HIGH CURRENT ELECTRON EMISSION FROM MICROSCOPIC TIPS

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Abstract

In order to find electron sources with low intrinsic emittance (< 5.10^{-8} m.rad) and high brigthness (B > 5.10^{13}A.m^{-2}.rad^{-2}), single tip field emitter as well as Field Emitter Arrays (FEAs) are investigated. By field emission very high current densities can be obtained (up to 10^{12}A.m^{-2}) from extremely small source sizes. Illumination of such field emitting sources by laser pulses (photo-field emission) gives in addition the possibility to pre-bunch the emission to very short pulse lengths. Maximum peak currents, measured from single tips of ZrC with a typical apex radius around one micrometer are presented. Voltage pulses of two nanoseconds duration and up to 50 kilovolts amplitude lead to field emission currents of several hundreds of milliamperes. By combining these electrical pulses with laser pulses, peak currents of several amperes were extracted from the tip apex. This high current emission mode is different from field emission or photo-field emission and has many similarities with the so-called explosive electron emission.

INTRODUCTION

Reducing the beam emittance while keeping high brightness is the most direct way to reduce cost and size of Free Electron Lasers (FELs). In linear accelerators, the parameters of the accelerated beam depend strongly on the performances of the electron gun. The beam emittance in the electron gun is ultimately limited by the intrinsic emittance at the electron source which can be expressed as follow [1,2]:

$$\varepsilon_{n,rms} = \frac{R}{2}\sqrt{\frac{2E_{kin}}{3mc^2}} \qquad (1)$$

where R is the beam radius in the case of a uniform radial distribution and E_{kin} is the mean transverse kinetic energy of emitted electrons (Maxwell energy distribution), m is the electron mass and c the speed of light. In order to reduce the thermal emittance one can either reduce the beam size (R) and/or the mean transverse kinetic energies (E_{kin}) of produced electrons. Field emitter arrays should be capable of producing electron beams with extremely low transverse kinetic energy due to a focusing electrode positioned just one micrometer after the emitting point [3-5]. A single tip electron source should also produce low emittance beam because of the extremely small emitting area (<1µm^2) [6]. Indeed, current densities as high as 10^{12} A.m^{-2} can be achieved by field emission [7]. In practice, the strong dependence of the field emitted current on the local field enhancement factor (down to nanometric scale) and on the local work function (which depends on contaminants, crystal orientation) makes this emission very difficult to control (breakdowns) and to stabilize (fluctuations). Laser illumination of field emission electron sources gave encouraging results in stabilising and increasing the total current emission [8]. If the regime of emission is dominated by photo-field emission, it should become possible to pre-bunch the emission down to 10-30ps with picosecond lasers while keeping high current densities.

LOW EMITTANCE GUN PROJECT

The goal of the Low Emittance Gun (LEG) Project [9] at Paul Scherrer Institute (PSI) is to produce electron bunches of 15ps rms duration with a normalized transverse emittance of 5.10^{-8}m.rad and a minimum peak current of 5.5A at an energy of 4 MeV (see also companion paper [10]). The requirement in peak current is already quite challenging for both FEAs and single tip cathodes. Furthermore, if the electron source is capable of reaching the targeted emittance then the acceleration of such a beam into the relativistic regime without emittance blow up remains very difficult. The LEG concept will combine diode and RF acceleration. A few millimeters gap will separate the electron source from the first radio frequency (RF) cavity. Voltage pulses of 0.5MV and 250ns duration will be applied across this diode gap at a repetition rate of 10Hz. The resulting high accelerating gradient should minimize the emittance growth caused by space charge forces. Comissioning of this high voltage pulser is under way at PSI [9]. After the diode gap the electron beam will enter the RF cavities. A two-frequencies RF cavity (1.5GHz and 4.5GHz) has been designed in order to obtain flat top acceleration waves which minimize the emittance dilution due to RF acceleration [11].

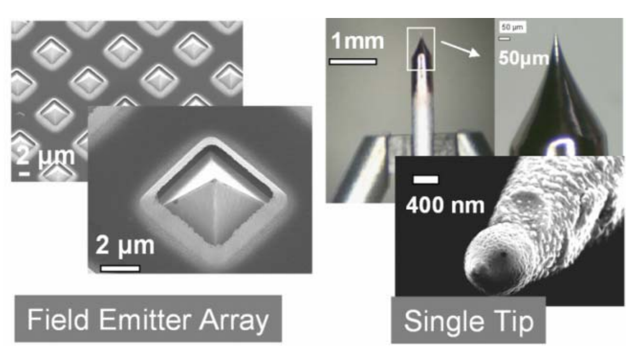

Figure 1: Field Emitter Array produced at PSI and single tip of ZrC from AP Tech Inc. .

