PRELIMINARY RESULTS ON A LOW EMITTANCE GUN BASED ON FIELD EMISSION

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Abstract

The development of a new electron gun with the lowest possible emittance would help reduce the total length and cost of a free electron laser. Recent progress in vacuum microelectronics makes field emitter arrays (FEAs) an attractive technology to explore for high brightness sources. Indeed, several thousands of microscopic tips can be deposited on a 1 mm diameter area. Electrons are then extracted by a first grid layer close to the tip apex and focused by a second grid layer one micrometer above the tip apex. In order to be a good candidate for a low emittance gun, field emission cathodes must provide at least the peak current, stability and homogeneity of current state of the art electron sources. Smaller initial divergence should then be achieved by the focusing grid and the intrinsic properties of the field emission process. Another important aspect for improving electron guns is to preserve the emittance during beam acceleration.

MOTIVATIONS

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

$$4\pi\varepsilon_n < \lambda\gamma \tag{1}$$

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. 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:

$$\varepsilon_{n,rms} = \frac{r_c}{2}\sqrt{\frac{E_{r,kin}}{m_0 c^2}} \tag{2}$$

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).

FIELD EMISSION CATHODES

Current accelerator guns use photocathodes or thermionic cathodes [1]. In both cases, the mean transverse energy of the extracted electrons is several hundred milli-electronvolts due either to the difference between photon energy and cathode work function or to the cathode temperature. This already limits the minimum achievable initial transverse kinetic energy of the produced electron beam. One alternative technology is field emitter arrays (FEA) where electrons are emitted with energies close to the Fermi level and the mean transverse energy is mainly determined by the geometry of the electric field lines.

These FEAs consist of thousands of conductive tips in

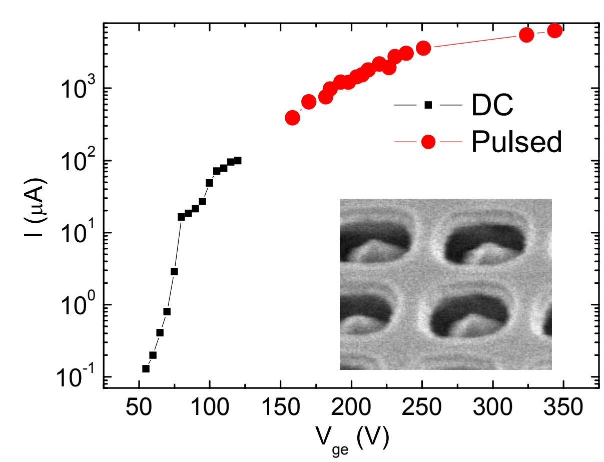

Figure 1: Current voltage characteristic in DC and pulsed regime for a FEA from the company XDI Inc (~3000 diamond tips). In caption: SEM picture of pyramidal diamond tips.

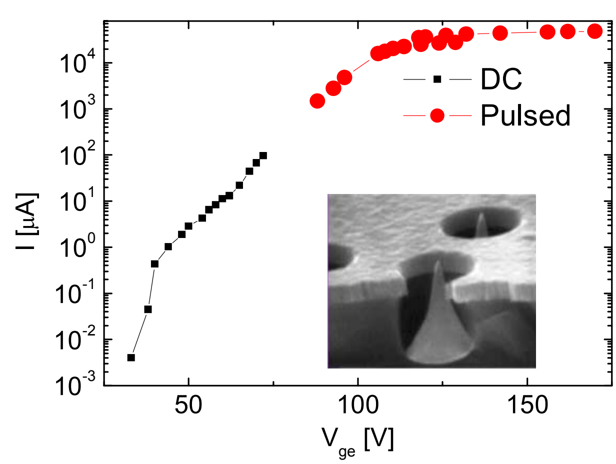

Figure 2: Current voltage characteristic in DC and pulsed regime for a FEA from the company SRI Inc (50000 Mo Tips) In caption: SEM picture of conical Mo tips from SRI website [3].

the micrometer size range separated from a conductive gate layer by a one micrometer thick dielectric layer (see Fig. 1 and 2). By applying a voltage between the tips and the gate layer (V_{ge}) electrons are emitted from the tip's apexes. In order to shape electron trajectories, FEAs can integrate two grid layers. The first grid extracts the electrons and the second focuses them.

