ULTRA-LOW EMITTANCE ELECTRON GUN PROJECT FOR FEL APPLICATION

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Abstract

Most of the current 1 Å Free-Electron Laser (FEL) projects are based on thermionic or photocathode guns aiming at an electron beam emittance of 0.5 to 1 mm·mrad. The design of a gun capable of producing a beam with an emittance one order of magnitude lower than the state of the art would reduce considerably the cost and size of such a FEL. Due to the recent advances in nanotechnologies and vacuum microelectronics, a field-emitter based gun is a promising alternative scheme. We present first measurements on commercial field-emitter arrays as well as 3-D numerical simulations of the electron beam dynamics for typical bunch distributions generated from field emitters in realistic gun geometries.

MOTIVATIONS

In a LINAC-driven FEL, the normalized electron beam emittance ε_n has to satisfy the condition [1]:

$$\varepsilon_n < \beta\lambda\gamma / 2\pi L_g \ ,$$

where λ is the radiated wavelength, β the beta function, γ the relativistic factor and L_g the gain length. For a given wavelength, a small normalized beam emittance would considerably reduce the required beam energy and thus the cost and size of the accelerator facility [2]. The required peak current to drive efficiently a FEL is also reduced when the emittance is smaller. Moreover, the emittance is limited by its initial value at the cathode which can be expressed as follows:

$$\varepsilon_n = \frac{\gamma r_c}{2}\sqrt{\frac{E_{r,kin}}{m_o c^2}} \ ,$$

where r_c is the cathode radius and $E_{r,kin}$ the mean transverse kinetic energy just after emission. Reducing the the size of the cathode and the mean transverse energy of the emitted electrons leads then to a lower emittance.

FIELD-EMISSION CATHODES

The standard emission mechanisms of the cathodes used in the accelerator electron guns are photoemission and thermionic emission. In both cases, the mean transverse energy of the extracted electrons is several hundreds meV 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. In such cathodes, the mean transverse energy is mainly determined by the geometry of the electric field lines [3].

These FEAs consist of thousands of conductive tips in 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 V_{ge} between the tips and the gate layer electrons are emitted from the tip's apexes. Additional control of the electron trajectories can be achieved by integrating a focusing second grid layer.

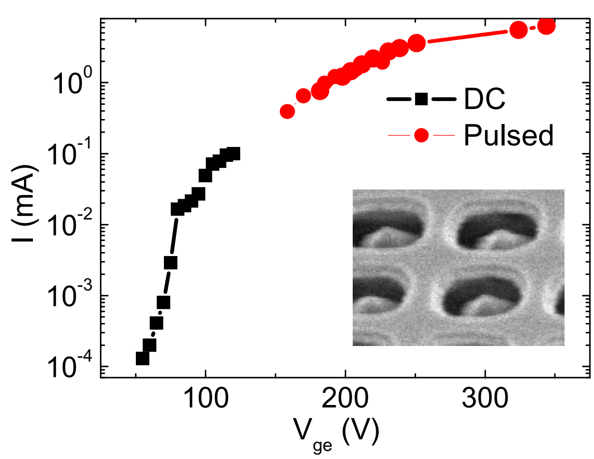

Figure 1: Current-voltage characteristic in DC and pulsed regime for a XDI Inc. FEA (170 µm diameter, 3,000 diamond tips). Insert: SEM picture of some pyramidal diamond tips.

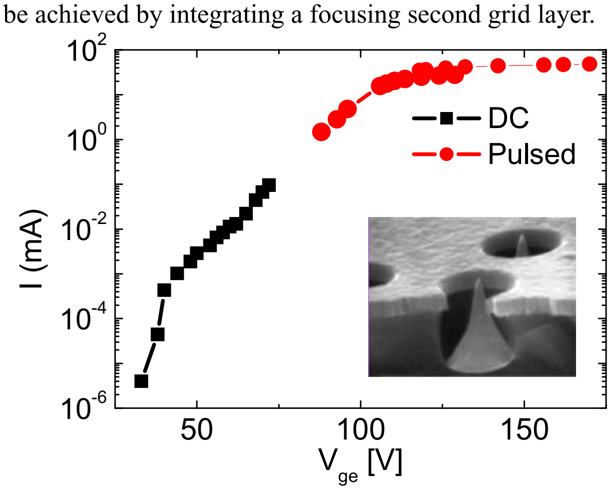

Figure 2: Current-voltage characteristic in DC and pulsed regime for a SRI Inc. FEA (1 µm diameter, 50,000 Mo tips) Insert: SEM picture of some conical Mo tips (SRI website [3]).

FIELD-EMITTED CURRENT MEASUREMENTS

The present work focuses on the maximum emitted current performances that can be obtained from FEA cathodes available on the market. The SEM pictures in Fig. 1 and 2 represent diamond tips from the company XDI Inc. [4] and molybdenum tips from SRI Inc. [5], respectively. A single tip in ZrC from APTech Inc. [6], without any gate layer, has been tested as well (Fig. 4). Field emitted currents were measured in a triode configuration where a collector was positively biased with respect to the gate layer and the tips.

