MEASUREMENT OF THERMAL EMITTANCE FOR A COPPER PHOTOCATHODE

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Abstract

Measurements of the thermal emittance of an electron beam produced by photoemission from the copper cathode of a high power RF cavity are presented. The RMS normalized emittance has been measured as a function of laser spot size, applied surface field, and polarization of the laser beam at normal incidence. Local field enhancement due to surface effects is found to increase the emittance substantially beyond that expected for a perfect planar surface.

1 THERMAL EMITTANCE

The value of the thermal emittance of an electron beam produced by a photoinjector is a measure of the temperature of the electrons emitted from the metal cathode surface. It is the minimum possible emittance for a given accelerator, and is an important determinant of FEL performance and linear collider luminosity. It is difficult to accurately measure because nonlinear space charge forces, lattice errors and variation in linear space charge and RF forces along the bunch all contribute to growth beyond the thermal value. The limits on peak current and bunch length are discussed in the sections below. Lattice misalignments and wakefields are negligible due to the very short distance (65 cm from the cathode) the beam is transported.

We assume a thermalized distribution of electrons is emitted from the copper surface. There is no correlation among momentum and position so that the normalized emittance is given by

$$\varepsilon_{xN} = \gamma\beta\sqrt{\langle x^2\rangle\langle x'^2\rangle} = \gamma\beta\sigma_x\sigma_{x'} \quad (1)$$

Lawson's expression [1] for the width of the momentum distribution of a thermalized beam is

$$\sigma_{x'} = \sqrt{\frac{E_k}{mc^2}} \Rightarrow \varepsilon_{xN} = \sigma_x\sqrt{\frac{E_k}{mc^2}} \quad (2)$$

where the kinetic energy of the electrons after emission is

$$E_k = h\upsilon - \Phi_{Cu} + \alpha\sqrt{\beta_{rf}E_{rf}\sin\theta_{rf}}\,, \quad (3)$$

$$\alpha = \sqrt{\frac{e}{4\pi\varepsilon_0}},\ h\upsilon = 4.67\text{ eV},\ \Phi_{Cu} = 4.59\text{ eV}.$$

and E_{rf}=95 MV/m and $\sin\theta_{rf}$ are the RF amplitude and phase. Equations (2) and (3) will be used to fit the measured data, yielding estimates of Φ_{Cu}, β_{rf}, E_k, and ε_N.

2 FIELD ENHANCEMENT FACTOR

On a microscopic level, the surface of the cathode is neither planar nor clean. As a result there are large variations in the surface electric field. The field enhancement factor β_{rf} [2] is the ratio of the microscopic electric field to the field for an ideal surface. Geometric surface irregularities lead to $3 < \beta_{rf} < 5$ for a polished surface. The field enhancement will usually be further increased by oxides, adsorbed carbon compounds, and contact potentials at grain boundaries in a polycrystalline metal.

For a perfectly flat, clean copper surface (β_{rf} = 1), Eq. 3 estimates that E_k = 0.26 eV, and Eq. 2 then estimates the normalized rms emittance is 0.35 mm-mrad for a 1mm hard-edge radius beam. These values are close to those estimated in references [3,4]. As shown below, including realistic values of β_r for a carefully prepared surface nearly doubles the thermal emittance.

3 SPACE CHARGE EFFECTS

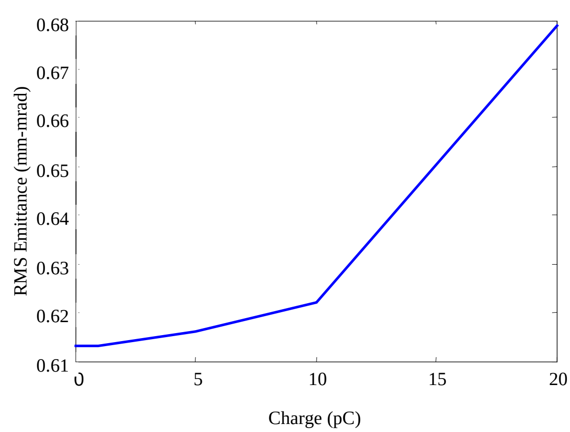

Figure 1: HOMDYN simulation showing scaling of emittance with beam charge. The initial, uncorrelated, normalized emittance is 0.60 mm-mrad. Bunch length is held fixed at 3 ps FWHM.

It is desired to reduce collective effects to negligible levels for two reasons. Space charge must not increase the width of the thermal distribution during acceleration in the photoinjector, and secondly, the emittance reconstruction method relies on linear transport matrices that also neglect space charge. Simulations with

HOMDYN [5] show (Fig. 1) that emittance growth due to space charge is less than 5% when charge is less than 10 pC. This is correlated emittance growth caused by rapidly varying space charge forces near the cathode.

A more restrictive limit on charge is imposed by the requirement for linear beam transport from the focusing solenoid to a small waist 30 cm downstream. To accurately reconstruct the beam parameters at the solenoid entrance, the space charge term in the envelope equation must not affect the waist beam size.

