STATUS OF THE LOW EMITTANCE GUN PROJECT BASED ON FIELD EMISSION

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The design of an electron gun capable of producing beams with an emittance one order of magnitude lower than current technology would reduce considerably the cost and size of a free electron laser radiating at 0.1nm. An electron source based on field emission is an attractive alternative for a high brightness source: thousands of high current density beams (10^8 A/cm^2) can be produced and individually focused. The development of a gun based on field emission cathodes implies many innovations in regards to current state of the art guns. The field emitter source will be inserted in a high-gradient diode configuration coupled with a radiofrequency (RF) structure. In the diode part a high electric field (several hundreds of MV/m) will limit the degradation of beam emittance due to space-charge effects. This first acceleration will be obtained with high voltage pulses (~500 kV in 500 ns) synchronized with the low voltage pulses applied between the tips and the extracting gate. This diode part will then be followed by an RF accelerating structure in order to bring the electrons to relativistic energies.

INTRODUCTION

A Free Electron Laser (FEL), driven by a single pass linear accelerator (linac), is today one of the most promising concept able to produce X-rays with laser-like properties and pulses shorter than 100 fs. The required beam energy to drive such an FEL can be considerably reduced if the normalized beam emittance is one order of magnitude smaller than current state of the art. This would allow a significant cost and size reduction of an FEL.

Ultimately, the normalized transverse emittance is limited by its initial value at the cathode which can be expressed as follows:

$$\varepsilon = \gamma \frac{r_c}{2} \sqrt{\frac{E_{r,kin}}{m_0 c^2}} \qquad (1)$$

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 the mean transverse energy of emitted electrons (roughly the initial divergence). In this project we are aiming at reducing both parameters thanks to field emission based cathodes. As a final target we would like to construct an electron source, capable to drive an FEL at 0.1 nm [1].

CONCEPT

Most of the accelerators use either photo-cathodes or thermionic cathodes. An alternative technology for generating electrons is a field emitter based cathode. Applications of field emitters for X-ray tubes and microwave tubes have already been explored in the past [2,3]. More recent studies report on the use of photo assisted field emission from needles for table top free electron laser applications [4].

At PSI we study the possibility of using field emitter tips (field emitter arrays or individual tips) for high quality beams in accelerator applications. Although the idea has already been proposed earlier [5-7], more recent progress in vacuum microelectronics and nanotechnology makes it worthwhile to reconsider field emitters for electron sources.

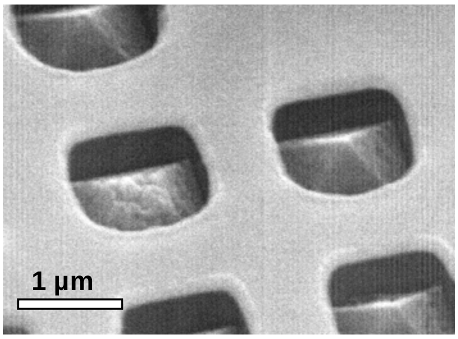

Fig. 1: Scanning electron microscope picture of gated diamond tips from XDI Inc. [8].

The major advantages of field emitters, compared to other types of cathodes are: the high achievable current density of the emission (up to 10^8 A/cm^2), and the small initial kinetic energy and energy spread of the emitted electrons (~0.2 eV). The latter is due to the fact that field emission is a tunneling effect where electrons are emitted with energies close to the Fermi level [6]. In field emitter arrays (FEAs), emission arises from tips located close to an extracting gate layer (Fig. 1 and Fig. 2).

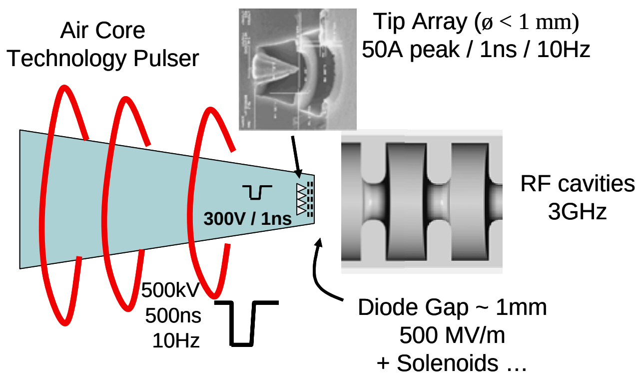

Fig. 2: Schematic of the gun concept, which combines diode acceleration with RF acceleration. Electrons are extracted by modulation of the gate layer and the first acceleration is given by high voltage pulses (SEM picture of tip taken from [9]).

