PERFORMANCE TESTS OF FIELD EMISSION SOURCES FOR A LOW EMITTANCE GUN

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The properties of the electron source define the ultimate limit of the beam emittance in linear accelerators. Photocathodes and thermionic cathodes are currently the most used electron sources. At PSI, we want to explore electron sources based on field emission, since higher current density and smaller initial kinetic energy (cold electrons) can be obtained with this process. In field emission cathodes, sharp tips emit the electrons. Usually they are used for low current applications like scanning electron microscopes. For an accelerator gun we need much a higher peak current together with a good beam emittance. Two technologies are studied: individual needle tips and arrays of microscopic tips produced with microelectronic techniques. The first limitation to reach high peak current comes from the environmental conditions in the vacuum chamber which can easily lead to tip destruction. Very short electric pulses at low frequency together with careful processing of the cathode and the vacuum tube seem to be the path to follow to reach high peak current.

MOTIVATION

In a free electron laser undulator, the required normalized transverse electron beam emittance ε_n must satisfy the following condition:

$$4\pi\varepsilon_n < \lambda\gamma \quad (1)$$

where λ is the radiated wavelength and γ the relativistic factor. Small normalized beam emittance would considerably reduce the required beam energy and thus the cost and size of the accelerator facility (see companion report [1]). On the other hand a smaller emittance would also reduce the required minimum peak current to efficiently drive a free electron laser. Ultimately the emittance is limited by its initial value at the cathode which can be expressed as follows:

$$\varepsilon_n = \gamma \frac{r_c}{2}\sqrt{\frac{E_{r,kin}}{m_0 c^2}} \quad (2)$$

where r_c is the cathode radius and $E_{r,kin}$ the mean transverse kinetic energy just after emission. To lower the emittance one can reduce the size of the electron source (r_c) and/or the mean transverse energy of emitted electrons (roughly the initial divergence).

ELECTRON SOURCES

Current accelerator gun developments are mainly focused on photocathodes [2] or thermionic cathodes [3]. In the photoemission process the average kinetic energy $<E_{kin}>$ of produced electrons can be close to 1eV [2] due to the difference between photon energy hυ and cathode work function Φ (Fig. 1). A typical current density obtained with a photocathode is around 10^4 A/cm^2. Photocathodes are illuminated by laser pulses and thus they can produce very short electron bunches (~ 20ps). With thermionic cathodes the mean kinetic energy is smaller and related to the temperature of the cathode (~ 300 meV). Thermionic cathodes are also more stable and robust than other types of electron sources. However the maximum current density stays below 10^2 A/cm^2 which leads to larger beam diameters than with photocathodes.

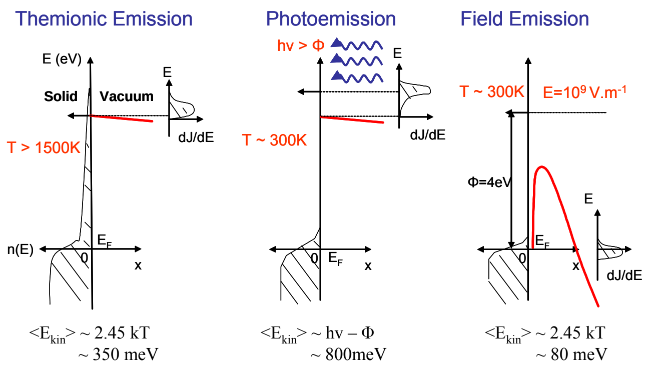

Fig. 1: Energy diagrams showing the three emission processes: thermionic emission, field emission and photoemission in an ideal one dimensional case.