Field Emitted Current

To be a good candidate for free electron laser application, FEAs must achieve a higher peak current than usual applications like flat panel displays or scanning electron microscopes. In addition, the field emitted beam must have small initial divergence due to the focusing layer together with a good uniformity and stability. In a first approach we focussed our work on the maximum emitted current performances. These tests concern cathodes available on the market. The SEM pictures in Fig. 1 and 2 represent diamond tips from the company XDI Inc [2] respectively molybdenum tips from SRI Inc [3]. A single tip in ZrC from APTech Inc. [4], without gate layer, has also been tested (Fig. 4). Field emitted current is measured on a collector positively biased in respect to gate and tip voltages.

In DC operation the limiting factor for high current emission in FEAs is the thermally induced desorption of atoms and the related contamination and sputtering problems. These well known environmental problems can lead to current emission fluctuations by changing either the work function or the tip geometry [5]. Local pressure rise can even lead to some destructive arcs. By operating the FEA with short voltage pulses at low frequency it is possible to considerably reduce these environmental problems. Consequently the emitted current can be increased with less risk of deterioration.

Fig. 1 represents the emitted current versus the applied tip to gate voltage for an array of ~3000 diamond tips distributed on an area of 170 micrometers in diameter.
The maximum current measured in continuous mode was ~800 µA but emission was subject to fluctuations and monotonic decay with time was observed [5]. By applying voltage pulses of 100ns at 50 Hz instead of DC voltage it was possible to reach up to 6 mA peak current. In this pulsed regime, emission was very stable in time and no decrease of the emitted current was observed after one day of operation. The maximum current performance was actually limited by the internal resistance of the field emitter array (~ 25 kΩ). This internal resistance also limits the minimum pulse width that can be applied between gate and tips. Fig. 2 represents a similar current voltage characteristic but for a standard FEA from the company SRI Inc. This FEA consists of 50000 Mo tips grown by the so called Spindt method [5] on an area of one millimeter in diameter. 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 to values around 50 mA (see Fig. 2). Fig. 3 shows the typical 100 ns current pulses collected from a 50000 Mo tips FEA.

Fig. 4 represents current pulses emitted by a single tip in ZrC. Since this tip does not have a gate layer, a copper anode has been placed five millimeter away from the tip and large voltage pulses (kilovolts) have been applied. As examples, some of the corresponding applied square voltage amplitudes are indicated on the graph. In order to protect the tip from too high current values, a 10 kΩ resistor is placed in series with the tip. That is why we observe a slow charging ramp on the current pulses of Fig. 4. Only the apex of the ZrC tip emits and the tip apex radius is less than one micrometer (specifications give values between 20 and 100 nm). If we assumed an emission area of one square micrometer, the corresponding current densities is as high as 10^5 A/cm^2.

High Gradient Acceleration

Another challenge in making a low emittance gun is to preserve the emittance against blow-up due to non-linear space charge effects. One approach in order to limit the emittance growth is to accelerate the produced beam with

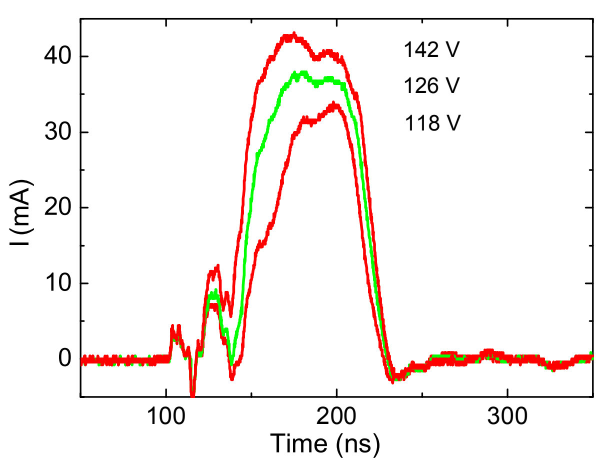

Figure 3: Current pulses emitted by a FEA with 50000 Mo tips from the company SRI Inc when applying square voltage pulses with an amplitude of 118, 126 and 142V.