In order to shape electron trajectories, FEAs can integrate a second gate layer, which focus the individual beamlets produced by each tip (Fig. 2). In our case, the height of the tips is about one micrometer, comparable to the distance between the apex and focusing layer. Typical emission areas per tip are about a few nanometers square [10]. In such field emitter cathodes, the emission bunching is achieved by pulsing the tip-to-gate voltage. After extracting and focusing the electrons, a high gradient acceleration is required to limit undesirable space charge effects. In addition, various magnetic guiding schemes are under investigation. Eventually, the field emission source will be inserted in the cathode side of a diode configuration. The anode would then be the aperture of an RF cavity (Fig. 2). This combination of diode and RF acceleration is inspired from the DC photogun built at TU Eindhoven [11]. In the diode gap, we hope to reach very high values of electric field gradients, i.e., higher than the values obtainable with RF acceleration. To reduce the probability of arcs, we will apply short voltage pulses (< 500 ns) between the cathode and the RF cavity at a low repetition rate (~10 Hz). The unwanted field-emitted current or dark-current will be minimized with conditioning methods, electrode geometry optimization and careful assembly.

This basic concept of this gun will serve to develop a first prototype. Problems that could affect the achievable beam emittance later, i.e., during further acceleration, are beyond the initial scope of this project. First we aim to evaluate the beam quality that could be obtained from a field emission gun.

PROJECT ACTIVITIES

To investigate the possibility of using field emitter tips for an improved electron gun, several activities are progressing in parallel.

Simulations

Standard MAFIA simulations of the beam dynamics at a micrometric scale (tip scale) as well as in the millimeter scale of the diode gap have been performed [12]. Further, to simulate the granularity of the beam emitted by a matrix with thousands of tips, a full 3D Maxwell solver using a particle-in-cell method has been developed [13] and compared with the 3D PIC solver of MAFIA. Simulations gave good agreement [14].

For Fig. 3 the 3D PIC code was used to simulate the non-uniformity of the emission from an FEA, when only a fraction of the total number of tips contributes to emission. The figure illustrates the evolution of field emitted particles when only 20 % of the FEA tips are emitting (see [12,13] for details). This preliminary simulation indicates that the normalized slice emittance can be four times larger than that of a uniform distribution of beamlets when 80 % of the tips are not emitting. Currently a refined version of this model is under development, where the initial condition is the distribution of the field enhancement factor on the array.

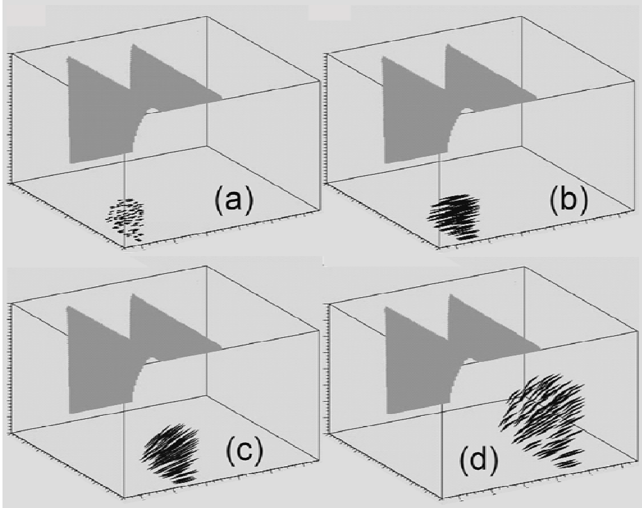

Fig. 3: Time evolution (*x*-axis) of the transverse particle distribution (*y,z*-axis) emitted by a matrix of individual emitters with 80 % failures: (a) at the cathode, (b) anode, (c,d) free drift after the anode iris.

