ELECTRON BEAM-LASER INTERACTION NEAR THE CATHODE IN A HIGH BRIGHTNESS PHOTOINJECTOR

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Abstract

The production of high charge short bunches in a high brightness photoinjector requires laser pulses driving the cathode with GW range peak power on a mm spot size. The resulting transverse electric field experienced by the electron beam near the cathode is of the order of 200-500 MV/m, well in excess of a typical RF accelerating field of 50-100 MV/m. We present here a preliminary study of the resultant beam dynamics. Simulations including the electron beam-laser interaction have been performed with the code HOMDYN taking into account the superposition of incident and reflected laser pulses as well as space charge fields. Under this conditions the emittance degradation is negligible, as predicted by analytical methods, but a longitudinal charge modulation occurs on the scale of the laser wavelength, in case of oblique incidence, driven by the longitudinal component of the laser field. Charge modulation is transformed into energy modulation via the space charge field, which may produce enhanced microbunching effects when the beam is further compressed in a magnetic chicane.

INTRODUCTION

Electron beam – laser interaction near the cathode surface could be important in case of short and strong laser pulses, when the involved field becomes high and the electrons have a very low momentum (emission is achieved slightly overcoming the cathode work-function to reduce thermal emittance). We consider in this study the case of a metal photocathode. Other kinds of photocathodes, such as high Quantum Efficiency (QE) Cs_2Te have no need to be driven at high power, in addition their response is slower (some ps), and the considerations that will be made in this framework require some slight adjustments to fit the alternative case of semiconductor cathodes. A large laser field at the cathode can produce "heating" of the electron beam through the induced wiggling motion. The degree to which the laser field causes emittance growth can be estimated as [1]:

$$\varepsilon_n = a_l \sigma_x \approx \frac{\lambda_l}{2\pi m_e c^2}\sqrt{Z_0 P_l}$$

Here a_l is the peak normalized vector potential of the laser field, P_l is the peak laser power and λ_l the laser wavelength (note the independence of the beam size σ_x). For example a laser pulse 300 fs long with an energy of 0.2 mJ as required by a blow out experiment [1], able to extract 0.33 nC charge from a 10^{-5} quantum efficiency cathode, results in a 0.04 μm induced emittance growth. This effect, while physically interesting, is negligible in this case. A more interesting effect is produced on the longitudinal phase space, as will be discussed in the next sections.

HOMDYN SIMULATIONS

The fast running code HOMDYN [2] has been modified in order to include the beam interaction with the laser field, here modelled as a simple truncated plane wave, in addition to the RF and space charge fields already implemented in the code, including the important effect of the cathode image charges.

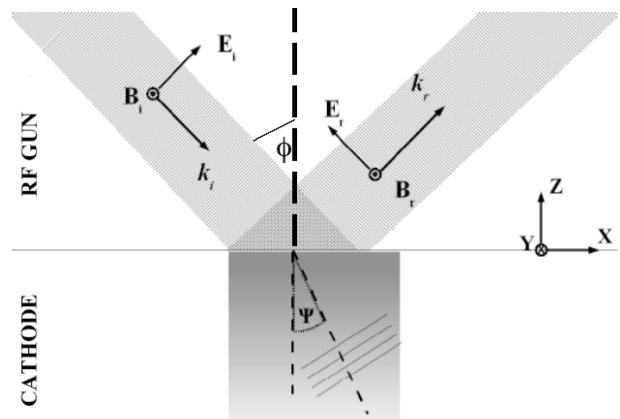

Figure 1: P-polarized plane wave incident on a lossy medium [3].

The expression of the electromagnetic field of a plane wave incident on a lossy medium for a p-polarized wave is the following, see also Fig. 1:

$$B_i = -\hat{y}(E_i / c)cos(k_i.r - \omega t + \varphi_i)$$

$$E_i = E_i[\hat{x}cos\vartheta + \hat{z}sin\vartheta]cos(k_i.r - \omega t + \varphi_i)$$

$$B_r = -\hat{y}R(E_i / c)cos(k_r.r - \omega t + \varphi_R)$$

$$E_r = E_i R[-\hat{x}cos\vartheta + \hat{z}sin\vartheta]cos(k_r.r - \omega t + \varphi_R).$$

Assuming a cathode reflection coefficient constant within the laser wavelenght spectrum. The previous expressions can be easily extended to the general case of a real laser pulse, without operating integration over the spectrum. It is sufficient to substitute the incoming envelope expression into the amplitude of the incoming field E_i.

