LOW EMITTANCE GUN PROJECT BASED ON FIELD EMISSION

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Abstract

The design of an electron gun capable of producing beam 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. Field emitter arrays (FEAs) including a gate and a focusing layer are an attractive technology for such high brightness sources. Electrons are extracted from micrometric tips thanks to voltage pulses applied between the gate and the tips. The focusing layer should then reduce the initial divergence of each emitted beamlet. This FEA will be inserted in a high-gradient diode configuration coupled with a radiofrequency (RF) structure. In the diode part the high electric field (several hundreds of MV/m) will limit the degradation of emittance due to space-charge effects. This first acceleration will be obtained with high voltage pulses (about one megavolt in a few hundreds of nanoseconds) synchronized with the low voltage pulses applied to the FEA (~ 200 – 300V in less than one nanosecond at a frequency lower than a kilohertz). This diode part will then be followed by an RF accelerating structure in order to bring the electrons to relativistic energies.

MOTIVATION

A Free Electron Laser (FEL), driven by a single pass linear accelerator (linac), is today the most promising mechanism able to produce 0.1 nm wavelength, with pulses shorter than 100 fs. In FELs, the electron beam emittance plays a major role in the laser saturation process. For an ideal electron-photon matching, the electron beam normalized emittance must satisfy the diffraction limit [1]:

$$\varepsilon < \frac{\beta}{L_G}\frac{\lambda\gamma}{4\pi} \qquad (1)$$

Where λ is the radiated wave length, γ the relativistic factor, β the beta function, L_G the gain length and ε the normalized emittance. This relation shows that the energy of the electron beam can be decreased, together with the linac length, provided that the emittance is sufficiently small. The electron source, with its initial emittance and current, becomes thus the first master piece of the driving accelerator.

Emittances on the order of 10^{-6}m.rad, and sufficient charge to drive an FEL, are presently achieved using RF photo-cathode guns. The linac energy for such a beam is in the 15-20 GeV range, for a peak current at the undulator between 2 and 5 kA. A substantial improvement (small linac, short gain length and relaxed peak current) would be achieved with emittances below 10^{-7}m.rad. Fig. 1 presents the FEL gain length versus the undulator period for different peak magnetic fields and normalized emittances of 1.2 mm.mrad and 0.1 mm.mrad. In these computations, it was assumed that the relative energy spread was 1.10^{-4}. Fig. 2 shows the required linac energy vs. the undulator period for three different undulator peak magnetic fields, the linac energy being determined by the resonance condition:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \qquad (2)$$

where λ_u is the undulator period, K=0.934 B[T] λ_u [cm] is the undulator deflecting parameter and B the peak undulator magnetic field.

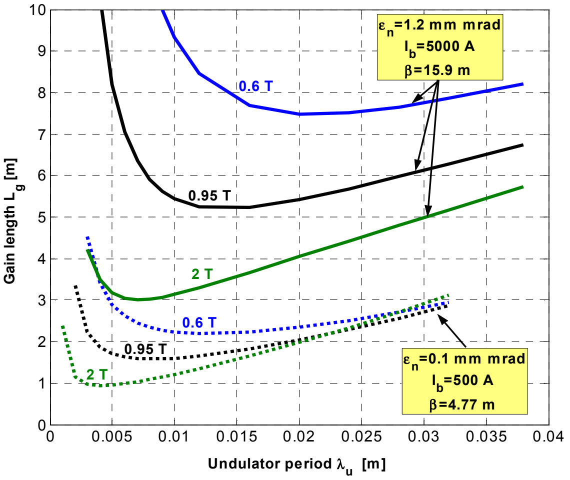

Figure 1: FEL gain length vs. undulator period for several undulator peak magnetic fields and two different electron beam emittances.

