# Emittance Measurements for the Illinois/CEBAF Polarized Electron Source*

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Abstract

The transverse thermal properties of the electrons photo-emitted from GaAs determine the intrinsic beam emittance, an important quantity in applications such as polarized electron sources and high-brightness sources. In this paper, emittance measurements using the Illinois/CEBAF polarized electron source are described. The emittance was measured as a function of both the laser beam spot size and laser wavelength at low currents. The data was used to infer the transverse thermal energy of the electrons photoemitted from GaAs for wavelengths between 514 and 840 nm. Near the bandgap the transverse energy is ∼34 meV, a factor of 3 lower than that of the beam from a typical thermionic electron gun.

## I. Introduction

Semiconductor photoemission electron sources are widely used for the production of polarized electrons. They are also attractive for non-polarized source applications such as free electron lasers [Si92] and linear colliders which require high brightness electron injectors that can deliver a wide range of currents with demanding time structures and a low emittance. As the intrinsic beam emittance is determined by the effective temperature of the electrons emitted from the photocathode, it is then important to know this temperature for the semiconductor in use under the operating conditions of the injector. The effective temperature of GaAs (the semiconductor most used for polarized electron production) has been measured at low acceleration voltages by other groups using several different methods with results around 0.1 eV, close to the value obtained from a typical thermionic gun.

In this paper, we report measurements of the emittance of the electron beam emitted from GaAs for various excitation wavelengths and laser beam diameters at 100 kV in order to study the thermal properties of GaAs photocathodes.

## II. Emittance Measurements

### *A. Theory*

Consider the motion of a particle through a beamline consisting of drift spaces and non-dispersive focusing magnets. In the x-plane (similar equations hold for the y-plane), the position vector at the end of the beamline is given by the product of the initial position vector and a transfer matrix, $\mathsf{X}_{final} = \mathsf{R}\ \mathsf{X}_{initial}$. Note that the motion in the x and y-planes must be decoupled to be able to use a separate $2 \times 2$ matrix representation for x and y, otherwise a more complete representation must be used.

A beam is made up of a collection of particles which is described by the ellipse, $\mathsf{X}^{\mathsf{T}} \sigma^{-1} \mathsf{X} = 1$, where $\sigma$ is the usual $2 \times 2$ beam matrix. The beam matrix is propagated through the beamline by $\sigma_f = \mathsf{R}\,\sigma_i \mathsf{R}^{T}$. Expanding the beam matrix at the end of a set of magnets and drifts in terms of the initial beam matrix then gives

$$\sigma_{11,f} = R_{11}^2 \sigma_{11,i} + 2 R_{11} R_{12} \sigma_{12,i} + R_{12}^2 \sigma_{22,i}. \tag{1}$$

Since the beam radius is given by $\sqrt{\sigma_{11}}$, equation 1 shows that a measurement of the beam size at the exit of the beamline for three different magnet settings is sufficient to determine $\sigma$ at the entrance to the beamline if the transfer matrix, **R**, is known [Ro87]. The emittance is then the area of the beam ellipse, or $\pi\sqrt{\det \sigma}$.

The most commonly used definition of emittance is that of the rms emittance, defined as

$$\varepsilon_{rms} = 4\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x\,x'\rangle^2}. \tag{2}$$

As an example of an application of rms emittance, consider the calculation of the emittance of an electron gun at low currents [La77]. Assuming that the electrons are emitted uniformly and isotropically from a cathode of radius R in the presence of an accelerating electric field, and if the cathode operates at a temperature T, then the distribution function for $x'$ is Maxwellian and $< x'^2 >$ can be calculated to be $kT/mc^2\beta^2\gamma^2$. The mean square value of $x$ is simply $< x^2 >= R^2/4$. Using equation 2 and the fact that $< xx' >= 0$ for this initial beam distribution, the emittance of an electron gun operating at a temperature T is:

$$\varepsilon_{rms} = 2R\sqrt{\frac{kT}{m\gamma^2\beta^2c^2}}. \tag{3}$$

This equation was used to infer T from measurements of $\varepsilon_{rms}$ for different initial beam radii.

### *B. Beamline Setup*

The measurements were carried out using the University of Illinois/CEBAF polarized electron source. It consists of a 100 keV GaAs photocathode electron gun, a spin rotation system and a Mott polarimeter (see [En93] and [Du93] for details). Ideally, one would measure the emittance at the exit of the gun to eliminate problems of disturbing the phase volume during beam transport. However, this was not feasible due to other experiments in

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progress, so the emittance was measured after the beam traversed a spin rotation system and polarimeter.

The actual beamline for the emittance measurements consisted of a pair of solenoid lenses followed by a drift space of 1 m to a wire scanner. The two solenoids are identical and powered with current flowing in the opposite sense to insure that they introduce no x–y coupling so that the formalism in section II-A can be used.