Dealing with lossy media (i.e. radiation must be absorbed to generate photo-electrons) the p-polarization is reflected again as p, but with a phase shift due to the complex index of refraction n. Photoemitted electrons experience a field that is sum of incoming and reflected wave. Inside photocathode the field amplitude is attenuated exponentially in direction normal to the surface, and propagates at a slightly different angle, this effect will be include in a future work.

Both normal and oblique laser incidence (at 70 degrees) have been taken in consideration in HOMDYN simulations. A laser field amplitude of 190 MV/m is assumed, the RF field experienced by the electrons injected in the gun with 26 phase degrees is 53 MV/m, (120 MV/m peak field). Laser wavelength was fixed at 266 nm, able to drive Cu and other metal photo-cathodes.

The first case considered here is a 10 ps long laser pulse at normal incidence and a 1 nC e-bunch charge, corresponding to the nominal SPARC parameters [4]. An integration time step of 0.1 fs (corresponding approximately to 10% of the laser central wavelength period) and 1000 slices 40 nm long (about λ/7) were used. As was expected, each slice experiences the fast varying field of the laser, as a cosequence slice centroids undergoes a fast oscillation in space. The amplitude of the oscillations grows with the time, and so this effect is enhanced in the first emitted slices compared to the last ones as shown in Fig. 2.

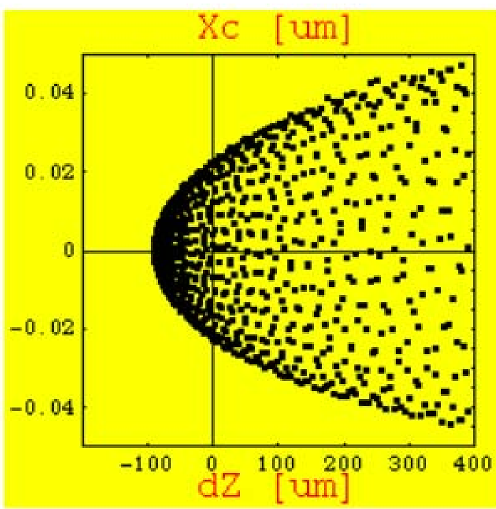

Figure 2: Slice centroids evolution during the interaction with the laser beam. Each dot represents a slice centroid located at a distance dz from the bunch central slice.

This effect occurs on a negligible scale , so that, looking at the macroscopic consequences on the beam, neither envelope, nor emittance or energy spread are affected in such a way to show a noticeable degradation of the beam quality. Emittance on a time scale of 10 ps reaches a value of 0.05 µm.

The case of grazing incidence is more interesting. First of all, the angle introduces an asymmetry on electron trajectories, depending on different field phase which particles experience at different emission times, Fig. 3. Once again, the transverse dynamics is affected by an even weaker effect, than in normal incidence

The computed emittance behaviour for a 1 ps laser pulse, 1 pC charge is shown in Fig. 4. As can be seen in the plot, after a time of 1 ps the emittance growth due to space charge prevails.

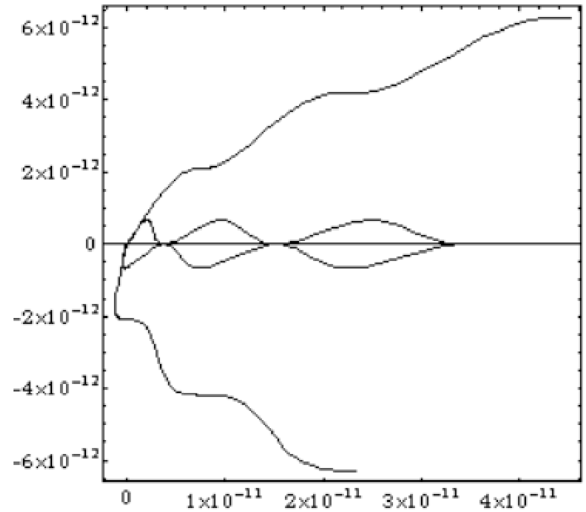

Figure 3: Electron trajectories for different injection phases in a laser field with grazing incidence. (Transverse displacement [m] versus time [s]).

