit to the first 5 points in Fig. 3. After many days the QE reached a saturation floor, shown as the dashed line in Fig. 3, which lies above the QE of polycrystalline copper.

Many factors in the violent environment of the RF photoinjector degrade the QE of theses alkali antimonide cathodes. The alkali metals in these semiconductors are very sensitive to air so poor vacuum conditions alters the surface chemistry, degrading the QE. If the cathode plug does not sit flush with the back plane of the gun, then the RF cavity will be detuned from resonance. At Pegasus we tune the cavity back to resonance with temperature, and any increase in temperature degrades the QE further.

Mean Transverse Energy

The MTE is related to the normalized emittance at the cathode by

$$\epsilon_{n,x} = \sigma_x \sqrt{\frac{\text{MTE}}{mc^2}}$$

where σ_x is the initial rms spread of the beam, m is the electron mass and c is the speed of light. Using the solenoid directly outside the gun we performed waist scan and use linear beam transport formalism to compute the 2D emittance. Waist scans done at 266 nm at different initial spot sizes allow us to compute an MTE = .7 ± 0.2 eV, as seen in Fig. 4, agrees with the expected value of 0.9 eV caluculated using MTE = $\frac{1}{3}(E_{\text{photon}} - \phi)$, where E_{photon} is the photon energy and ϕ is the effective work function [10]. The scans

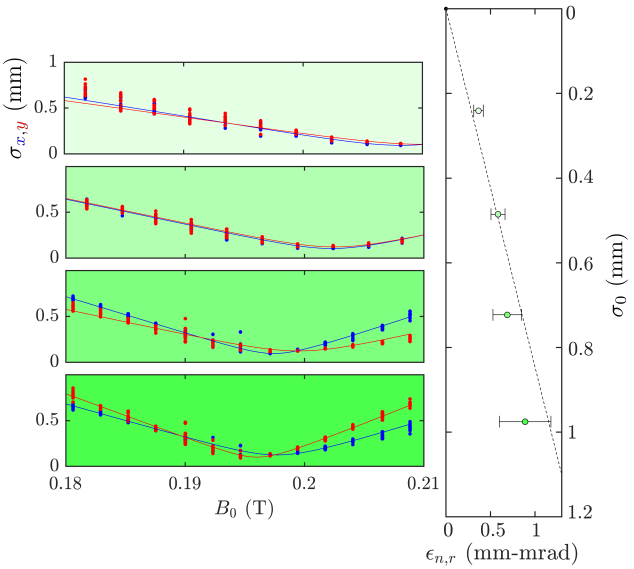

Figure 4: Solenoid scans (left) taken at 266 nm at different initial spot sizes to genertate an MTE plot (right).

are done with < 150 fC bunch charge and short laser pulse, reducing contributions of the rf and space charge fields to the emittance growth. The emittance retrieved using the linear transport model is attributed to the intrinsic emittance of the photoemission process. The accuracy of the solenoid scan in reporting a small emittance is limited by the resolution of how small of a beam can be measured. We measure the waist of the beam on a YAG screen downstream of the gun. Any

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resolution limits will result in our emittance calculations giving artifically higher emittances.

Dark Current

Field emission current was focused onto a calibrated screen as the accelerating gradient was increased to measure the charge extracted at a given field created by a 2.5 µs RF pulse. We plotted this against field emission from other photocathodes tested at UCLA, seen in Fig. 5, such as copper, cesium antimony (CsSb) and previous NaKSb photocathodes.

The range of past data sets do not overlap as they were taken when the gun was powered by a PFN klystron amplifier that was slightly more powerful but less stable than our current solid state modulator. These low work function photocathodes display more field emission than metals, as expected. The most recent data set from 2024/05/13 was taken with a 3 μs pulse during conditioning of the gun, which explains why we see more charge from this NaKSb cathode compared to previous ones.

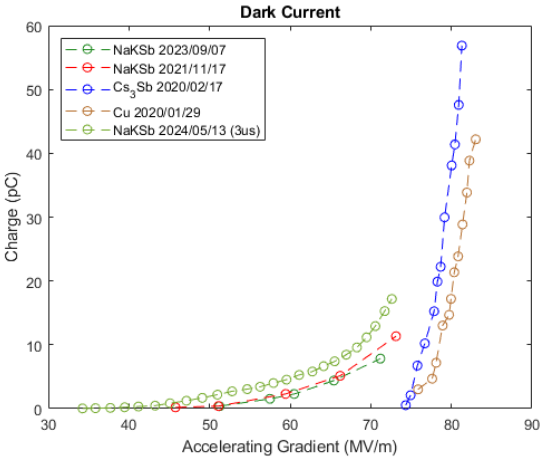

Figure 5: Dark current measured from NaKSb and other photocathodes. Measurements from 2020 used a more powerful PFN modulated klystron amplifier to power the gun.

CONCLUSION & OUTLOOK

We report on the initial measurements done on NaKSb photocathodes at high gradients. Further studies are planned to study the spectral response of the QE and MTE as well as measuring the temporal response. New methods to better measure the MTE and temporal response, MCMC and tomography respectively, are being developed with the help of particle tracking through simulation [11].

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