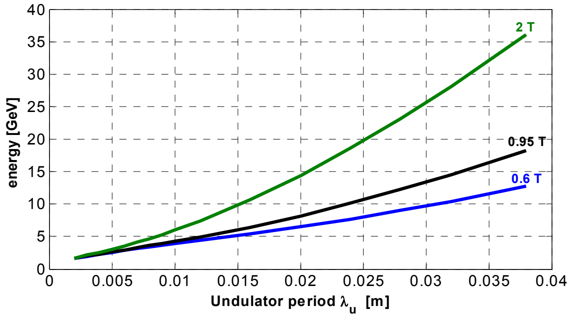

Figure 2: Beam energy vs. undulator period for several undulator peak magnetic fields.

The FEL parameters considered for these comparisons have been fixed accordingly.

As shown in Fig. 1 the required beam current and the FEL gain length can be considerably reduced by improving the electron beam properties (see also [2]). The size of the linac (Fig. 2) can be decreased as well, allowing an appreciable cost reduction of the accelerator facility.

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

$$\varepsilon = \gamma \frac{r_c}{2} \sqrt{\frac{E_{r,kin}}{m_0 c^2}} \qquad (3)$$

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). In this project we are aiming at reducing both parameters thanks to field emission based cathodes.

CONCEPT

Most of the accelerators use either photocathodes or thermionic cathodes. An alternative technology for generating electrons is field emitters based cathode. Applications of field emitters for X-ray tubes and microwave tubes have already been explored in the past [3,4]. More recent studies report on the use of photo assisted field emission from needles for table top free electron laser applications [5]. At Paul Scherrer Institut we are studying 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 [6-8], recent progress in vacuum microelectronics and nanotechnology makes field emitters an attractive solution for new electron sources. The best advantages of field emitters on other types of cathode are probably the high achievable current density of the emission (up to 10^8 A/cm^2) and the low temperature of the emitted electrons. Field emission is a tunneling effect where electrons are emitted with energies close to the Fermi level. They follow then mainly the electric field lines [7].

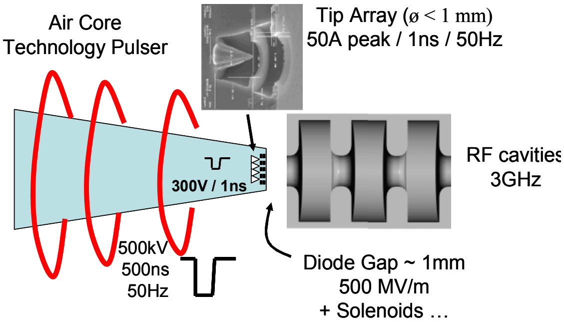

Figure 2: Schematic of the gun concept which combines diode acceleration with RF acceleration. Electrons are extracted by modulation of the gate layer and first acceleration is given by high voltage pulses (SEM picture of tip from [9])

In field emitter arrays, emission arises from tips thanks to a close spaced gate layer (see Fig. 2 and 3). In order to shape electron trajectories, FEAs can integrate a second grid layer which focus the individual beamlets produced by each tip (see Fig. 2). The tips height is about one micrometer as well as the distance apex - focusing layer. Typical emission area is about a few nanometers square per tip [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 space charge effects. The FEA will be inserted in the cathode side of a diode configuration. The anode would then be the iris of an RF cavity (see 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 gradient. Arc probability will be considerably reduced by applying short voltage pulses (< 500 ns) between the cathode and the anode at low repetition rate. The unwanted field emitted current or dark current will be minimized thanks to various conditioning methods, electrodes geometry optimization and careful assembling. Emittance compensation schemes will also be considered.

Many problems which could affect the achievable beam emittance are not solved yet. It is the aim of this project to evaluate the beam quality that could be obtained from field emitters.

PROJECT STATUS

In order to investigate the possibility of using field emitter tips to make an improved electron gun, several activities are progressing in parallel.