One alternative process to photoemission or thermionic emission is field emission where electrons are emitted by the tunneling effect with energies around the Fermi level E_F (Fig. 1). With field emission the mean kinetic energy is also related to the temperature of the cathode which is smaller than in a thermionic cathode (~ 100 meV). The mean transverse energy is then mainly determined by the geometry of the electric field lines [4,5]. The achievable current density by field emission is also much higher than with any other type of cathodes (up to 10^9 A/cm^2) so that the emitting area could be very small. Field emission cathodes are usually made with tips: either a needle tip obtained by etching a thin wire (ø ~ 0.5 mm) or an array of microscopic gated tips produced with microelectronic techniques. In those field emitter arrays (FEAs), thousands of conductive tips in the micrometer size range can be deposited on an area of one millimeter in diameter. They are separated from a conductive gate layer by a one micrometer thick dielectric layer (Fig. 2 and 3). By applying a voltage between the tips and the gate layer (V_{ge}), electrons are emitted from tip's apexes. In order to shape electron trajectories, FEAs can integrate two grid layers. The first grid is used for extracting the electrons while the second grid provides focusing of the electrons. At the difference of FEAs, needle tip cathodes do not have integrated gate. However, they can be mounted like thermionic cathodes so that they can be heated. Heating the tip helps to clean and smoothen the apex surface. Also the radius and shape of the apex can be controlled if the appropriate heat and field is applied [6]. For a high peak current application such a needle tip would require a fairly large apex radius (around a few micrometers).

FIELD EMITTER LIMITS

To be a good candidate for a free electron laser application, the field emitting source must achieve peak currents of at least several amperes and produce a beam emittance between 10^{-8} and 10^{-7} m.rad (see companion report [1]).

In a first approach we focused our work on the maximum achievable emitted current. Typically a standard molybdenum tip (e.g. Spindt type from Fig. 3 with an apex radius ~ 50 nm) is capable of emitting a few microamperes in DC operation [7]. The limiting factor for higher current emission in DC operation is the excessive heating of the tip as well as the electron bombardment of surrounding materials (gate, anode, etc.). This leads to a series of thermally induced surface changes like desorption of contaminants or surface migration. When ionized, these desorbed contaminants can also bombard the tips backwards. Eventually, local pressure rise can initiate destructive arcs. These well known environmental problems are also responsible for current emission fluctuations by changing either the surface work function or the tip geometry [8]. Because of the strong dependence of field emitted current on the geometry of the tip (field enhancement factor β) and its surface composition (work function Φ), even small surface changes lead to strong variations in the current intensity. This can be illustrated by Fowler-Nordheim's equation which describes the dependence of the field emitted current density on these parameters:

$$J = C\frac{(\beta V)^2}{\Phi}\exp\left(\frac{10.4}{\sqrt{\Phi}}\right)\exp\left(\frac{-B\Phi^{3/2}}{\beta V}\right) \qquad (3)$$

where C, B are approximately constant (B~$6.4.10^{7}$, C~$1{,}5.10^{-6}$), V represents the applied voltage between electrodes, Φ is the work function in eV and β is the geometric field forming factor in cm^{-1} (E= βV, where E is the local electric field).

One way to increase the total emitted current without overheating is to apply very short electric pulses at low frequency. Several authors have mentioned the benefit of the pulsed mode of operation to extract higher current [9,10]. Ultimately the emission should stop before that tip surface reaches its melting temperature. For a typical 400 nm tip radius emitting one ampere, this limit can be reached in a few nanoseconds [6,11].

At PSI we investigated two kinds of field emission sources: individual tips inserted in a Vogel mounting without any extracting gate layer (Fig. 6) and FEAs made with microelectronic techniques (Fig. 2 and 3). Individual tips do not have the problem of uniformity and the emitting area defines the size of the electron beam (< 10 μm²). On the other hand they do not have a comparably narrow gate so that nanosecond pulses of several tens of kilovolts are needed to reach the required peak current [11]. In FEAs, up to 50'000 tips can be deposited on an area with one millimeter in diameter and thanks to the close spaced gate only a few hundred volts are needed. However, the uniformity becomes crucial and the current density is then averaged over the entire surface of the array.

