RESULTS OF THE PSI DIODE-RF GUN TEST STAND OPERATION

F. Le Pimpec, B. Beutner, H.H. Braun, R. Ganter, C. Gough, C.P. Hauri, R. Ischebeck, S. Ivkovic, K. Li, M. Paraliev, M. Pedrozzi, T. Schietinger, B. Steffen, A. Trisorio
Paul Scherrer Institut, 5232 Villigen, Switzerland

Abstract

In the framework of the SwissFEL project, an alternative electron source to an RF photo-gun was investigated. It consists of a high voltage (up to 500 kV), high gradient pulsed diode system followed by single stage RF acceleration at 1.5 GHz. The electrons are produced from photocathodes or from field emitter arrays. The final goal of this accelerator is to produce a 200 pC electron beam with a projected normalized emittance below 0.4 mm.mrad and a bunch length of less than 10 ps. We present comparisons between beam dynamics simulations and measurements, as well as thermal emittance and quantum efficiency (QE) measurements obtained by producing photo-electrons from various metal cathodes.

ACCELERATOR BEAM LINE

The accelerator beam line, operating at 10 Hz repetition rate, is shown in Fig.1. The elliptical electrodes and their polishing procedure, the 500 kV pulser, the diagnostic beam line and the laser systems have been described in details in [1, 2, 3].

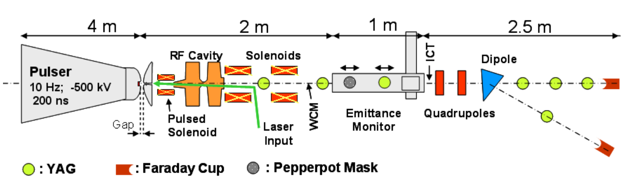

Figure 1: Accelerator beam line including the 500 kV pulser and the 2 cells 1.5 GHz RF structure.

The PFN driven pulser uses a Tesla coil to generate a damped oscillating waveform with a dominant negative peak voltage (250 ns FWHM). The peak voltage is stable to ±0.1% and is adjustable 0-500 kV [4, 5]. The gap between the electrodes is adjustable 0-30 mm, and allows easy exchange of electrodes. The zero location of the beam line is taken at the anode position. For mechanical constraints, the anode is separated from the RF cavity entrance plane by a drift distance of 166 mm. To prevent an expansion of the beam during this drift and to match the beam size to the RF acceleration cavity, a pulsed solenoid is installed 51 mm after the anode iris, Fig.2. The two-cell RF cavity, Fig.1 and 2, has a frequency of 1.5 GHz and is fed with an RF forward power of 4 MW to 5 MW with 5 μs pulses, corresponding to an accelerating gradient between 40 and 45 MV/m [6].

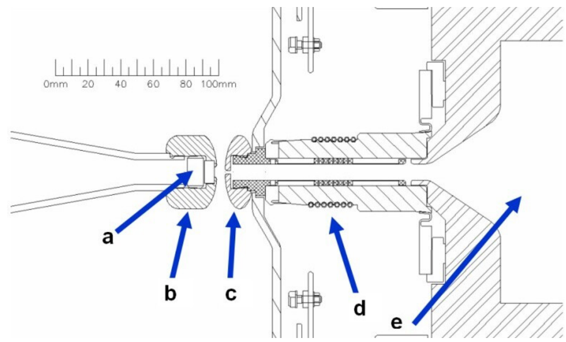

Figure 2: Electron source layout, a) insert, b) hollow cathode, c) anode, d) pulsed solenoid, e) RF cavity

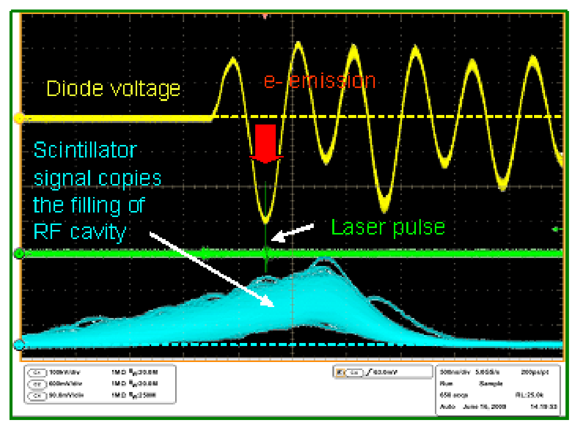

Figure 3: Measured waveform of the HV pulse 300 kV (upper trace) and X-ray scintillator signal lower trace.

Two independent laser systems were used for the results presented here: a Nd:YLF regenerative laser system providing 262 nm laser wavelength and a Ti:sapphire based system which provides laser pulses with wavelength ranging between 262 nm and 282 nm. Both laser have a uniform transverse profile with a diameter D (0.5 mm $<$ D $<$ 1.8 mm) and a Gaussian longitudinal profile with a duration, $\sigma_{\rm laser}$ = 4 ps (rms). With this duration, the electron beam sees a quasi DC acceleration coming from the pulsed diode, Fig.3. The X-ray (XR) signal seen in Fig.3 correspond to X-rays produced mainly by the RF dark current. During sole diode operation, no dark current is detected along the beam line. XR scintillator is used for machine protection system. A "breakdown" could be triggered by sole RF activity. An electrode breakdown is characterized by correlating the cathode voltage and the XR signals waveform, as well as observing the electrode camera. [1].

