CHARACTERISATION OF THE BEAM FROM THERMIONIC RF-GUN ADAPTED FOR PHOTO CATHODE OPERATION[*]

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Abstract

The existing thermionic RF-gun (tungsten-BaO cathode) at the MAX-lab linac injector has been adapted for photo cathode operation. Important parameters of this system for free electron laser experiments, like emittance and charge, were measured giving 5.5 mmmrad at 70 pC (see below). A more detailed report on that setup, including laser and electron optics is given.

INTRODUCTION

For operation of a free electron laser the emittance of the electron bunch is of great importance. A test-FEL facility at MAX-lab uses the electron gun (1.6 MeV) and injector (total 400 MeV with recirculator) which is used for injection of storage rings and nuclear physics research. Although it is usually run as thermionic gun, for operation of the FEL it is used as photo cathode gun. An ultraviolet laser beam (263 nm, 130 μJ, 10 Hz repetition and 9 ps length) is used to create photoelectrons from tungsten impregnated barium-oxide cathode. Important characteristics of created electron beam (such as charge dependence on laser energy, influence of the charge on emittance, and optimal RF-phase) were measured. Measurements show that this cathode can be used to produce electron beam at the linac entrance of sufficient quality for operation of the test-FEL (required 5.5 mmmrad and 70 pC for harmonic generation) [1].

EXPERIMENTAL SETUP

The gun

To stop the thermionic emission, the temperature of the gun is reduced from 1050°C to 700°C. Only the part of the cathode that is hit by the laser beam (about 3 mm diameter) participates in photo-emission. The gun is a $\frac{1}{2}$+$\frac{1}{2}$+1 cell structure and the fields inside the gun reach 25 MV/m at the cathode and 80 MV/m in the main cell. The total energy of electrons that leave the gun is in the end 1.6 MeV. The electron bunch passes a solenoid for focusing (whose strength needs to be set differently for photo-electron operation because of different charge), and after that several quadrupoles and an energy filter (dipoles that bend the electrons for 2× 60° with an edge in the middle to filter out electrons during thermionic operation). The electrons then pass a quadrupole that is focusing in the bending plane which was used to do emittance measurements.

Laser system

The laser system is a Ti:Sapphire oscillator (790 nm, 93.7 MHz, Femtolasers Synergy) which is locked with 3GHz RF clock with relative jitter less than 0.2 ps. The pulse of the oscillator is then amplified by a chirped pulse amplification setup and tripled to 263 nm (up to 500 μJ per pulse). The UV laser pulse then passes spatial filtering and an optical delay stage which allows adjustable time of arrival relative to the RF cycle (relative phase). The energy of the laser pulse can be changed, and during the measurements it is checked constantly by a photo-diode (calibrated with an Ophir Nova II energy-meter).

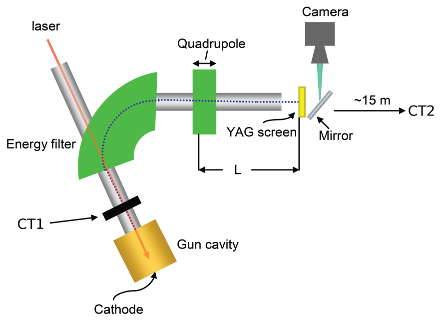

Figure 1: Schematics of the experimental setup.

Measurements

Figure 1 shows schematics of the gun system: gun cavity and cathode, the energy filter, laser direction, quadrupole and screen for emittance measurements, and current transformers (CT) for charge measurements.

The emittance of interest was measured by quadrupole scans with a quadrupole which is positioned after the energy filter and focusing in horizontal plane, the same plane as the energy filter. The emittance measured includes space-charge effects, scraping of the electrons by the energy filter and dispersion from the energy filter, and although not measured by the optimal technique at these energies the technique was the only one available in this section of the machine. The transversal beam profile was observed on a fluorescent YAG (yttrium aluminium garnet) screen about 25 cm after the quadrupole. Images from the YAG screen were captured by a 10bit firewire (IEEE1394) camera.

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Charge measurements were done by integrating the signal from two different CTs. CT1 was right after the gun and CT2 about 15 meters downstream of the quadrupole used for emittance measurements. It was checked that this method of integrating signals on those current transformers with short bunches gives good results by cross-calibration with a Faraday cup. The laser energy was changed between 0.2 μJ and 130 μJ. Measurements of extracted charge relative to the laser energy allowed calculation of the quantum efficiency.