PULSED MODE OF OPERATION

For these preliminary tests, we used cathodes available on the market. The SEM pictures in Fig. 2 and 3 represent diamond tips from the company XDI Inc [12] and molybdenum tips from SRI Inc [13] respectively. XDI's cathodes have around 3'000 tips distributed on a 170 μm diameter disc area. These diamond tips have a pyramidal shape due to the molding technique used for their fabrication. The tip material is a mixing of diamond and graphite which is electrically conductive [14]. Tips are surrounded by a dielectric material (SiO_2) which isolates them from the molybdenum gate layer. The typical height and base size of each tip as well as the gate aperture diameter is about one micrometer. The FEAs from SRI support around 50'000 molybdenum tips on a 1 mm diameter disc area. The dimensions of these conical tips are close to XDI's pyramidal tips but the growing method is different. SRI Inc. has developed the so called Spindt method [7] to grow molybdenum tips in a gated structure with nanometer tolerances. In order to test the emission of these gated structures we used a triode configuration. Field emitted current is measured on a one centimeter diameter collector tube positively biased with respect to the gate and tip voltages. In addition to FEAs, we also investigated the emission from single ZrC and HfC tips from the company APTech Inc. [15].

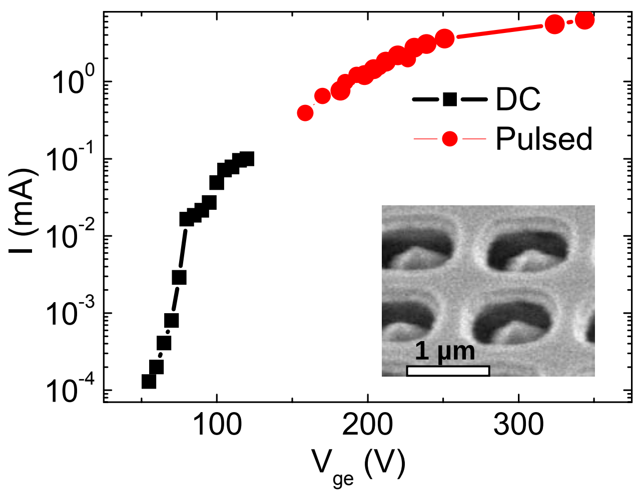

Fig. 2: Current voltage characteristic in DC and pulsed regime for a FEA from the company XDI Inc (~3,000 diamond tips, ø = 170 μm). Insert: SEM picture of diamond tips.

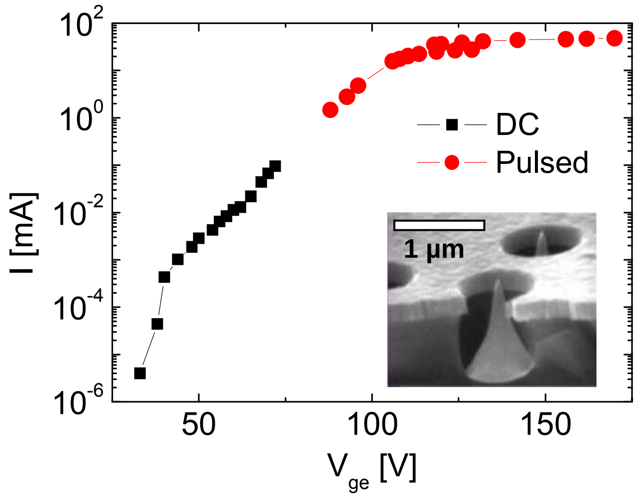

Fig. 3: Current voltage characteristic in DC and pulsed regime for a FEA from the company SRI Inc (50,000 Mo Tips, ø = 1000 µm). Insert: SEM picture of conical Mo tips (from SRI website) [13].

By operating the FEA with short voltage pulses at low frequency it is possible to considerably reduce the heat brought to the tips and therefore to eliminate most of the thermally induced problems. Consequently the emitted current can be increased with less risk of deterioration. Fig. 2 represents the emitted current versus the applied tip to gate voltage for an array of about 3,000 diamond tips distributed on a 200 micrometers diameter disc area.