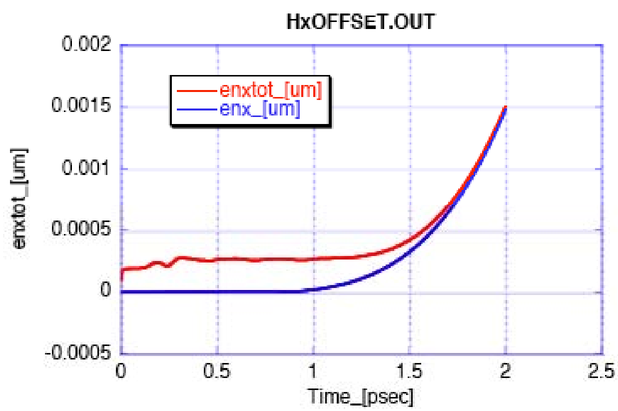

Figure 4: Normalized emittance vs. time for the 1 ps laser, 1 pC case. Blue line: space charge induced emittance Red line: total emittance including laser induced emittance.

On the other hand since laser contribution is now mainly longitudinal, we expect a some effect on the longitudinal motion. Preliminary simulations show that even if the induced energy spread is negligible, a charge modulation on a scale of the laser wavelength occurs. Different groups of slices emitted within different half periods of the laser field will experience in fact accelerating or decelerating laser fields components, while the electron velocity changes from a non-relativistic to a relativistic regime, due to the superimposed RF accelerating field. The initial extraction velocity $\beta=v/c=0.002$ in this case is enough to prevent backward acceleration. This periodic shrinking and broadening of the slices, that last until the end of the electron-laser interaction, results in a slice current modulation, as shown if Figures 5 and 6. Notice that the current modulation can reach a 40% depth. Downstream the cathode the beam evolution is dominated by space charge effects and will transform this current modulation in energy modulation [5].

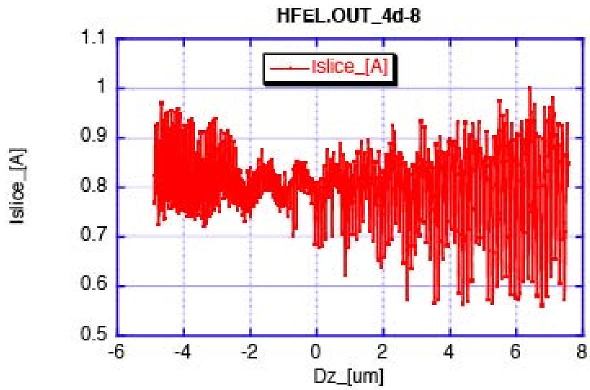

Figure 5: Normalised beam current modulation at the end of the photo-emission process.

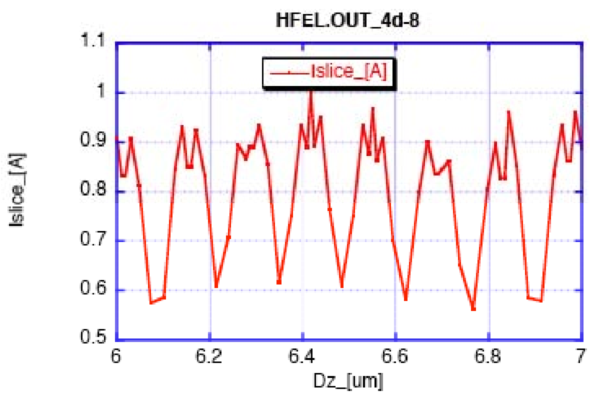

Figure 6: Normalised beam current modulation at the end of the photo-emission process, blow up of Fig. 5. Notice the deep current modulation (40%) on the laser wavelength scale.

This effect could be important when a magnetic compressor is installed in the downstream beam line because it could produce an enhanced micro-bunching on the scale of the photo-injector laser wavelength [5].

CONCLUSIONS

Though laser field doesn't affect in a relevant way the electron beam emittance and energy spread, in the case of grazing incidence it generates a current modulation inside the bunch. Current modulation is trasformed into energy modulation via the space charge field, which may produce enhanced micro-bunching when the beam is further compressed in a magnetic chicane. On the other hand, as a concluding and wishful remark, one can take profit of such an energy modulation as a possible alternative to laser heating [6]. By means of a high power longer wavelength (I.R.) laser conditioned photo-emission (i.e. illuminating the cathode with an IR laser light in addition to the required UV light), one may think to pre-heating the electron beam by enhancing the current modulation at the cathode. The space charge induced energy spread is then tranformed in an uncorrelated energy spread in a downstream chicane with negative R_{56} [5]. A more detailed study on this subject is under way to asses the amplitude of the achievable energy spread.

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