ANALYSIS OF RADIATIVE EFFECTS IN THE ELECTRON EMISSION FROM THE PHOTOCATHODE AND IN THE ACCELERATION INSIDE THE RF CAVITY OF A PHOTOINJECTOR USING THE 3D NUMERICAL CODE RETAR

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Abstract

The three-dimensional fully relativistic and self-consistent code RETAR has been developed to model the dynamics of high-brightness electron beams and, in particular, to assess the importance of the retarded radiative part of the emitted electromagnetic fields in all conditions where the electrons experience strong accelerations. In this analysis we evaluate the radiative energy losses in the electron emission process from the photocathode of an injector, during the successive acceleration of the electron beam in the RF cavity and the focalization due to the magnetic field of the solenoid, taking also into account the e.m. field of the laser illuminating the cathode. The analysis is specifically carried out with parameters of importance in the framework of the SPARC and PLASMONX projects.

INTRODUCTION

RETAR is a hybrid point to point 3D tracking code for the beam dynamic of charged particles, in particular we are focusing on high brightness electron beams. The code is fully relativistic and calculates the self-fields directly from convenient integral forms that can be obtained from the usual retarded expressions [1].

The electric and magnetic field used into the motion equations take into account both external and self-fields. The self-fields are calculated directly in terms of charge density $\rho(x,t)$ at time t and at all preceding times through the following equations:

$$E(x,t) = \int dx' \rho(x',t) Q_E(x-x',t)$$

$$B(x,t) = \int dx' \rho(x',t) Q_B(x-x',t)$$

where $\tau = t - \frac{1}{c}\left|x-x'\right|$ and

$$Q_E = \frac{n\times((n-\beta)\times\dot{\beta})}{c\left|x-x'\right|(1-n\cdot\beta)^2} + \frac{(n-\beta)(1-n\cdot\beta)^{-2}}{\gamma^2\left|x-x'\right|^2}$$

$$Q_B = -\frac{n\times(\dot{\beta}(1-n\cdot\beta)+\beta(n\cdot\dot{\beta}))}{c\left|x-x'\right|(1-n\cdot\beta)^2} - \frac{(n\times\beta)(1-n\cdot\beta)^{-2}}{\gamma^2\left|x-x'\right|^2}$$

In addition, $n = (x-x')/\left|x-x'\right|$, $\beta = v(t)/c$, and all time dependent quantities in (3) and (4) are calculated at the retarded time τ.

In this paper we will analyse the radiation emitted by a high charge (1 nC) bunch of electrons moving in assigned electric and magnetic fields and under the effect of the self consistent field. We performed the analysis of the electron beam during the extracting from the photocatode and the tracking into a RF Gun. A solenoid field is present to perform the emittance compensation scheme [2-3]. We are interested in the particular aspects of the effects of the retarded radiation on beam dynamic and its exploiting for an non destructive diagnostic.

CHARGE EXTRACTION

In a point to point tracking code, to simulate the electrons extraction from the photocatode surface in a refined way, it is necessary a huge number of macro-particles (mp) that involves very high time-machine. If the simulations are performed with a low number of mp, numerical noises appear in the phase-spaces, like stratifications and unphysical correlations. To avoid these problems, by using a reasonable numbers of mp, it has been developed an algorithm able to manage the mp like 3D distributions that grow up from the cathode in a gradual way, with an adaptable charge scaled by the outer portion and with an adaptable position fixed in the distribution barycentre. In Fig. 1 (top) there are shown transversal and longitudinal phase-spaces, at 1ps and 2ps, for a flat-top 10ps bunch length and 1 nC bunch charge and the respective transversal views accompanying with their self-fields.