Cathode Evaluation

Preliminary studies of field emitter arrays (or single tip) properties have been performed (see companion paper [12]) on commercially available field emitters. First tests concerned the maximum emitted peak current. It has been

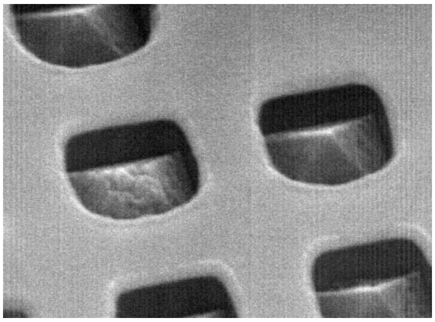

Figure 3: Scanning electron microscope picture of gated diamond tips from XDI Inc. [13].

found that emission during short pulses (~ 100 ns) at low repetition rate (few Hz) prevent tips from overheating and thus enable larger emission intensities and better stability than in DC regime. In this pulsed regime we finally reached the saturation of the FEAs at about 50 mA due to the highly resistive silicon wafer. This high silicon resistivity is required in DC operation but not for our application which use short emission pulses at low frequency. Another way to reach higher current is to increase the emission uniformity. During the fabrication of FEAs, geometric differences at the nanometric scale between tips lead to bad emission uniformity at initial turn on. Fig. 3 illustrates such differences between two neighbouring tips. A specific test stand, called SAFEM (scanning anode field emission microscope [14]) is under construction for studying non uniformities of the emission.

We also investigated characteristics from single tip in ZrC. We showed that such single tip in ZrC is capable of emitting several milliamperes during microsecond long pulses. This corresponds already to a quite high brightness between 10^{12} and 10^{13} A.(m.rad)$^{-2}$ if we take into account an emitting area of 200 nm in diameter and an initial divergence angle of 20 degrees [8]. We hope to reach even higher peak current with shorter pulses.

These preliminary tests on commercially available field emitters enable us to better understand our needs in terms of cathode development for our particular application. In parallel to collaborations with companies specialized in field emitter fabrication, we also initiated the development of field emitter arrays at the micro and nanotechnology laboratory of PSI.

High Gradient Acceleration in the Diode Gap

As described above, the electrons are extracted from the tips by a grid layer and focalized by a second grid layer one micrometer above the tip apexes. After this focusing layer, electrons enter a drift region until the iris of the radiofrequency cavity. In this gap the electric gradient must be as high as possible in order to limit space charge effects. Space charge forces have a non linear effect on beam spreading which leads to emittance growth.

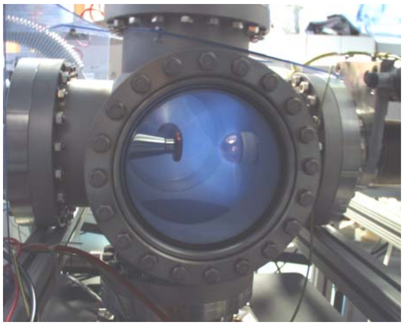

Figure 4: Picture of the high gradient test stand during helium glow discharge treatment used for cleaning / polishing the electrodes.

However, 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 [15]. This dark current must be as small as possible in order to limit his influence on the useful beam and the risks of arcs. Since dark current is also field emitted current, it depends on local field enhancement factor (roughness, dust, …) and surface work function (e.g. adsorbed contaminants). As for tips in FEAs (see companion paper [12]) it is the overheating of the dark current emitter which eventually leads to the generation of an arc. In order to prevent local dark current emitters from generating arcs we plan to apply short voltage pulses (a few hundred of nanoseconds) at low repetition rate. For this purpose, a first pulser prototype delivering pulses of 500 kV amplitude and 500ns length is currently under construction.

To limit dark current intensity (even if it does not generate arcs) very good polishing and cleaning methods for the electrodes as well as clean room conditions during assembling are required. In addition, we are also looking for some in-situ conditioning method once electrodes are sealed under vacuum. For this reason, a specific test stand has been developed in order to test the field strength between two electrodes of similar size to what is foreseen for the final gun (see Fig 4). Different in situ conditioning techniques have been investigated in order to improve the field strength. Fig. 5 represents the dark current measured between two massive copper electrodes of several square centimetres. After glow discharge treatment of the electrodes, the required electric field for 1 nA of dark current went from about 50 MV/m to 75 MV/m. Then we applied a series of 100 ns voltage pulses between electrodes with a small gap in order to draw large dark current pulses. These large current pulses tend to smooth and blunt the dark current emitters. This is a similar method to the one used for the conditioning of tips in field emitter arrays [16]. Other materials, as well as polishing and cleaning processes are under investigation in this test