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 [7]. Local pressure rise can even lead to some destructive arcs. By driving the FEAs with low-frequency short voltage pulses it is possible to reduce drastically these environmental problems. Consequently, the emitted current can be increased with less risk of deterioration.

Fig. 1 shows the variation of the emitted current with the applied tip-to-gate voltage for an XDI Inc. array of about 3,000 diamond tips. The tips were distributed on a 170 micrometers diameter disc area. The measured maximum current in the continuous mode was about 800 μA but emission was subject to fluctuations, a phenomenon already pointed out in [7]. Monotonic decay with time, also mentioned in [7], was observed as well. However, in the 50-Hz pulsed regime, with 100-ns applied 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 25-kΩ internal resistance of the field-emitter array. This internal resistance also limits the minimum pulse length that can be applied between the gate and the tips. The current-voltage characteristic for a standard FEA from SRI Inc. (Fig. 2) shows a similar behavior. This FEA consists of about 50,000 Mo tips grown by the so-called Spindt method [7] on an area of one millimeter in diameter. Again, the sensitivity to environmental conditions was much less important in the pulsed mode than in DC. The maximum emitted current was limited by the silicon wafer resistance to values around 50 mA (see Fig. 2). Fig. 3 shows the typical 100 ns collected current pulses collected with a SRI Inc. FEA.

Fig. 4 represents some collected current pulses for a single ZrC tip. Since this tip does not have any gate layer, a copper anode was placed five millimeter away from the tip and large (several kV) voltage pulses 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. 4. Only the apex of the ZrC tip emits, the tip apex radius being less than one micrometer (specifications give values between 20 and 100 nm). Assuming an emission area of one square micrometer, the corresponding current density is as high as 100 kA/cm^2.

3-D BEAM DYNAMICS SIMULATIONS

To assess the projected emittance and the slice emittance of an electron beam generated with a pulsed DC gun equipped with a field-emission cathode, MAFIA simulations have been performed for different cathode-anode geometries. The active emitter diameter was 0.5 mm and the electron bunches were assumed to have a longitudinal Gaussian distribution such that the rms bunch length was 8.3 ps (20 ps FWHM). The applied voltage between the cathode and the anode plate was 1 MV and the cathode-anode distance was varied from 10 mm to 1 mm leading to average electric fields ranging from 100 MV/m to 1 GV/m. The iris diameter in the anode plate was accordingly varied from 4 mm to 1 mm.

The variations of the projected and slice (1 ps long) emittances with the peak current are shown in Fig. 5 and

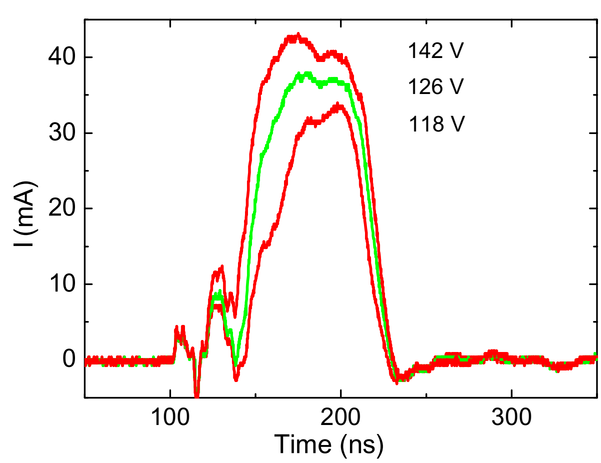

Figure 3: Collected current pulses for a SRI Inc. FEA with 50,000 Mo tips for 100 ns square applied voltage pulses of 118, 126 and 142 V.

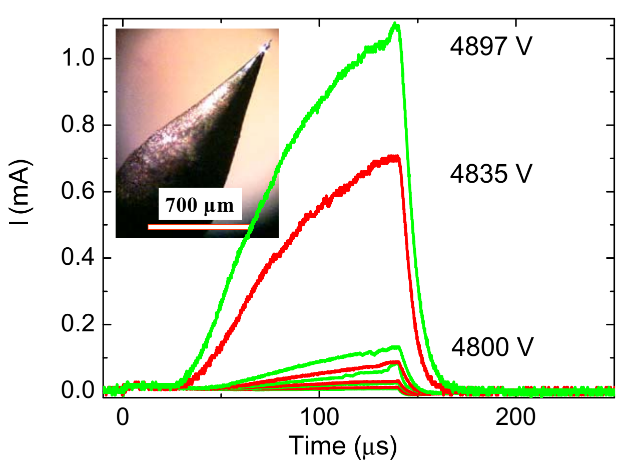

Figure 4: Collected current pulses for a single ZrC tip from APTech Inc. for different 100 μs square applied voltage pulses.