The maximum peak current reached with commercial FEAs [12] was around 120 mA [8] for a one millimeter diameter array with 50000 tips. The main limitation comes from the non uniformity of the emission from tip to tip. The intrisic emittance of the same commercial single gated FEAs (no focusing grid) has recently been measured to be around 2.10^{-6}m.rad [13] for a one millimeter diameter cathode. Performances achieved with commercially available FEAs enabled us to better define the ideal FEA for LEG. PSI is currently developping an own production of FEAs based on a self aligned moulding technique. With this technology, pyramid shaped tips can be produced (see Fig. 1) which should better dissipate the heat and thus be able to carry more current. Since FEAs are still under development at PSI the rest of the paper will focus on single tip electron sources.

Single tips are produced by etching a wire which is then inserted in a so called Vogel mounting (see Fig. 1). This mounting allows current circulation and thus tip flash heating as well as field forming [14] of the apex. Metal carbides, like ZrC, are conductors with lower work functions (~ 3.5 eV) than commonly used W or Mo surfaces [15]. ZrC surfaces are also known to be more resistant against sputter damage and the threshold temperature for surface migration (~ 1500 K) is higher than for W or Mo surfaces [16]. We used commercially available ZrC tips from APTech Inc. [17] (McMinnville, USA). Field emission is always localised to small surface imperfections which have a smaller work function and / or a more favorable geometry for field enhancement so that current density goes rapidly to values as high as 10^{12} A/m^2 [7]. The consequence is a fast local heat up with an increased risk for a vacuum arc. The best way to limit the heat up is to emit during very short pulses and at low repetition rates. Nanosecond voltage pulses were applied to a ZrC tip in order to increase the emission current.

EXPERIMENTAL SETUP

Fig. 2 represents the experimental setup used to measure the emitted current from single tips of ZrC [17]. A fast pulser from the company FID GmbH delivering pulses up to 100 kV in amplitude and with 2ns duration (FWHM) at 10 Hz was connected to the tip. A special broad bandwidth (up to 1 GHz) coaxial vacuum feedthrough has been designed to feed the ZrC tip. The tip has a fairly large apex radius (r ~ 1 µm) and is positioned 1 mm behind an aluminium gate electrode (see inset in Fig. 2). The gate has a 2 mm diameter hole and is grounded. The faraday cup is also grounded and about 5 mm away from the tip apex on the same axis.

FIELD EMISSION FROM SINGLE TIPS

Fig. 3 represents the current pulses collected by the faraday cup when voltage pulses of amplitude V_{Tip} were applied to the tip.

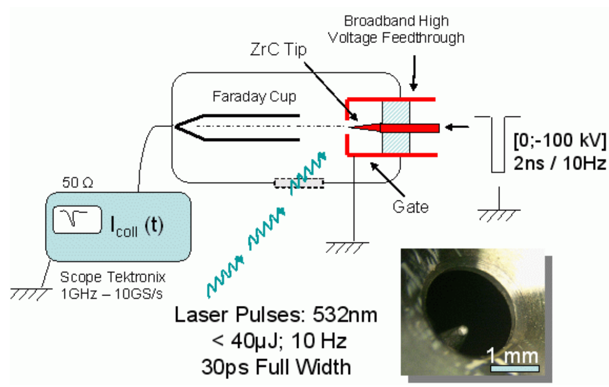

Figure 2: Experimental setup for pulsed field emission and photo-field emission tests.