MODELLING AND EXPERIMENTAL RESULTS

The SwissFEL requirements for projected normalized emittance are 0.3 (0.6) mm.mrad for 10 (200) pC, at undulator entrance. We have measured normalized emittances of 0.2 mm.mrad and 2 mm.mrad, respectively, Fig.4. A 5 MeV electron beam extracted from a Cu insert after 50 MV/m (300 kV) diode and RF acceleration and with charges from ∼0 to 200 pC was used to compare measurement to ASTRA simulation [7]. Results are overlayed on Fig.4. Modification of the "hollow cathode" geometry, and using a uniform laser profile (transverse and longitudinal) should enable us to approach the requirements.

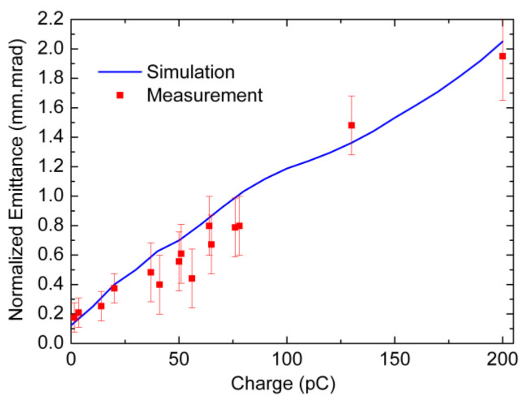

Figure 4: Comparison of normalized emittance measurement, using an hollow cathode, and ASTRA simulation vs charge (pC), using 90% of the charge.

Thermal emittance measurement at 274 nm using two different methods, Fig.5, are well reproducible and match well equation 1 [8].

$$\varepsilon_{\text{thermal}} = \sigma_x \times \sqrt{\frac{h\nu - \Phi_0 + e^{\,3/2}.\sqrt{\frac{E}{4\pi\epsilon_0}}}{3m_0c^2}} \tag{1}$$

Where the parameters are in SI unit : σ_x the RMS horizontal beam size, Φ_0 the work function of a technical metal, which differs from an atomically clean surface, e the elementary charge and E the applied electric field.

The thermal emittance is directly proportional to the laser spot size and measurements of projected emittance at very low charge ($<$ 1 pC, space charge effects can be neglected) and short pulse duration ($<$ 3 ps) approach this theoretical value. Fig.5, illustrates measurements carried out on single crystal Nb(110) insert as well as on a polycrystalline Cu. The agreement between the two measurement methods (Pepper-pot and solenoid scan) are good. The theoretical slope matches the data points if one assumes a work function of 4.13 eV for Nb(110). The values of Φ_0 of atomically clean and oxidized Nb(110) are respectively ∼4.8 eV and ∼4.4 eV [9]. Our Nb(110) is not atomically clean and has a RMS roughness of ∼500 nm. The Schottky effect due to the applied electric field (∼ 25 MV/m) reduces the barrier further to around 3.93 eV. The initial kinetic energy of electrons is about 0.6 eV when using 274 nm photons (4.53 eV). More measurements were performed on OFE Cu with a varying laser wavelength, to minimize the initial kinetic energy of electrons. The results are published in [3, 10].

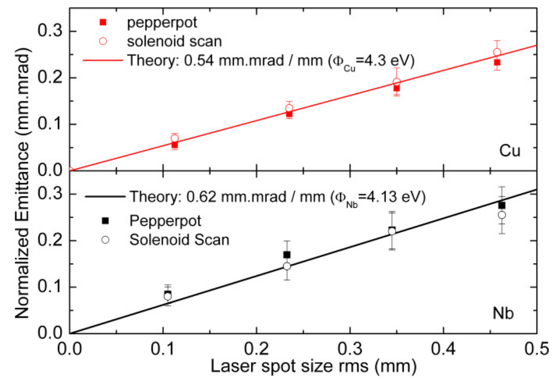

Figure 5: Normalized thermal emittance of Cu and Nb(110) insert vs laser spot size at 274 nm.