For emittance dependence on charge a quadrupole scan was done for each value of laser energy. Arrival time of the laser pulse was adjustable by an optical delay stage and dependence of emittance on RF phase was measured. The position of the laser pulse was changed from 5 ps to 50 ps in the accelerating part of the RF cycle, which (at 3 GHz) corresponds to a bit more than 50° in phase.

Data analysis

Images from the camera for emittance measurements were analysed in MATLAB and for each quadrupole strength four images were taken and averaged. Two methods of analysis of those images to get the horizontal beam size were used (and they gave results within expected error in measurements).

The first method lined out one or several rows of pixels going through the center of the beam spot and fitted a Gaussian distribution on readout thus retrieving standard deviation for each quadrupole strength. The second method applied median filtering of noise and background subtraction and then calculated square root of the second central moment (standard deviation without assuming Gaussian distribution) after projecting all pixel values to horizontal axis. The first method is less noise dependant but more unstable and it assumes Gaussian distribution, the second method was more robust and faster but requires good signal to noise ratio and proper background subtraction. Once dependence of rms beam size (σ) on quadrupole strength k is known the emittance (ϵ) can be calculated from coefficients of second order polynomial fit

$$\begin{aligned}\sigma_x^2 &= c_1k^2 + c_2k + c_3 \\ \epsilon &= \frac{1}{L^2 l}\sqrt{c_1c_3 - \frac{c_2^2}{4}}\end{aligned}$$

where L is distance of the screen from the quadrupole and l is the thickness of the quadrupole.

RESULTS

Figure 2 shows the extracted charge from the gun (measured on CT1) depending on the laser energy in one pulse. For higher laser energies the results deviate more and more from a straight line, this can be explained by longitudinal space charge effects where initially extracted electrons shield the cathode from the accelerating field and effectively reduce it. This saturation happens around 40 μJ in our case and the effect of saturation corresponds to earlier observations in photo-cathode RF guns [2] and the measured value of 1.1×10^{-4} is in agreement with previous measurements on BaO [3].

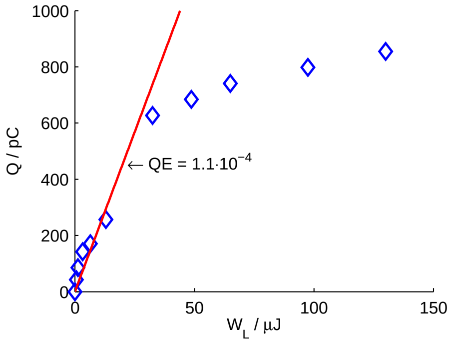

Figure 2: Extracted charge (as measured on CT1) depending on the laser energy. Quantum efficiency of the cathode in linear part; the saturation is caused by shielding of the extracting field by initial extracted electrons.

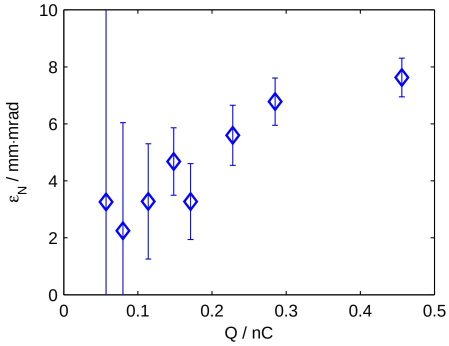

Figure 3: Normalized emittance dependence on extracted charge. Laser energy was changed to control charge, while the RF phase was kept constant on 20° where emittance measurements showed lowest emittance. Uncertainty at low charges is because of low signal after the energy filter where emittance was measured. At higher charges the charge reduction by the energy filter defines the emittance.

Figure 3 shows dependence of the emittance after the energy filter on the charge that is extracted from the gun (the charge is measured on the CT1). The charge that is transported through the energy filter is lower than the charge extracted from the gun and it influences signal to noise ratio on the screen which is used for emittance measurements, so the points with low charge have very big error bars. During the scan the laser energy was changed to change the extracted charge and the relative phase (laser to RF cycle) was kept at 20° where simulations showed lowest expected emittance. Theory predicts linear behaviour [4] and our measurements agree with those expectations.