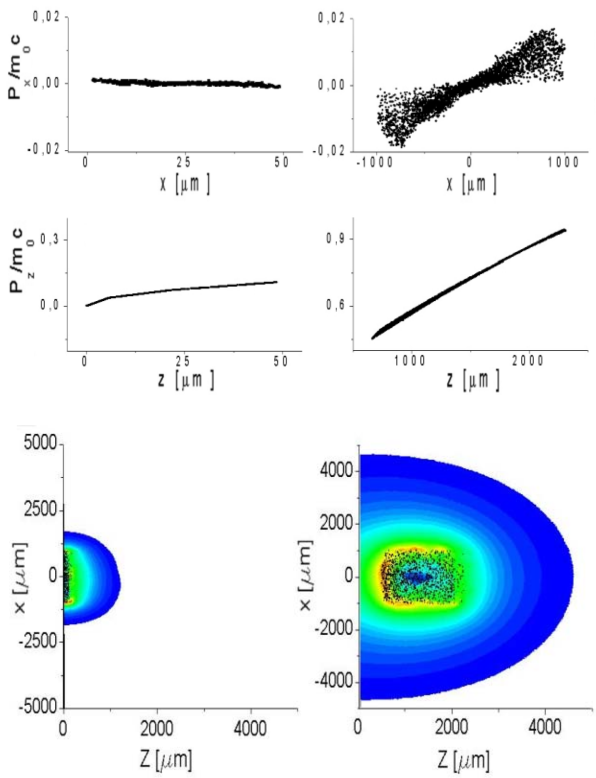

Figure 1: Longitudinal and transverse phase-spaces and electric field density plot for a 1 nC bunch at times t=1ps (left) and t=12 ps (right)

ACCELERATION AND RADIATION LOSSES

The amount of emitted radiation is negligible during the extraction process, due to the low accelerations experienced by the electrons. Here the dynamic is dominated by space charge effects: the electric field, starting from a minimum in the centre of the bunch, increases linearly and approaches its maximum on the bunch's edge, as is expected from a uniform cylindrical charge distribution. In particular, from Fig 1 (bottom), we see the strong electric fields generated by the image charges and affecting mostly the trailing area of the bunch. The situation radically changes as the beam begins to gain energy due to the external RF field. In Fig. 2, we see that two wings of emitted radiation build up around the bunch. They manifest a cylindrical symmetry around the z axis, as expected from the symmetry properties of the source. Such wings are only the most intense portion of a spherical-like wave, with the bunch on the right edge. We note also that the granularity present in the exit phase due to the macroparticle scheme is completely smeared out.

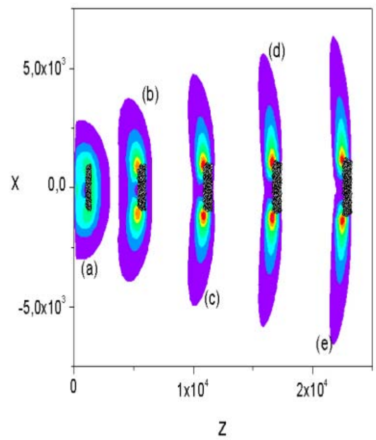

Figure 2: A density plot of the electric vector field for a 1 nC at different times: (a) t=17psec,(b) 34psec,(c) 51psec,(d) 67psec (e) 84psec

An evaluation of the radiative losses can be given by computing the flux of the Poynting vector through a surface (for instance a cylinder S) surrounding the electron beam.

The power irradiated is in fact

$$P_R = \int E \times B \cdot n \, da \tag{1}$$

and the total energy irradiated is given by

$$W_R = \int dt \int E \times B \cdot n \, da \tag{2}$$

The power P_R on a cylinder surrounding the beam and with a radius r=5mm as function of time is represented in Fig 3.

The power is initially zero until a time $t \sim r/c$, due to the delay in arriving on the surface of the cylinder, is elapsed, followed then by a sequence of maxima and minima.

From the comparison between the shape in time of the power emitted and the shape of the external electric and magnetic fields as seen by the electrons of the bunch, we can say that the first peak of radiation is due to the first maximum of the accelerating electric field, reshaped by the retard effects, while the second peak corresponds to the second peak of acceleration, superimposed with the entrance into the magnetic field. Afterwards there is a less accentuated peak of radiation, corresponding to the exit from the solenoid, that for the case of the larger charge is not visible on the scale of the graph.

The evaluation of the power emitted by the beam on the basis of the Larmor formula (3), applied as if the beam were a single charge of 1 nC, gives a peak of radiation of $P=8.3\ 10^4$ Watt. Accounting for the internal structure of the beam diminishes this value of a factor 10-20%, and this difference increases with increasing charges.

The integration in time of the power gives the total energy. For the values Q=1 nC and 5 nC the total energy is respectively E=2,25 10^{-5} J and E= 1,9 10^{-4} J. Values of this order should not be difficult to measure experimentally.