Experimental Evaluations of Cathodes

Studies of field emitter arrays (or single tip) properties have been performed (see companion report [15]) on commercially available field emitters. First tests concerned a study on the maximum emitted peak current. To be a potential candidate for an FEL application, the cathode must be capable of emitting several amperes of peak current. It has been found that emission during short pulses (~100 ns) at low repetition rate (few Hz) prevents tips from overheating and thus enables larger emission intensities and better stability than in DC regime.

Field Emitter Arrays

With FEAs in the pulsed regime we reached saturation at 50 mA, due to the high resistivity of the silicon wafer. Better performance can be expected with a lower resistivity. Unfortunately this is a property difficult to obtain from commercially available emitters, which mainly aim at DC operation.

The peak current may also be increased with improved emission uniformity caused by geometric differences between tips, see Fig. 1.

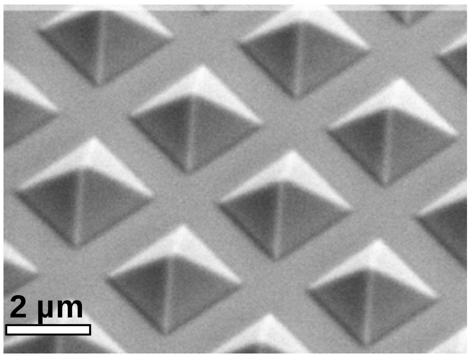

Fig. 4: Molybdenum tips, based on the technology from XDI Inc. [16], and further developed at PSI – LMN.

A specific test stand, called SAFEM (scanning anode field emission microscope [17]) has been assembled for studies.

In parallel we initiated the development of field emitter arrays at the micro and nanotechnology laboratory of PSI [18]. Fig. 4 represents an SEM picture of pyramidal tips developed at PSI. These tips have been obtained by the so-called molding technique [16].

Single Tips

With an individual ZrC tip without close by spaced gate layer we demonstrated a peak current of several milliamperes with microsecond long pulses [19]. This corresponds to a high brightness indeed, i.e., between 10^{11} and 10^{12} A/m^{-2}/rad^{-2} if we take into account the emitting area of 400 nm diameter, and assume an initial divergence angle of 20 degrees [7]. Such an individual tip represents an excellent source if it can emit several amperes as reported in [20]. To test such a single tip solution, an ultra-short high voltage pulser (100 kV, 3 ns) has been purchased [21].

High Gradient DIODE Acceleration

As described above, electrons are extracted from tips by a grid layer and focused by a second grid layer one micrometer above tip apexes. After this focusing layer, electrons enter a drift region until the aperture of the radiofrequency cavity. Between the focusing layer and the anode the electric gradient must be as high as possible in order to limit the emittance blow up due to space charge forces. Unfortunately, when a high electric field is applied between two massive metallic pieces, unwanted field emission is generated from all the surface defects of the cathode support [22]. This dark current must be as small as possible to limit its influence on the useful beam and the risks of arcs. Since the dark current is also a field emitted current, it depends on local field enhancement factors caused by surface irregularities (roughness, dust, etc.) and surface work function (e.g., adsorbed contaminants). When such a surface defect starts to emit current, it gets hot and can eventually lead to the generation of an arc. Hence, to achieve high gradient acceleration we need to prevent or eliminate local dark current emitters.

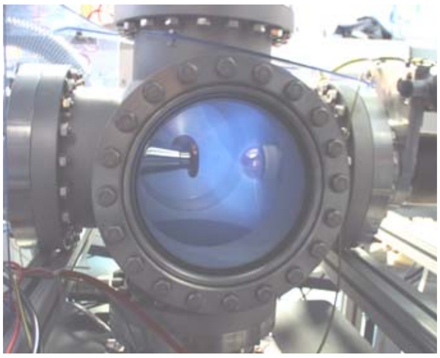

Fig. 5: Picture of the high gradient test stand during helium glow discharge treatment used for cleaning / polishing the electrodes.