### C. *Laser Setup for the Emittance Measurements*

To cover the desired range of wavelengths, three lasers were used: a helium-neon laser (633 nm), an argon-ion laser (514 nm), and a argon-pumped titanium sapphire laser (700-900 nm). To eliminate problems that could arise from poor laser beam pointing stability and a difference in beam profiles between lasers, the laser beam was focused onto a circular aperture which was then imaged to a uniform, circular spot on the photocathode. An achromatic lens with a focal length of 1 m was placed on an x-y positioning stage 2 m from the cathode. The set of apertures was mounted on an adjustable stage another 2 m upstream from the lens along the laser beam path. Each laser in turn was then roughly collimated using a small telescope to produce a 5 mm diameter beam and steered onto the aperture of choice. All of the optical elements were then adjusted until an image of the aperture was centered on the photocathode. Periodically, the image was diverted by a movable mirror so it could be viewed on a CCD camera; the spot was uniform to within $\sim$10% across the beam (see figure 1). To change beam diameters, a different aperture was centered on the laser beam while observing the image on the CCD camera. This setup allowed the laser spot size and location to be reproduced accurately independent of the laser wavelength. It also improved the pointing stability since the collimated laser beam spot was substantially larger than the aperture.

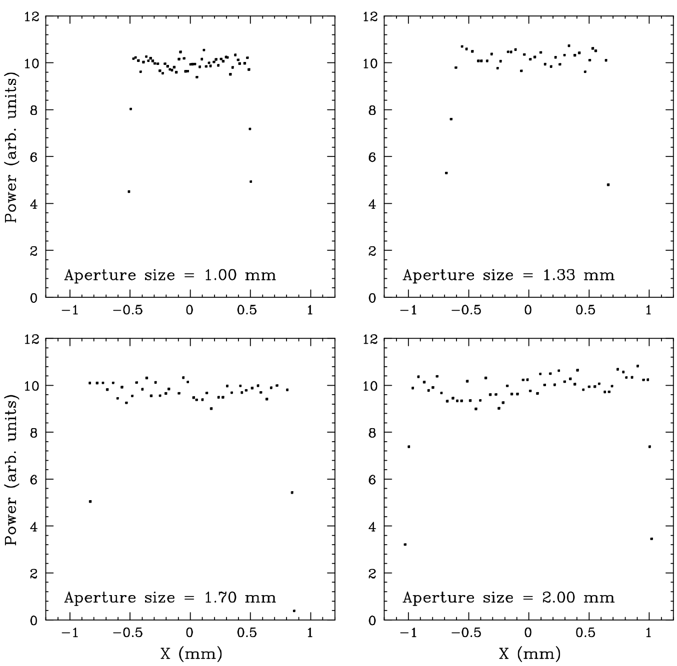


Figure. 1. Profiles of the laser beam spot as viewed on a CCD camera. The plots are cuts through the center of the laser beam image for each of the four apertures.

### D. *Determination of Beam Width*

The electron beam profile was measured using a standard wire scanner driven by a stepper motor. The wires were 50 $\mu$m gold-plated tungsten and the signals on the x and y wires were read out using an I-V preamplifier with variable gain and a accurate digitial voltmeter (all measurements were with a DC beam). The rms beam radius was calculated directly using $\langle x^2 \rangle = \sum (x_i - x_{avg})^2$, as the beam profile was not, in general, gaussian. Background subtraction was performed by fitting a line to the region of data outside of the beam area.

## III. Results and Discussion

The electron beam emittance was measured for wavelengths of 514, 633, 710, and 840 nm for spatially uniform laser beam spots with diameters of 1.00, 1.33, 1.70, and 2.00 mm. The GaAs photocathode that was used had quantum efficiencies of between 1 and 2% at 633 nm after heat cleaning and activation with cesium and nitrogen tri-fluoride. All measurements were made at currents between 5 and 10 $\mu$A and a beam voltage of 100 keV so that space charge effects were not important. This was verified by measuring the emittance as a function of current for the smallest spot size.

Figure 2 shows a plot of the rms-emittance data as a function of the laser beam diameter for four laser wavelengths. The straight lines are fits to the data; the transverse thermal electron energy, $E_T$, is obtained from the fitted slope by inverting equation 3: $E_T = (slope)^2 mc^2 \beta^2 \gamma^2$. The error bars for the emittance values are mainly instrumental in nature and were determined to be $\sim$6% [Du93].