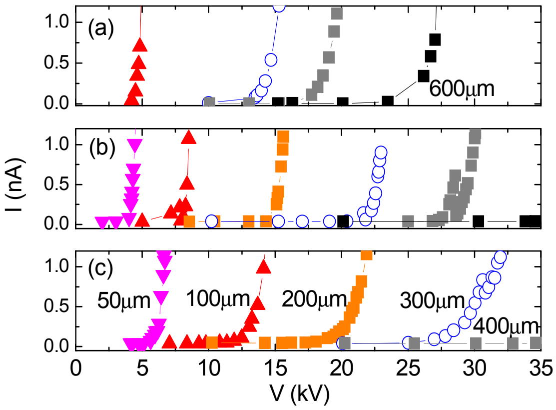

Figure 5: Dark current versus applied DC voltage. The numbers 50 to 600 indicate the electrode gaps in µm. (a) Initial situation at 10^{-9} mbar, (b) after glow discharge treatment of electrodes for several hours and (c) after pulse conditioning (100ns at 50 Hz).

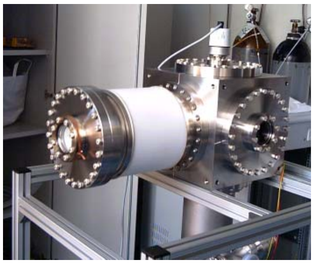

Figure 6: 100kV test stand for evaluation of beam emittance produced by field emitters.

stand in order to reduce dark current in the diode gap of the gun.

Space Charge Compensation

In addition to high-gradient acceleration, magnetic compensation schemes are also considered for emittance preservation. A 100 kV DC gun test stand (see Fig. 6) integrating several beam diagnostic tools is currently under development. This should provide preliminary measurements of beam emittance at 100 keV. This gun prototype will also be used to test various magnetic compensation schemes with solenoids. Fig 6 shows the test stand (not yet completed). This test stand will also enable comparisons with simulation results on beam dynamics.

Simulations

MAFIA simulations have been performed in order to improve the anode – cathode geometry in the 100 kV gun test stand [17]. The purpose of these simulations was to minimize emittance increase at gun exit. Further simulations including solenoid effects have been done and will be compared to measurements done in the gun test stand.

In order to simulate the granularity of the beam emitted by a matrix of thousands of tips, a full 3 dimensional Maxwell solver using particle in cell method has been developed [18]. Comparisons of this 3D PIC solver with Mafia simulation gave good agreement [17].

For example, this 3D PIC code enables simulation of non uniformity of the emission from a field emitter array, when only a fraction of the total number of tips does contribute to the emission. Fig 7 illustrates the evolution of field emitted particles when only 20 % of the FEA tips are emitting (see [18] for details). This preliminary simulation shows a 20 % increases in the normalized transverse emittance when going from a uniform distribution of beamlets to this much worse case where 80 % of the tips are not emitting.

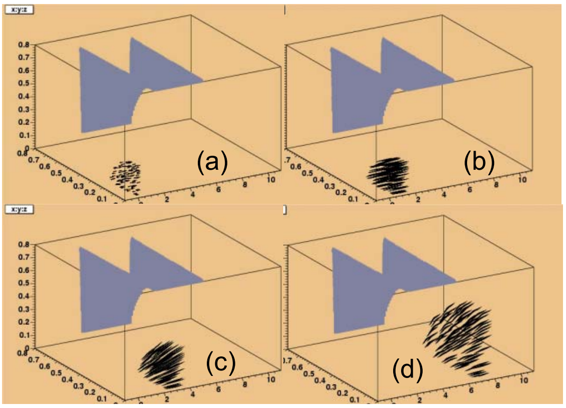

Figure 7: Time evolution of particles emitted by a matrix of individual emitters with 80 % failures. Position in the A – K gap (a), (b) and after the anode iris (c), (d).

CONCLUSION

In order to achieve high quality electron beam for a free electron laser application, 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 integrating such cathodes in high electric gradients are under way.

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