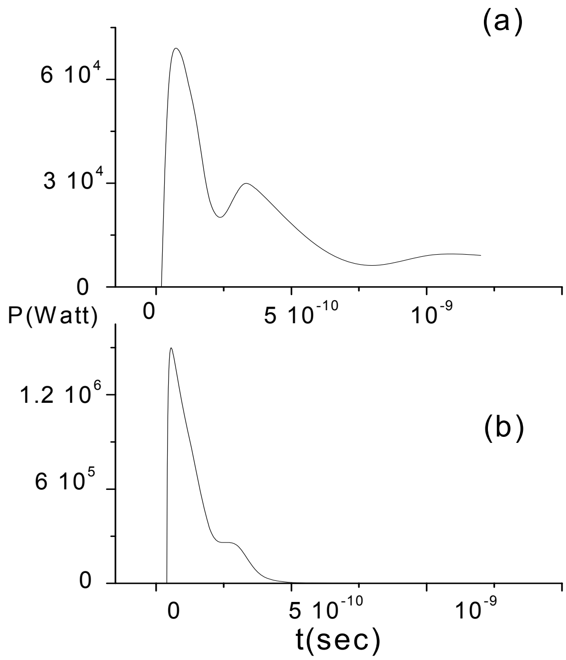

Figure 3: Total emitted power for (a) Q=1nC and (b) Q=5 nC

Using of the Radiated Energy/Power as a Diagnostic Tool

The monitoring of the emitted retarded radiation can be used to gain information about the bunch. As an example, from the Liénard result that generalizes the Larmor formula for point-like charge far from the source

$$P = \frac{2}{3}\frac{q^2}{c}\gamma^6\left[(\dot{\beta})^2 - (\beta \times \dot{\beta})^2\right] \qquad (3)$$

we see that the total emitted energy scales with the square of the bunch charge. Deviations from this dependence can appear for large values of beam charge due to space charge effects and for measurements taken near to the beam. For a 1 nC bunch, the total radiated energy (over 2π angle) is about 22.5 µJ; the power pulse can be thought of as an emission peak with a rise time of about 100 ps and a 70 kW peak value, followed by a 400 ps tail.

For sake of simplicity we model it as a 75 kW square pulse of 300 ps duration, yielding the same pulse energy, and expect an associated bandwidth of about 3 GHz. Assuming a 1% coupling to a 1 GHz device, we have a coupled peak power of 750 W. For a 1 Hz bunch repetition rate the average power is 0.225 µW. These results agree with the data shown in Fig. 4, where the electric field calculated in a point far from the beam is shown as a function of time (top), together with its FFT (bottom).

Typical diode detector sensitivities are about 0.5 – 1 mV/µm so an output voltage of about 0.1 – 0.2 mV should be expected, for a CW or long pulse. Because of its short duration, the single pulse measurement is not feasible, but an integrated and averaged measure over many pulses can be achieved. In this way indication of the bunch charge can be obtained.

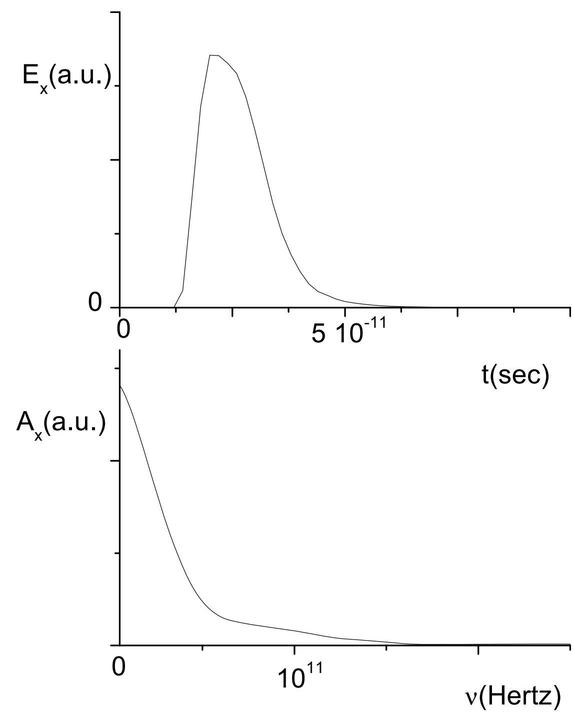

Figure 4: The electric field as a function of time(top) and the signal FFT (bottom).

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