The maximum current measured in continuous mode was about 800 µA but emission was subject to fluctuations and monotonic decay with time was observed as in [9,16]. However in the 50 Hz pulsed regime, with 100 ns long voltage pulses, it was possible to reach up to 6 mA peak current. In this mode of operation, emission was very stable and no decrease of the emitted current was observed after one day of operation. The maximum current performance was limited by the internal resistance of the field emitter array (~ 25 kΩ). This internal resistance originates from the silicon wafer on which the tips are deposited. In DC applications it is preferable to have a highly resistive silicon wafer in order to protect tips from brutal current rises. In a pulsed mode, a smaller resistivity could be tolerated. This internal resistance does also limit the minimum pulse length that can be applied between gate and tips by introducing a large charging time constant (the capacitance between gate and tip layers has been measured to be around 5 pF for these cathodes from XDI Inc.). Fig. 3 represents a similar current voltage characteristic but for a standard FEA from the company SRI Inc. This FEA consists of 50'000 Mo tips grown by the so called Spindt method [7] on a one millimeter diameter disc area. Again, the sensitivity to environmental conditions was much less important in the pulsed regime than in DC. The maximum current performance was limited by the silicon wafer resistance (6 kΩ) to values around 50 mA. Fig. 4 shows typical 100 ns current pulses collected from a 50'000 Mo tips FEA.

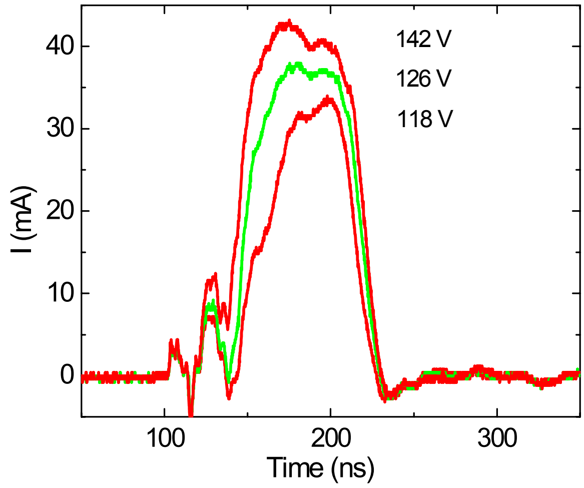

Fig. 4: Current pulses emitted by a FEA with 50,000 Mo tips from the company SRI Inc. when applying square voltage pulses with amplitude of 118, 126 and 142V.

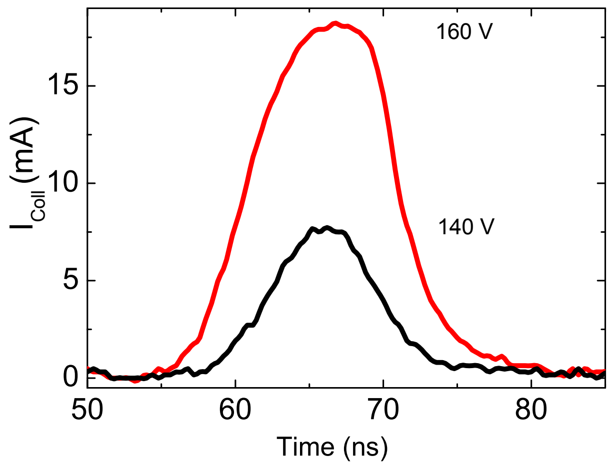

Fig. 5: Current pulses from a similar cathode than in Fig. 4 but having a lower wafer resistance. Two applied tip to gate voltages (140 and 160 V) are represented.

More recently FEAs with a lower wafer resistance have been purchased from SRI Inc. and are currently under tests. This second generation of cathodes can be driven with shorter pulses and should be able to reach higher peak currents. Fig. 5 shows 10 ns long current pulses collected from this second generation of SRI cathodes.