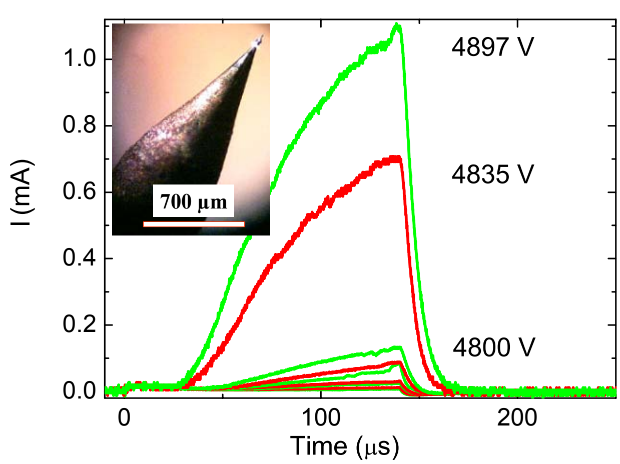

Figure 4: Current pulses emitted by a single ZrC tip from the company APTech Inc. for different square voltage amplitudes of 100 microseconds.

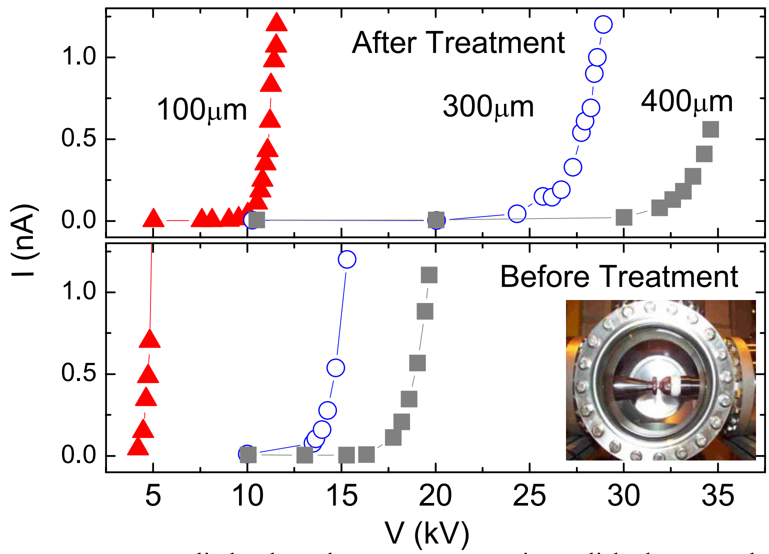

Figure 5: Dark current versus applied voltage between two massive polished copper electrodes (picture). The electrode gap is indicated beside each curve. The two graphs compare the effect of helium glow discharge treatment at 0.5 mbar, 1kV, 5 cm gap during 5 hours.

the highest possible gradient. The combination of a diode and a radiofrequency gun could be a solution to integrate a field emission cathode. The high electric gradient would then be applied between the cathode which integrates the FEA and the iris of the first radio frequency structure. When high electric field is applied between two massive metallic pieces unwanted field emission is generated from all the surface defects of the cathode support [6]. It is thus important to have some in-situ processing method to decrease dark current.

Fig. 5 represents the dark current measured between two massive copper electrodes of several square centimetres when DC voltage is applied. The corresponding gap between electrodes is indicated on Fig. 5. After helium plasma treatment of the cathode the required electric field for 1nA of dark current went from 50 MV/m to 100MV/m. Different materials, polishing and cleaning processes are under investigation in this test stand in order to reduce dark current in the diode part of the gun.

CONCLUSION

Preliminary results on peak current performance of certain field emitter samples showed that higher values and more stable current can be emitted with less contamination problems when using shorter square voltage pulses at low frequency. For a free electron laser application such peak current values are still too small, but with the help of even shorter pulses and smaller internal FEA resistance we hope to reach the required current. In parallel to field emission cathode evaluation, tests of integrating such cathodes in high electric gradients are under way.

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