HOLLOW CATHODE GEOMETRY AND QUANTUM EFFICIENCY

Hollow cathode, Fig.2, have been designed to accommodate, and exchange easily, either a 14 mm diameter piece of metal used as a photo-cathode (Cu, Mg, Nb, Bronze, etc.) or a field emitter array insert [11]. Both electrodes are coated with a diamond like film (DLC) of 2 μm, which easily holds off 100 MV/m [12, 13]. All inserts have been prepared following the in-house polishing recipe described in [1]. On-axis electric field at the insert surface is about half of the accelerating field. The combination of a uniform transverse profile from the Ti:Sa laser and the DLC cathode brings a reduction in emittance at the exit of the diode due to electrostatic focusing of the cathode lips. The ASTRA simulation, Fig.6 (pulser voltage vs electrode gap), shows the emittance monitored at the exit of the anode hole from two different cathode openings (center hole as shown in Fig.2). Normalized emittance measured, 2.1 m downstream of the anode, at constant voltage and charge (500 kV - 200 pC) with a Nb(110) insert, a DLC cathode of 3 mm opening, and for 80 MV/m and 100 MV/m field gradient was ∼1.1 mm.mrad and ∼1.4 mm.mrad respectively, which is 20% to 40% higher than simulated at the exit of the diode. Those values although significantly above predictions are nevertheless better than what was achieved with elliptical cathodes. In addition to emittance measurement, QE measurements were carried out, Fig. 7. Cu QE presented here are slightly lower (factor 2) than as received Cu measured, Fig.9 in [1]. When using equation.10 in [8] at 266 nm, 28 MV/m and using Φ_0 and reflectivity from the literature for atomically clean material one finds that

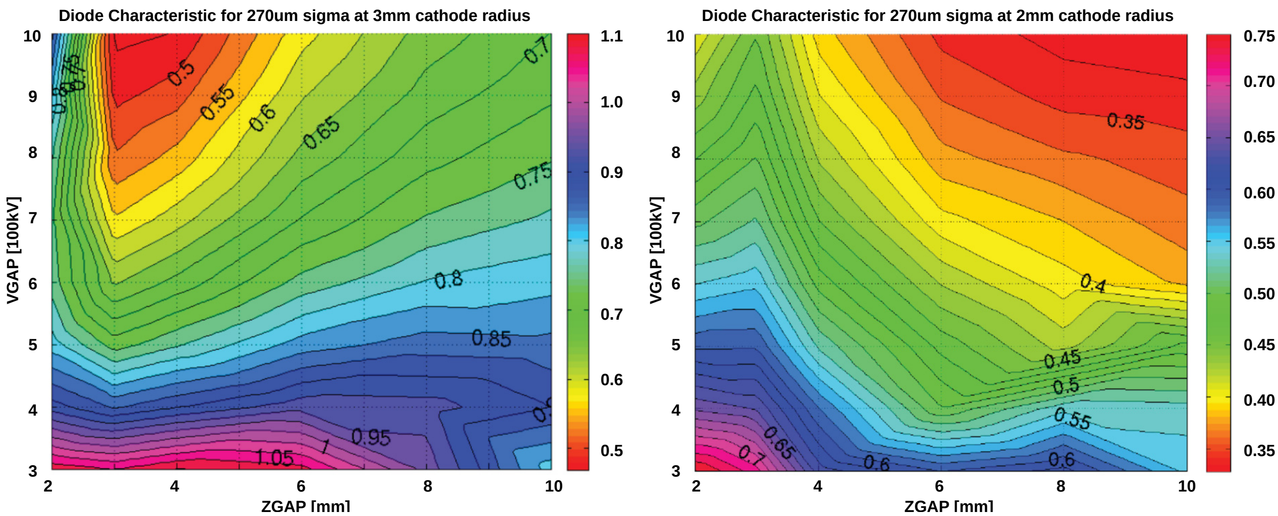

Figure 6: Emittance map simulation (with 200 pC) at the exit of the diode configuration with a hollow cathode opening of radius 3 mm (left) and 2 mm (right), using the uniform (transverse and longitudinal) Ti:Sa Laser beam.

QE of Cu (Al) is almost a factor 10 above (lower) from the measurements. The QE, in Fig.7, seems insensitive to the field gradient, which is rather surprising comparing to theory. A variation of Φ_0 of 30 meV due to Schottky effect can make the QE jump by a factor 2. However, this behaviour was seen previously for as-installed Cu. QE sensitivity to gradient is more marked after a longer period of operation, Fig.9 in [1].

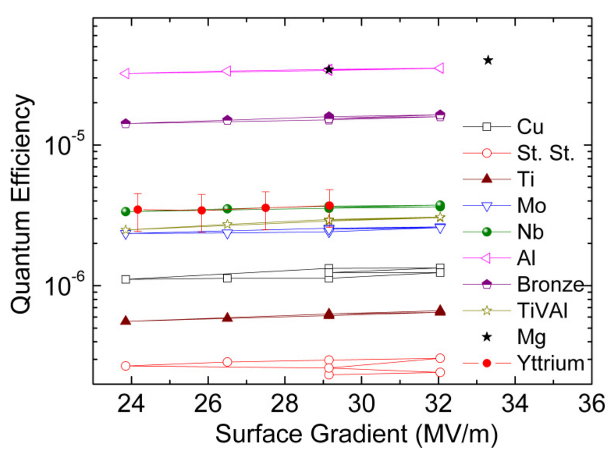

Figure 7: QE of various insert vs insert surface field at 266 nm.

CONCLUSION

Emittance comparison between ASTRA simulation and experiments have shown very good agreement. Simulations predict better emittances at the exit of the diode when using a 2 mm, instead of 3 mm, opening for the hollow cathode. Good agreement between thermal emittances theory and measurements were also found. The nature of the surface preparation (chemistry and roughness) affects strongly the QE of the materials. One can use the theory, using parameters for atomically clean material, to have an estimate of the QE of a technical surface in an order of magnitude.

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