The envelope equation for a round beam with time-symmetry in a drift is

$$\sigma_x'' = \frac{eI}{8\pi\varepsilon_0\gamma^3\beta^2 mc^3\sigma_x} + \frac{\varepsilon_{xN}^{\;2}}{\gamma^2\sigma_x^{\;3}} \qquad \textbf{(4)}$$

Integrating Eq. 4 we find that the peak current must be less than 3 A, or Q less than 7 pC for a bunch length of 2.5 ps, in order to have less than 5% growth of the waist size at the screen location.

Diagnostics successfully measure charge and bunch transverse profiles for charge less than 1 pC. For the measurements presented, the charge was set at 2 pC.

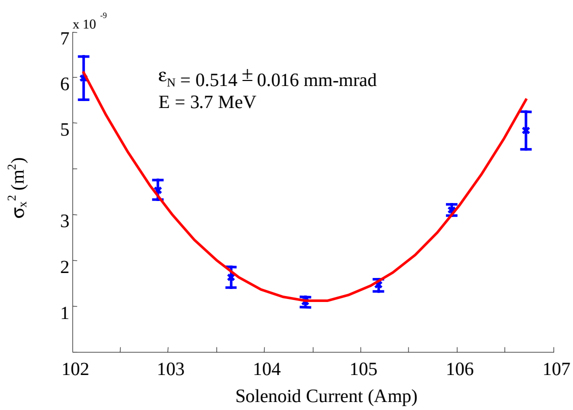

Figure 2: Data from a typical solenoid scan. Charge = 2 pC, bunch length = 2.5 ps FWHM.

The solenoid scan method [6] is used to measure emittance. The data is generally very clean (Fig. 2) compared to beam measurements done at high energy and high charge. This is because the spatial mode of the gun drive laser has been carefully cleaned up [6] with a very restrictive pinhole filter (only low laser power is needed at low charge), and no wakefields, space-charge effects, or accelerator misalignments contribute to beam halos.

4 PULSE LENGTH EFFECTS

The variation of transverse RF forces with phase causes different slices of the beam to have different orientations in phase space (increasing projected emittance) for long pulses [7].

HOMDYN estimates less than 5% emittance growth due to varying RF forces when the bunch length is less than 5 ps. This is correlated emittance growth caused by different slices of the beam sampling different RF phases.

RF zero phasing measurements (Fig. 4) of bunch length [8,9] indicate FWHM = 2.5 ps. Bunch length may be tuned from less than 1 ps to 5 ps by varying the photocathode drive laser pulse length.

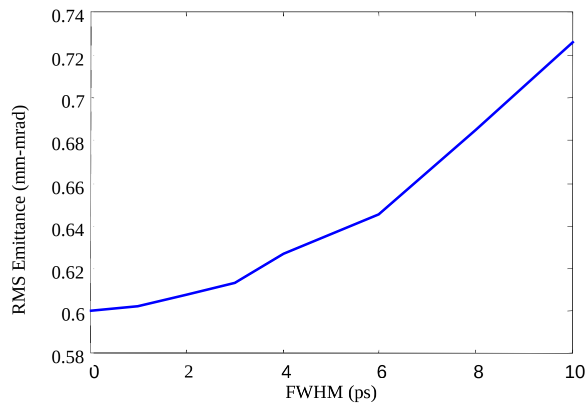

Figure 3: HOMDYN simulation of emittance vs bunch length. Charge is fixed at 2 pC, peak cathode field is 95 MV/m.

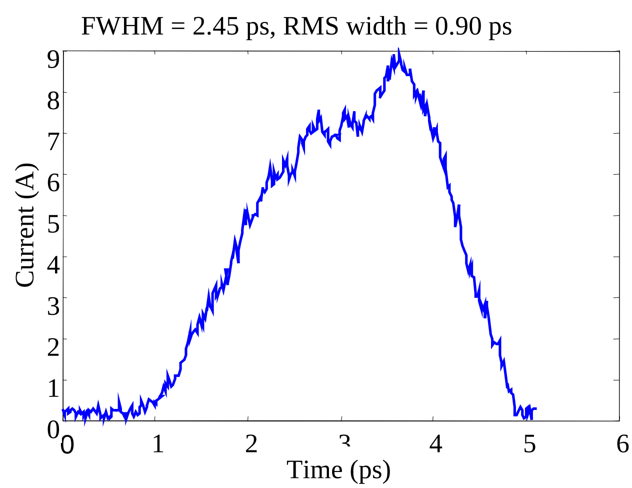

Figure 4: Time profile of electron beam using RF-zero phasing method at 75 MeV. Electron beam is transported to end of linac for this measurement.