Measurements of the emittance depending on the RF phase are shown in Fig. 4 (all emittance measurements show normalized emittance). During the scan the laser en-

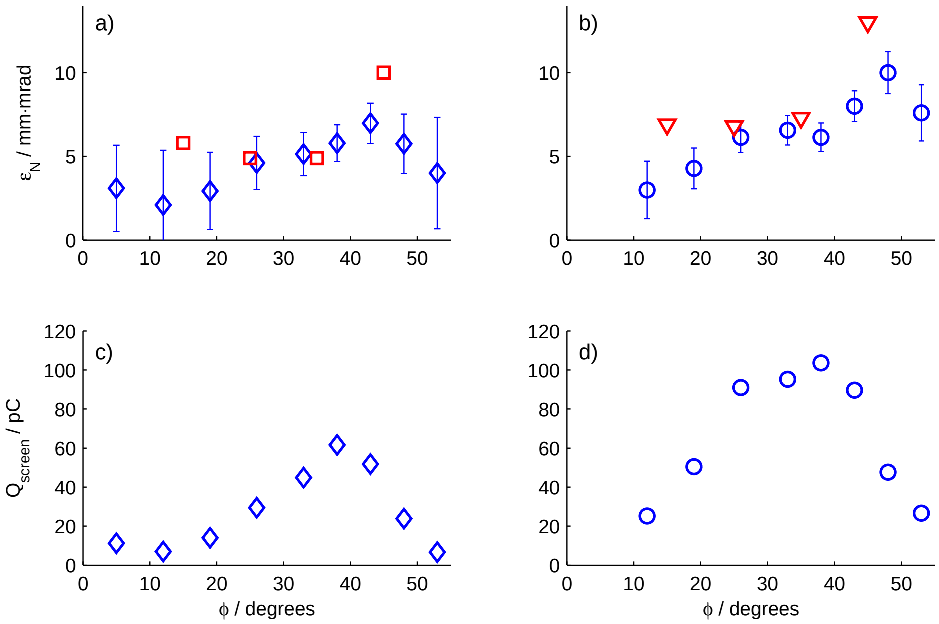

Figure 4: Emittance dependence on RF phase for two different charges being extracted (a) 110 pC directly after the gun plus simulation with PARMELA (red squares)(b) 220 pC directly after the gun plus simulation expectations in PARMELA (red triangles)(experimental data has error bars); (c) and (d) corresponding charge that is transmitted through energy filter.

ergy was changed to give the same extracted charge from the gun and the settings on the energy filter were kept constant. Figures 4(a) and 4(b) also show comparisons with simulations done in PARMELA [5], the measurements do not agree well with the simulation where the energy filter is scraping off electrons since the tracking code does not take that into account, but they agree well in the middle range. To reach 70 pC (100 pC) at CT2 extraction of 110 pC (220 pC) from the gun is needed and that results in an emittance of 5.5 mm mrad (7 mm mrad).

Emittance of the cathode is dependant both on the excess photon energy and the cathode temperature. Normalized emittance is given by [6]

$$\epsilon_{n,rms} = \frac{R}{2}\sqrt{\frac{2}{m_e c^2}\left(\frac{\Delta E}{3} + kT\right)} \qquad (1)$$

where R is cathode radius, ΔE excess photon energy (incident energy minus work-function), and T the temperature of the cathode (m_e, c, and k are electron mass, the speed of light and Boltzmann's constant). The work-function for BaO can be as low as 2.4 eV [7] which gives ΔE of 4.7 eV - 2.4 eV = 2.3 eV. The cathode temperature T has two contributions, one coming from the fact that the cathode is kept on some temperature and the other one from the laser heating it (total maximum 1000°C). Characteristic of thermionic emission is non-linear growth of charge with the temperature, while our measurements show linear growth of the charge with temperature (proportional to deposited laser energy). This linear dependence is a characteristic of photoemission. The thermal emission is not dominant process; in fact, the pre-heating and excess energy give an emittance increase of about 0.9 mmmrad (dominated by excess energy), which is low enough not to influence these measurements (less than 10% of the charge is created in processes other than photoemission).

CONCLUSION

The performance characteristics of a thermionic gun, working as a photocathode gun with no major adjustments has been tested. The quantum efficiency was measured to be 1.1×10^{-4} and the emittance 5.5 mmmrad (normalized) can be achieved at a charge of 70 pC which would be sufficient for test-FEL operation. Tungsten impregnated BaO performs well, specially when one accounts the not so high requirements in laser power. Since it is easily switched between thermionic and photoelectric mode of operation, its versatility could be used for conventional storage ring injection, single bunch pattern injection and the test-FEL.

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