Field emitted current starts to be detected at voltages around 20 kV (Fig. 3); peak currents as high as 460 mA were measured for applied voltages around 50kV. At this level of current, amplitude fluctuations became relevant (as illustrated by the two pulses at 51kV on Fig.3, left graph) and a monotonic decay of the amplitude was observed. Fluctuations usually indicate that the surface temperature became high enough to activate surface migration of contaminants which in turn change the field emission properties. At lower currents (Fig. 3, right graph), the emission was more stable and the current - voltage characteristics could be measured. These measurements are also represented in a Fowler-Nordheim (F-N) plot (Fig. 4, right graph). From the F-N plots, one can estimate the field enhancement factor β as well as the emitting area [18,19]. The local electric field F_{loc} at the tip apex is then defined as $F_{loc}= \beta.V_{Tip}$. A linear fit (see Fig. 4) of measured values gives $\beta \sim 2.10^5$ m^{-1} and an emitting area around $S \sim 10^4$ nm^2 (assuming a work function of 3.5eV for ZrC). This is consistent with a tip radius of 1 µm. With such a small emitting area and if we assume a divergence of sixty degrees [20] a rough estimate gives a normalized emittance less than 5.10^{-8}m.rad and a beam brightness around: $B \sim 10^{13}$ A.m^{-2}.rad^{-2}.

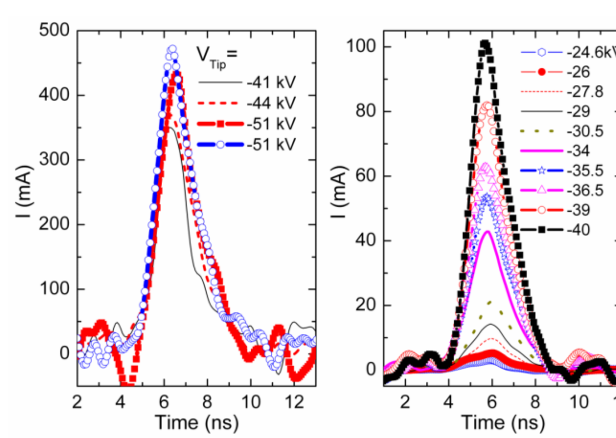

Figure 3: Current pulses collected on the faraday cup for different voltage pulse amplitudes V_{Tip}.

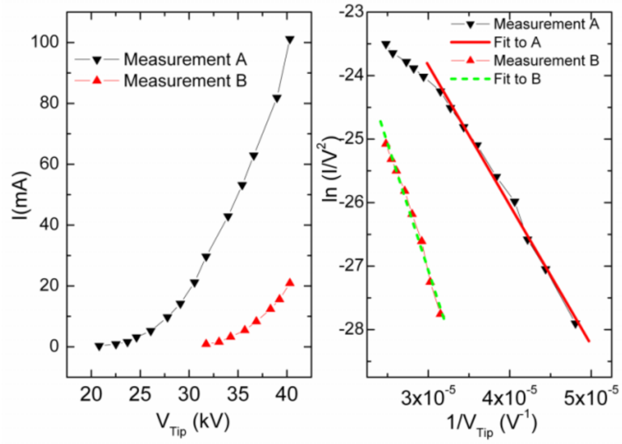

Figure 4: Current voltage characteristics acquired at 5 min interval (left) and Fowler-Nordheim representation of the same curves (right).

With the use of short (2ns) high voltage pulses at low repetition rate, it has been possible to limit the heat up of the tip and to increase the current that can be extracted from a ZrC tip up to 470 mA. For comparison, with a DC electric field, only currents below 10 µA could be safely extracted. However, these high current field emitted pulses revealed strong fluctuations in amplitude. The illumination of the tip with picosecond laser pulses should help to increase the stability and to reach higher peak currents.

LASER ASSISTED ELECTRON EMISSION

Laser assisted field emission [21] [22] is an interesting approach to combine the advantage of field emission (high brigthness) and laser photo-emission (stability, short time modulation). In the photo-field emission regime, the high electric field around the apex lowers the potential barrier of the crystal so that photoemission with large wavelength (λ>532nm) becomes possible and efficient. In previous experiments, similar ZrC tips were illuminated by laser pulses while a DC electric field was applied [8]. Peak currents as high as 580 mA were reached with 10ns long laser pulses of 532nm wavelength. Shorter laser pulses of 1ns (FWHM) at 1064nm produced photo-field current pulses of similar duration [23] suggesting the possibilty to pre-bunch the emission to even shorter levels. In consequence, we recently combined the voltage pulser presented in the first part of the paper with a picosecond laser from the company Time Bandwith Products (see Fig. 2).