Fig. 6. For peak current below 100 mA, the projected emittances are constant for the considered four average electric fields and are less than 1.10^{-7} m·rad. In this range of peak currents the projected emittance decreases as the average electric field gradient is lowered. However, as a consequence of space-charge effects, above 5 A, there is a clear advantage to operate with large electric field gradient: the increase of the projected emittance is less pronounced as the field gradient gets higher. As for the slice emittance, similar conclusions can be drawn although the mechanism of dilution as the peak current gets higher is also due to the excitation of longitudinal wakes, a consequence of the temporal variation of the local bunch current density. In the 100 MV/m case, the slice emittance is about $0.1.10^{-7}$ m·rad for current below 100 mA and increases to reach 1.10^{-7} m·rad for a current of 10 A. In the 1 GV/M case, the slice emittance is constant and is slightly below $0.7.10^{-7}$ for peak currents less than 10 A, dilution occurring for higher currents. For currents above 25 A, the lowest slice emittance is obtained in the 1 GV/m field gradient case.

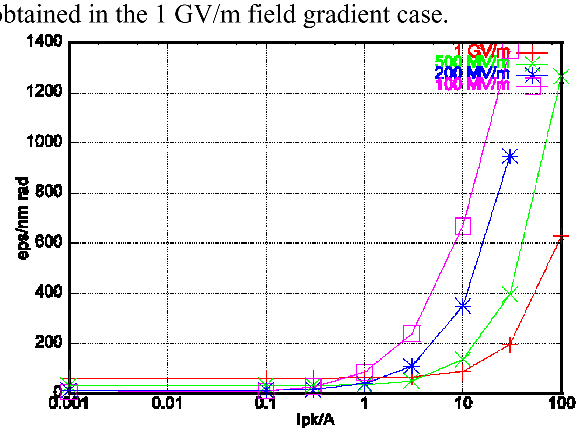

Figure 5: Projected emittance vs. peak current for a longitudinal Gaussian bunch distribution – DC gun configuration.

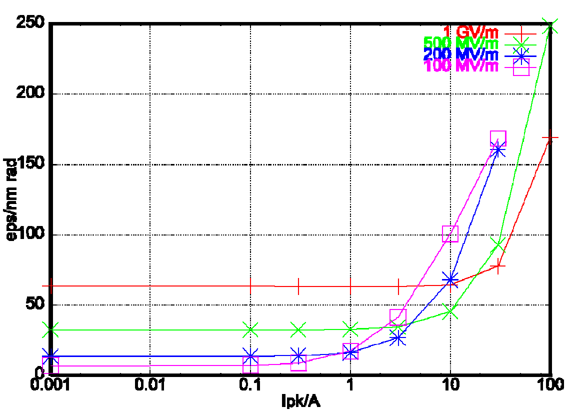

Figure 6: Slice emittance vs. peak current for a longitudinal Gaussian bunch distribution – DC gun configuration.

The above calculated emittances have been compared to the performances that could be obtained from a 3 GHz 2.5-cell RF gun configuration. MAFIA computations were performed with a modified version of a CLIC gun, the characteristics of which are described in [8]. In this RF gun, the active emitter diameter was reduced to 0.5 mm and the initial electric field gradient to 50 MV/m (peak gradient of 100 MV/m). The projected and the slice emittances along the axis of the RF structure are shown in Fig. 7 for a 3 A peak current. The projected emittance at the exit of the RF gun is about $3.6.10^{-7}$ m·rad, slightly higher than in the DC configuration. As for the slice emittance, it is about $0.25.10^{-7}$ m·rad, comparable with the value obtained in the DC gun configuration.

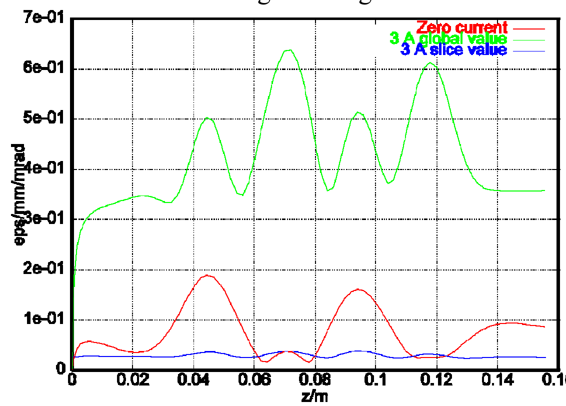

Figure 7: Emittances vs. distance – RF gun configuration.

CONCLUSIONS AND OUTLOOK

Some commercial field-emitter arrays have been tested and high and stable peak currents under pulsed operation have been obtained. For a free-electron laser application [2], the obtained peak currents are still too small. However, with shorter pulses and smaller internal FEA resistance, peak currents of at least a few amperes are expected. Beam dynamics simulations of such a cathode embedded in a DC gun configuration have shown that slice emittances smaller than $0.7.10^{-7}$ m·rad are achievable for peak currents smaller than 5 A and for an average electric field ranging from 100 MV/m to 1 GV/m. In parallel to field-emission cathode evaluations, a 100-kV gun test stand is under construction [9]. A 500-kV pulser is also under evaluation as well as studies of a combined DC/RF gun configuration.

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