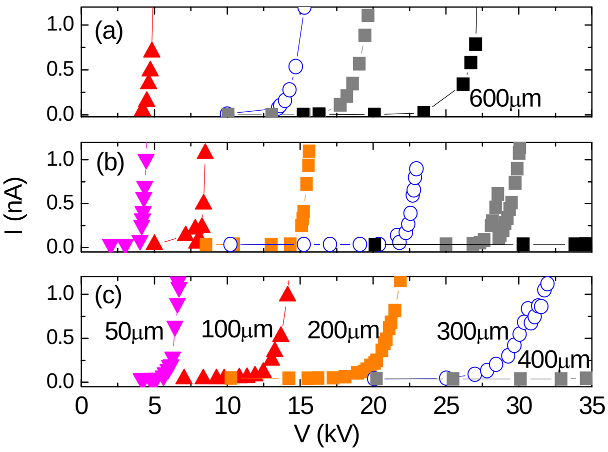

Fig. 6: Dark current versus applied DC voltage. The numbers 50 to 600 indicate the electrode gaps in µm. (a) Initial situation at 10^{-9} mbar, (b) after glow discharge treatment of electrodes for several hours and (c) after pulse conditioning (100 ns at 50 Hz).

Elimination of dark-current emitters may be achieved by surface polishing and cleaning. Prevention may also be obtained with short voltage pulses at low repetition rate, as it inhibits a temperature increase of the surface. For the latter, a pulser prototype (Fig. 7) based on air core technology and delivering pulses of 500 kV amplitude and 500 ns length is currently under construction at PSI [23].

For the elimination of dark-current we need good polishing and cleaning methods for the electrodes in addition to clean room conditions during the assembly. In addition, we are looking for some in-situ conditioning methods once the electrodes are sealed under vacuum. For this purpose, a specific test stand has been developed in order to test the field strength between two electrodes of similar size as it is foreseen for the final gun (Fig. 5). Fig. 6 represents the dark current measured between two massive copper electrodes of several square centimeters. After glow discharge treatment of the electrodes, the required electric field for 1 nA dark current increased from about 50 MV/m to 75 MV/m. After conditioning we applied a series of 100 ns voltage pulses between electrodes with a small gap in order to draw large dark current pulses.

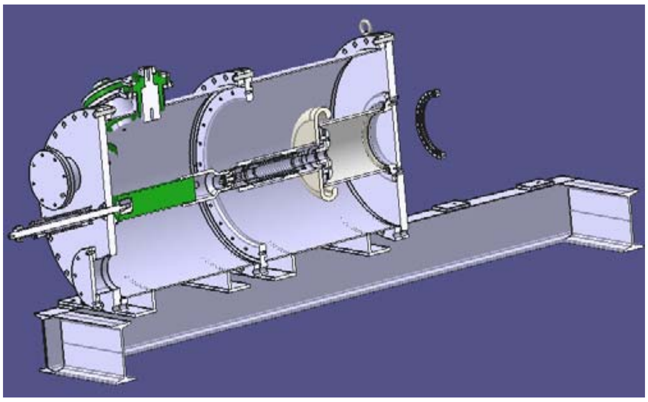

Fig. 7: High voltage tank containing the air core transformers for the 500-kV pulser developed at PSI.

These pulses tend to smoothen and blunt the surface defects. This method is similar to the one used for the conditioning of tips in field emitter arrays [24]. Other materials, as well as polishing and cleaning processes are under investigation in this test stand in order to investigate the reduction of dark current in the diode gap of the gun.

Beam Emittance Measurements

In addition to high-gradient acceleration, magnetic focusing schemes are considered for emittance preservation. For this a 100-keV DC gun test-stand is currently under construction [25]. The setup contains several beam diagnostic tools and will allow measurements of energy spread, beam current and beam emittance from field emitter cathodes.

CONCLUSIONS AND OUTLOOK

To achieve a high quality electron beam for free electron laser applications, a research project on a field emission based gun has been initiated. This gun would combine diode and RF acceleration and the electrons would be produced by field emission cathodes. Test stands development, beam dynamic simulations as well as preliminary studies of cathode properties are currently in progress. In parallel to field emission cathode evaluation, tests of such cathodes in high electric gradients are under way.

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