The laser system provides 30 ps long laser pulses at 532 nm with a maximum energy per pulse of 40 µJ. The laser was focused on the tip apex with a lens positioned at the focal distance (200 mm) from the tip outside the vacuum chamber. Nanosecond voltage pulses were applied to a ZrC tip while laser pulses were illuminating the tip apex at a repetition rate of 10Hz. If emission is dominated by photo-field emission then the expected current pulse should be as short as 30 ps (FWHM). Unfortunately the bandwidth of our faraday cup (< 1GHz) limits the detection of such short current pulses. The incident laser energy per pulse can be varied between 1 and 40µJ. At low laser energy (<5 µJ/pulse) no change from the pure field emission mode was observed. Above 5 µJ, the current increased suddenly by one order of magnitude leading to the current pulses shown on Fig. 5.

Figure 5 represents the current pulses measured by the faraday cup when laser pulses (532 nm, 20 µJ, 10^8-10^9 W.cm^{-2}) were synchronised with the high voltage pulses for different voltage amplitude V_{Tip}. The collected peak current was as high as 5.5 A at a repetition rate of 10 Hz. The shape of the current pulse follows the applied voltage pulse (the satellite peak at t=3ns corresponds to a similar reflexion in the applied voltage). No significant jitter or amplitude variations were observed as it would be the case for vacuum breakdowns. No decay of the amplitude was observed after several hours of 10 Hz operation and pressure was stable around 10^{-8} mbar. This electron emission was probably not resulting from photo-field emission since it was lasting several nanoseconds. The dependence of the extracted current on laser energy (step like dependence) indicates that there is a threshold above which this large current emission is detected. This has much in common with the so called explosive electron emission (EEE) which is a kind of stable vacuum arc regime. EEE has been largely described by Mesyats [24] and Fursey [7,25]. EEE takes place when a large amount of energy is concentrated into a small volume (by joule effect or laser heating) which eventually explodes and generates a large flow of electrons together with other particles. The difference between this regime of EEE and normal vacuum arcs is the very good reproducibility and stability of the process. The quasi-stationary behaviour is based on the fact that at each explosion the surounding surface melts and some new micro protrusions (and nearly identical) arise which serve as new emitting centers.

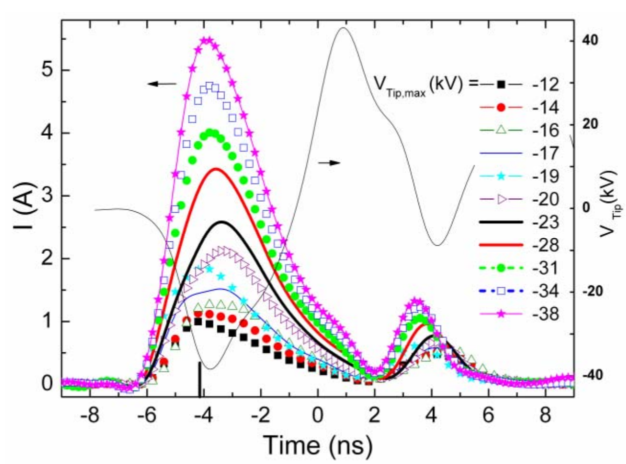

Figure 5: Current collected on the faraday cup when picosecond laser pulses were synchronised (at t ~ -4ns) with high voltage electrical pulses. One example of the voltage applied to the tip is also represented.

The current density during EEE can be extremely high usually above 10^{12} A.m^{-2} so that the size of the emitting center is small (around 1 μm). Further tests are required to better understand and estimate the interest of these large current pulses for a low emittance gun application.

CONCLUSION

Field emission naturally produces very large current density beam so that good performances in terms of beam emittance and beam brightness can be expected from a single tip. The consequence of large current density emission is a high risk of overheating with generation of vacuum arcs. For accelerator application field emission sources must provide a minimum peak current of several amperes. Pulsed field emission at low repetition rate showed that larger peak currents (from 10 μA in DC to almost 500 mA in pulsed mode) can be extracted from a single tip of ZrC. In order to reach LEG goals, photo-field emission is an attractive mechanism which allows time modulation with fast lasers. Preliminary tests of illumination of a tip with picosecond laser pulses while nanosecond voltage pulses are applied have been made. An interesting regime of electron emission (similar to explosive electron emission) delivering stable current pulses of several amperes has been observed. Further tests are still required to see if it has some relevance for a low emittance gun application.

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