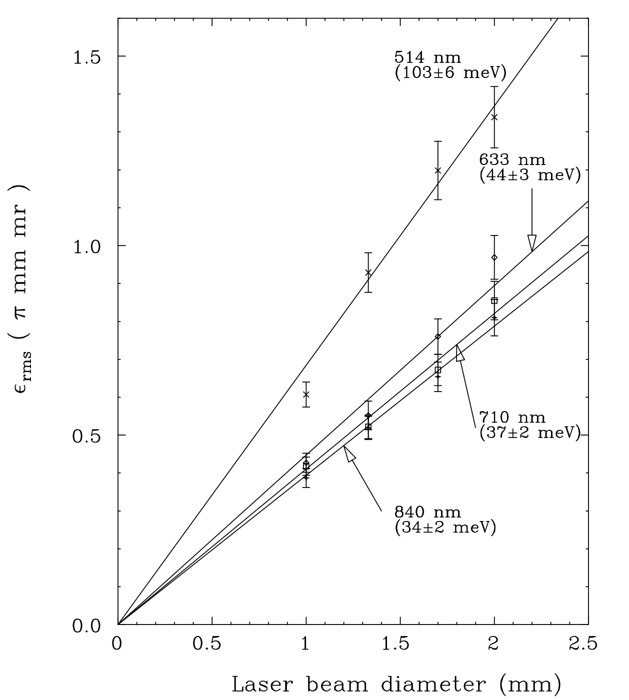


Figure. 2. The rms-emittance as a function of laser beam diameter for several laser wavelengths. The inferred thermal energies are shown in parenthesis.

A number of researchers have measured the transverse thermal energy of electrons emitted from GaAs photocathodes using a variety of methods different than the method used here. Most of the experiments made measurements either with only one excitation wavelength or with a white light source, and all made the measurements at low electron energies, typically under a thousand volts.

For example, Feigerle *et al* [Fe84] were interested in GaAs photocathodes as a intense source of monochromatic electrons. They measured the electron distribution curves (EDC's) for electrons emitted from a GaAs cathode (driven by a 810 nm laser diode) with a spherical deflection electron kinetic energy analyzer. The measured widths (FWHM) of the EDC's were 97 meV at 300K and 31 meV at 77K.

In a study of the photoemission from activated GaAs, Drouhin [Dr85] measured very high resolution EDC's using a cylindrical deflection energy analyzer. They measured an $E_T$ of $\sim$40 meV at 800 nm and reported a doubling of the effective energy at wavelengths lower than 633 nm. They suggest that the increase in width of the EDC's with increasing photon energy is due to two effects. First, electrons excited by higher energy photons have more energy to lose as they become thermalized into the conduction band minimum so that their complete thermalization would require a longer time. Second, because of the decreased absorption depth of the higher energy photons, the electrons are excited closer to the surface of the crystal and thus spend less time in the crystal before emission. The combination of the two effects means that electrons excited by higher energy photons are more likely to leave the crystal before completely thermalizing than lower energy photons. They also discuss the effects on the shape and width of the EDC's due to the amount of negative electron affinity and the doping level. For example, as the cathode quality degrades over time, the electron affinity rises nearer to the vacuum level and decreases the width of the EDC's, thus reducing the effective energy of the emitted electrons.

Bradley [Bra77] derived the effective transverse energy of electrons photoemitted from GaAs (using a white light source) from limiting resolution measurements. As their interest was in the resolution of imaging tubes, the method involved measuring the smallest resolvable spacing of a standard bar pattern projected onto the cathode. They determined the effective electron energy to be 108 meV over an electric field range of 1–4 MeV/m (our source operates at 1 MeV/m at the cathode) using voltages of several thousand volts. They also studied models of electron emission from rough surfaces to explain the high values of the $E_T$ (compared to room temperature). If the surface is rough, small areas will have local surface normals different from the average normal of the crystal. If the local normal is much different than the average normal, the projection of the local normal onto the surface will contribute to a larger effective transverse electron energy than might be measured for a perfectly smooth crystal surface.

In conclusion, the effective transverse thermal energy of the electrons emitted from a GaAs photocathode was measured as a function of wavelength by a new method. The measurements were carried out at a beam energy of interest for accelerator applications, 100 keV; this energy is much larger than the voltage used in earlier experiments. The value of $E_T$ inferred from the measured rms emittance increased with decreasing photon wavelength from 34 meV at 840 nm to 103 meV at 514 nm. The measured results were generally lower than those of other researchers, where possible differences could be due to the beam energy, surface preparation techniques, surface quality, surface roughness, and heat treatment cycles. $E_T$ also increased with increasing photon energy, as expected. The most interesting conclusion that can be drawn is that the effective transverse electron energy was measured at an energy of interest for accelerator applications, and was found (for wavelengths less than 633 nm) to be a factor of three lower than a thermionic gun operating at 1160K.

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