Fig. 6 represents the peak current performance from an individual tip of zirconium carbide (ZrC). Since this tip does not have any gate layer a copper anode has been placed five millimeter away from the tip and large voltage pulses (< 5 kilovolts) were applied. To protect the tip from too high current values, a 10 kΩ resistor was placed in series with the tip. The effect of the resistor is the slow charging ramp on the current pulses seen in Fig. 6. More than 3 mA peak current has been measured out of such a single tip. Only the apex of the ZrC tip emits and the tip apex radius is between 200 and 400 nm. The emission area for an individual tip can be approximated by $2r^2$ where r is the tip apex radius [17]. In the case of Fig. 6 this area is around 0.2 µm^2.

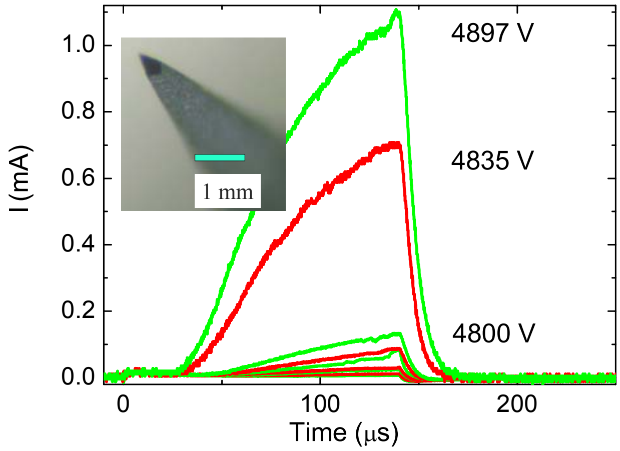

Fig. 6: Current pulses emitted by a single ZrC tip from the company APTech Inc. for different square voltage amplitudes of 100 microseconds.

The corresponding current density is then as high as 10^6 A/cm^2. With a typical beam divergence, for a single tip, around 20° [5] the initial emittance would be in this case already below 10^{-7} m.rad.

Literature reports measurements of several amperes out of a single blunted tungsten tip (see [6,11]). In these measurements they used nanosecond long voltage pulses with amplitudes higher than 50 kV. At PSI we tried to test such blunt tips (tip radius > 500 nm) for our gun application. The pulsed power supply used for the measurement shown in Fig. 6 cannot deliver more than 5 kV. To overcome the need of high voltage we developed a special support where a gate can be adjusted one millimeter away from the tip (Fig 7). Unfortunately the emitted current did not exceed one hundred microamperes and the tip was rapidly contaminated or damaged. In fact, a few percent of the total emitted current is intercepted by the gate which leads to a strong desorption and ion back bombardment. A power supply delivering pulses of 100 kV amplitude and a few nanoseconds duration has been purchased from FID GmbH. This pulser should enable us to reach high peak currents from individual tips as reported in [6,11].

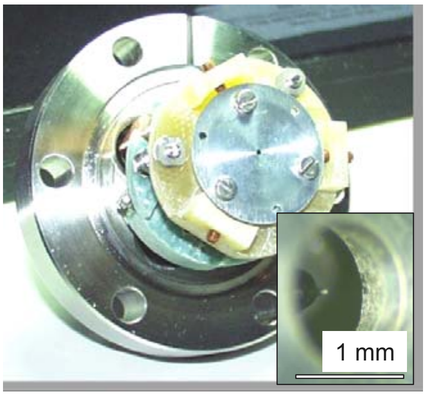

Fig. 7: Single tip cathode support developed at PSI – AMI. The aperture of the aluminum gate plate is one millimeter in diameter. The ZrC or HfC tip can be centered relative to the gate.

CONCLUSIONS AND OUTLOOK

Preliminary tests on commercial field emitter samples showed that higher peak current and more stable emission can be achieved when using short square voltage pulses at low frequency. For a free electron laser application such peak current values are still too small [1], but with the help of even shorter pulses and with FEA having a smaller internal resistance we hope to reach the required current.

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