5 EMITTANCE SCALING

Figure 5 shows plots of emittance vs RMS laser spot size. The slope of the curve is a measure of the average electron kinetic energy at emission. Linear fits yield

$$\varepsilon_x[mm-mrad] = 0.16 + .93\sigma_x[mm]$$

$$\varepsilon_y[mm-mrad] = 0.11 + .92\sigma_x[mm]$$

Differentiating Eq. 2 and using the fitted values the electrons' thermal kinetic energy is estimated as

$$E_k = mc^2\left(\frac{d\varepsilon_{\mathrm{N}}}{d\sigma_x}\right)^2 = 0.43\,\mathrm{eV} \qquad \textbf{(5)}$$

The linearity of the data in Fig. 5 indicates that collective effects and RF correlations have little effect on the beam under these experimental conditions. However, the large kinetic energy is the first indication that the surface electric field is not uniform.

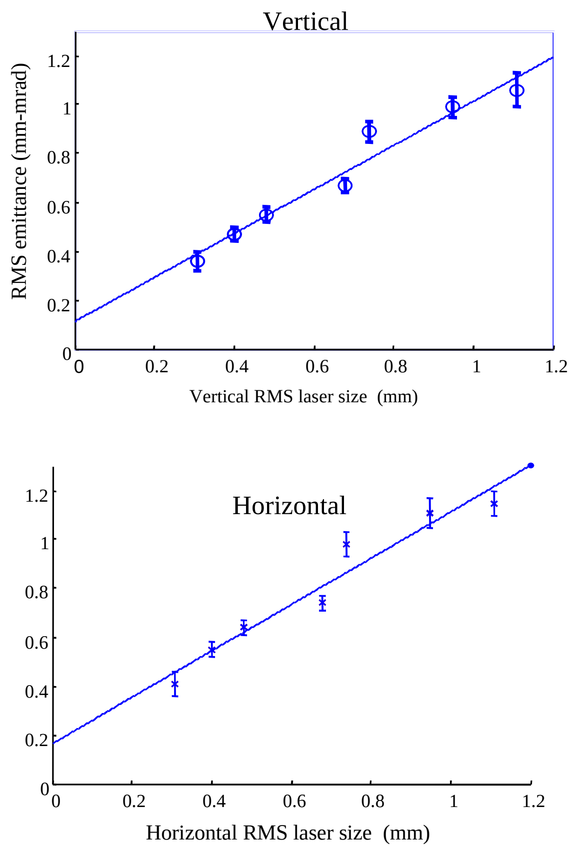

Figure 5: Plots of emittance vs RMS laser size showing linear dependence.

A second interesting scaling is found by studying the emittance vs applied field on the cathode. This is done by varying the laser arrival time on the cathode so that the effects of different field strengths are measured.

Combining Eq.'s (2) and (3) and performing a nonlinear least squares fit with β_{rf} and Φ_{cu} as parameters, the data yields β_{rf} = 3.10 +/- 0.49 and Φ_{cu} = 4.73 +/- 0.04 eV. The plotted data points are the average of the x and y measurements, and the curve is the fit with these parameters. The fit provides a second estimate of the electron kinetic energy E_k = 0.40 eV, in close agreement with the estimate from the radial dependence of emittance.

In all of the plots presented the laser polarization is in the horizontal plane. This is verified with a polarizing UV beam-splitter just before the laser enters the accelerator beam line. A slight, but persistent, asymmetry in emittance and beam parameters is observed between x and y.

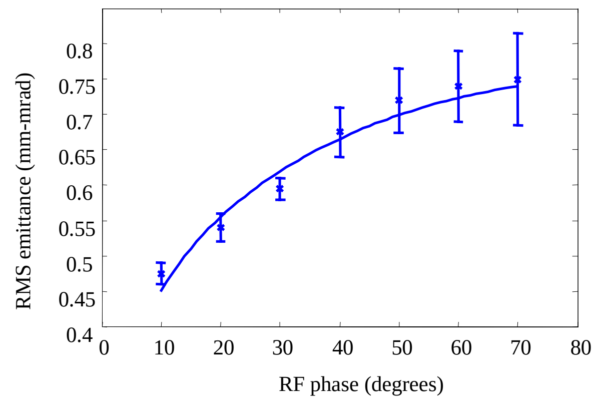

Figure 6: Data points are average of horizontal and vertical emittance plotted vs laser arrival phase at the cathode. Curve is fit using Eq.'s 2 and 3. Charge = 2 pC, FWHM = 2.5 ps, RMS laser size = 0.7 mm.

To test if this is due to polarization, the laser polarization was rotated into the vertical plane with a wave plate and again verified with the UV beam splitter. Within experimental error, the emittance values are unchanged, so that no polarization dependence is found. For a thermalized beam, no polarization dependence is expected.

6 CONCLUSIONS

The thermal emittance for a copper photocathode has been measured. Tests of scaling laws with initial spot size and applied RF field were performed and good agreement was found between theory and experiment. The field enhancement factor that accounts for microscopic variations in applied field is found to strongly influence the emittance, causing it to be larger than that expected of a perfect planar surface. No dependence on laser polarization is found for normal incidence.

7 REFERENCES

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